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Research Article

Nuisance or not? Tourism impacts from spongy moth tree defoliation in U.S. National Park Units

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ABSTRACT

Non-native and native invasive defoliators can decrease recreation visitor enjoyment. We use data on observed recreation visitation to investigate the impact of spongy moth, Lymantria dispar L. (Lepidopetra: Erebidae) outbreak events. Spongy moth is a polyphagous defoliator pest that emerges in the early spring and feeds through the summer months. Caterpillar feeding can completely defoliate trees during outbreaks, sometimes resulting in tree mortality. We gathered data on defoliation events in U.S. National Parks and estimated a fixed effects regression model with lags to estimate the dynamic impact of outbreak events. We found that there is a decrease in visitation in the year of the outbreak infestation, with statistically significant effects up to five years after the event. Future analyses could differentiate between the infestation event itself and the management actions, such as chemical or biological treatments, taken to control outbreaks.

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Key policy highlights

1. Spongy moth defoliation events on National Park Units resulted in a statistically significant decrease in recreation visitation.
2. Park managers could plan for declines in recreation visitation and thus drops in fee revenue or tourism satisfaction during outbreak years to the impacted park.
3. Differentiating between the effect of defoliation from subsequent treatments may be important for planning effective management responses that consider the preferences of recreation visitors.

1. Introduction

Non-native and native forest insects, such as spongy moth [*Lymantria dispar* L. (Lepidoptera: Erebidae), formerly known as 'gypsy moth'], emerald ash borer [*Agrilus planipennis* Fairmaire (Coleoptera: Buprestidae)], mountain pine beetle [*Dendroctonus ponderosae* Hopkins (Coleoptera: Curculionidae)], and others, have caused considerable damage to forests in the United States (U.S.), which can decrease visitor enjoyment (e.g. Arnberger et al. 2018; Schneider et al. 2019; Hicke, Meddens, and Kolden 2016; Gould, Fierke, and Hickin 2022; Lindroth et al. 2024). There is a body of literature that quantifies the impacts of wildfires and other disturbances on tourism and recreation

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behaviour (e.g. Gellman, Walls, and Wibbenmeyer 2022; Sánchez et al. 2021); yet, the impacts of non-native, invasive species, and particularly invasive insects are understudied. In addition, the management of invasive species might also impact recreation and tourism. In this study, we quantify the impacts of spongy moth on recreation and tourism in U.S. National Park Units (NPUs). Specifically, we propose a way to test two research questions. First, does spongy moth impact recreation and tourism in NPUs? Second, if there is an impact, does it persist over time?

Nature-based tourism is a rapidly growing sector of the economy (Winter et al. 2019), where recreationists travel to destinations to explicitly connect with the outdoors via activities such as hiking, fishing, photography, and others. Spongy moth was introduced to the northeastern U.S. in the late 1860s. Since then, spongy moth has had the potential to reduce benefits for recreation visitors due to decreases in esthetic scenery, impacts to the natural environment, and potential human health hazards (such as allergic reaction).

Federal quarantines and numerous management programmes have limited spongy moth spread to several midwestern and eastern states. Though spongy moth is polyphagous, meaning it can feed on various food sources, the most susceptible trees are oak (*Quercus spp.*), birch (*Betula nigra, B. papyrifera*, and *B. populifolia*), basswood (*Tilia americana*) and *Populus* spp. (*Populus balsamifera, P. grandidentata,* and *P. tremuloides*) (Liebhold et al. 1995). While conifers are not preferred hosts, they are more vulnerable to mortality, possibly since they are not adapted to rapid leaf turnover (Davidson, Gottschalk, and Johnson 1999).

In general, moth outbreaks occur over 5–10-year intervals, oak-dominated forests routinely experience shorter intervals, and some pine forests experience longer intervals between outbreaks. Findings from Johnson, Liebhold, and Bjørnstad (2006) suggested that oak-pine and oak-hickory had strong periodicity of 4–5 years, while white-red-jack pine and maple-beech-birch had periodicities of 8–12 years. Once an outbreak occurs, they typically last between one and three years (Elkinton and Liebhold 1990).

Methods exist to effectively manage spongy moth outbreaks, including aerial application of mating disrupters, biopesticides (*Bacillus thuringiensis* var. *kurstaki*), and insect growth regulators (Diflubenzuron and Tebufenozide) (Coleman et al. 2023a). Fall egg mass surveys and trap-catch data are frequently used to predict spongy moth densities for the following year and to inform subsequent management actions (Liebhold et al. 1994; Coleman, Foelker et al. 2023). Suppression treatments are assigned based on the potential for the continuation of an outbreak and tree injury and mortality, management goals, and the budget of the coordinating agency. Typically, suppression treatments occur after spongy moth defoliation is observed, suggesting that unsightly views and health impacts may occur in the early phases (or first year) of an outbreak, and treatments may impact visitation in future years (i.e. temporary closures of high-use sites for pesticide application via aerial spraying).

Esthetic impacts from invasive species have been quantified for distant vistas such as via panoramic views and highway overlooks, as well as short-range (i.e. near-view) from a point of interest such as a hiking trail. Past studies have considered defoliation 'light' if less than 30% of the tree is defoliated, 'moderate' if between 30-60% is defoliated, and 'heavy' if greater than 60% is defoliated (Davidson, Gottschalk, and Johnson 1999). As described by Twery (1991), the Skyline Drive National Parkway, in Shenandoah National Park, potentially lost attractiveness due to defoliated hillsides during June and July after a spongy moth outbreak. While the authors expected to find a decrease in visitation, qualitative results suggested that the increase in light spurred growth in the understory, which resulted in no change in visitation preferences (Twery 1991). Hollenhorst et al. (1993) sought to quantify the preferences of recreation visitors from visual damages in 'near-view' caused by spongy moth. In June 1989 three photos were taken at 25 sites in Somerset County, Pennsylvania with and without spongy moth damages. Images were shown to 400 individuals, who rated the images on a 10-point scale for preference and appeal for visitation. They found that preference for visitation increased as spongy moth-induced tree mortality reached 30-40%, and only after mortality exceeded 40% did preference for visitation decrease. It is possible that short

term changes in forest composition (e.g. increase in understory flowers such as mountain laurel) from 'light' levels of defoliation may be tolerated or even preferable by recreationists (Davidson, Gottschalk, and Johnson 1999; Twery 1991; Brock, Hollenhorst, and Freimund 1991).

Additionally, visitor effects may differ between recreation users (Twery 1991). For example, high-use areas (such as picnic grounds, camping sites, popular trails, or monuments surrounded by host trees) may be more impacted by spongy moth nuisances as compared to backcountry trails or recreation areas that have indoor attractions. During spongy moth outbreaks, copious amounts of frass (caterpillar solid waste or excreta) and leaf fragments can rain down from trees (Appendix A). Furthermore, contact with larvae can cause skin wheals, rashes, and other allergic reactions (Twery 1991; Gooderham et al. 2021). Goebl (1986) conducted a recreation user survey on Allegheny National Forest in 1986. At the time of data collection, Allegheny National Forest was approximately 500,000 acres with moderate to severe defoliation, which occurred on 78,100 acres (approximately 16% of the forest area). The researchers found that 51% of recreationists were aware of the spongy moth while taking the survey. The researchers hypothesized that participant knowledge was due to previous years of defoliation events. Approximately 26% of users stated that they shortened their visit due to the infestation, and 79% disliked the loss of esthetic value. Of those surveyed, 27% said they would not return the following year if the spongy moth were present (Goebl 1986). Similarly, Moeller et al. (1977) conducted interviews among 201 recreation managers about the effects of spongy moth infestation in New York and Pennsylvania. From 16 recreation managers surveyed who managed public lands, 25% reported a loss equaling 36,660 person-days due to the spongy moth outbreak (Moeller et al. 1977).

Much of the literature has pointed to anecdotal evidence (Moeller et al. 1977) or relied on stated preference methods (Goebl 1986; Hollenhorst et al. 1993) to assess tourism and recreation impacts from spongy moth outbreaks. In fact, the majority of studies that have assessed the impact of forest pests, including emerald ash borer and mountain pine beetle (Arnberger et al. 2018; Meitner, South, and Wieler 2011; Schneider et al. 2019), have used stated preference methods, primarily surveys, to assess tourism impacts. For instance, Schneider et al. (2019) found that 80% of recreationists would change their plans after being shown images of varying levels of tree mortality caused by bark beetle outbreaks. Approximately 68% of respondents reported that they would likely switch to a different site when the preferred location had high levels of tree mortality, and 2% said that would stay home. Arnberger et al. (2018) examined the impacts of bark beetles specifically on the esthetic qualities of recreation sites in the U.S. and in Germany, finding that visitors preferred healthy forests over those with considerable amounts of dead wood. Arnberger et al. (2017) similarly assessed the impact of emerald ash borer, a non-native, invasive wood borer causing elevated tree mortality of native ash (*Fraxinus* spp.) in the U.S., using discrete choice photo-questionnaire methods. In general, larger and near-view clearcuts, dense understory vegetation, high densities of small even-aged trees, and presence of dead wood from timber harvests or snags decreased visitor preferences. Stated preference studies such as Schneider et al. (2019), Arnberger et al. (2017), and Arnberger et al. (2018) have an advantage in that they can focus their impacts on specifically the esthetic aspects of invasive species management but may misestimate the decrease in recreation visits.

Our study is the first to collect observational data to assess recreationist preferences during and post the spongy moth outbreak. The outdoor recreation economy is estimated to be 1.8% of the U.S. gross domestic product (Outdoor Industry Association 2022) and provides more than 19 billion in federal tax revenues from the combined mid-Atlantic, New England, and North Central U.S.A. (Outdoor Industry Association 2017). On average, over 840,000 recreation visitors travel to NPUs in the northeastern U.S., where the current range and quarantine area of the spongy moth occurs, such that outbreak events are possible. The objective of this study was to assess the impacts of spongy moth outbreaks on recreation visitors to U.S. NPUs in defoliated counties in the northeastern U.S. using data from a 17-year period. The rest of the paper is organized as follows. We discuss the methods used to assess the impact of spongy moth outbreaks at NPUs in the northeastern U.S., followed by a detailed discussion of the data collected and aggregated to conduct the study. We

then summarize findings and explore implications of these findings for recreation visitors. We end with some conclusions and directions for future research.

2. Data

Data for model estimations were collected from several sources, including the National Parks Service (NPS) Visitor Use Statistics webpage, the National Oceanic and Atmospheric Administration (NOAA) 'climate at a glance' webpage, ArcGIS Hub, as well as the USDA Forest Service Forest Health Monitoring (FHM) programme (Table 1). Information for a total of 94 NPUs was collected from 1993 to 2019 from spongy moth-infested states, or states that had known spongy moth infestations (see Figure 1). Of those parks in known infestation areas, 6 of them had recorded defoliation events. Spongy moth defoliation events were mapped in ArcGIS along with NPU and county boundaries. We collected the number of acres in each NPU, and the percentage of each NPU defoliated (Table 1, Source E). We then mapped NPS trails and 'interest points', meaning the visitor centres, vistas, and camping sites (Table 1, Sources F and H). For example, in Catoctin Mountain Park, we mapped the visitor centre, Thurmont Vista, Chimney Rock, Camp Misty Mount, Camp Round Meadow, and Owens Creek Campground (see Appendix B). Similar to Lee, Suter, and Bayham (2023), a buffer of one mile[1] was extended around each interest point, assuming that the defoliation event may impact scenic views. If any defoliation event was within the buffer of the interest point, then we considered that location to be impacted. Further, we quantified percent of trails impacted by defoliation, which was measured by area of the trail that intersected the defoliation event.

Next, we merged NPU boundaries (Table 1, Source A) with several U.S. County level datasets. Many parks crossed one or more counties. Precipitation was averaged across counties to get the average precipitation for each NPU, and the same was conducted for temperature (Table 1, Source C). For each NP, we merged total yearly recreation visits from the NPS visitor use statistics (Table 1, Source B). Visitation to NPUs is normally distributed around the summer months, typically

Table 1. Sources of data collection.

Data source ID	Data	Source	Citation
A	National Parks System (NPS) Shape Files	ArcGIS, NPS tract and boundary data created by the Land Resources Division	National Park Service. Accessed 2024. https://public-nps.opendata.arcgis.com/datasets/nps::nps-boundary-4/explore?location=36.189880%2C-82.222532%2C7.90
B	National Parks System (NPS) Visitor Use Statistics	U.S. Department of the Interior	National Park Service Visitor Use Statistics. Accessed 2024. https://irma.nps.gov/Stats/
C	'Climate at a Glance' Precipitation by County	National Oceanic and Atmospheric Administration (NOAA)	NOAA, National Centers for Environmental Information. Accessed 2024. https://www.ncei.noaa.gov/access/monitoring/climate-at-a-glance/county/mapping/110/pcp/199312/12/value
D	United States County Shape Files	ArcGIS Hub	ArcGIS Hub, USA Counties. Accessed 2024. https://hub.arcgis.com/datasets/esri::usa-counties/explore?location=22.156496%2C56.950742%2C4.00
E	Spongy Moth Historical Defoliation events Shape Files	USDA Forest Service	Received from Forest Health Monitoring. Received 2023.
F	Trails	National Park Service Trails ArcGIS	National Park Service, NPS Trails. Accessed 2024. https://public-nps.opendata.arcgis.com/datasets/nps-trails-web-mercator-1/explore
H	Interest Points	U.S. National Park Service	NP Webpage Maps, *For Example*: Catoctin Mountain Park, Accessed 2024. https://www.nps.gov/cato/planyourvisit/maps.htm

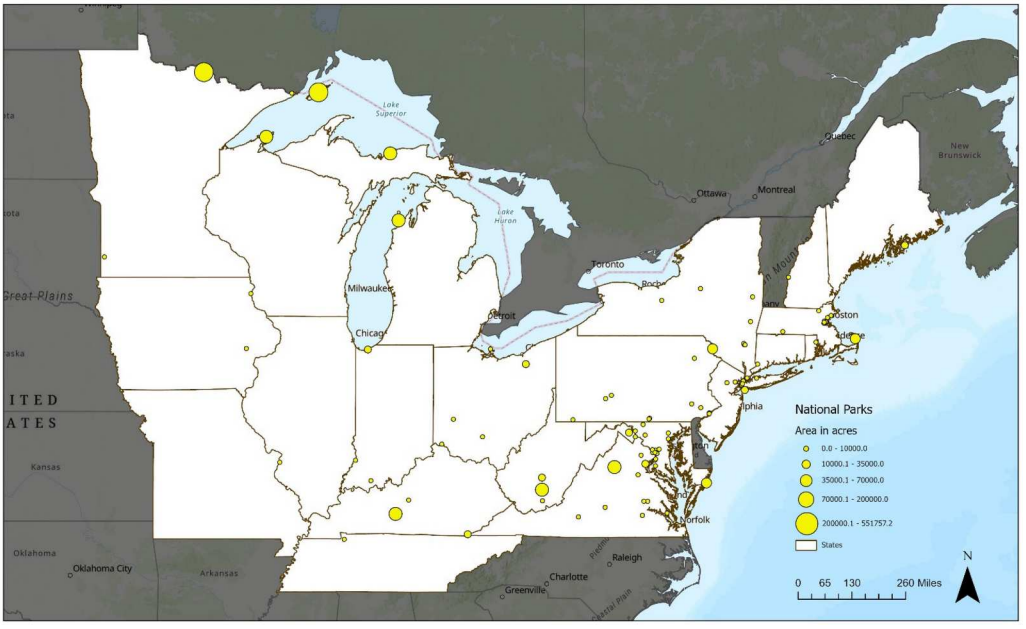


Figure 1. States with National Parks (NPs) used to estimate the effect of spongy moth infestation on tourism. Tennessee is included here, because Cumberland Gap National Historic Park and Fort Donelson National Battlefield cross state boundaries (TN, VA, & KY, and TN & KY, respectively). For a full list of NPs please see Appendix A.

peaking in June or July. Peak spongy moth caterpillar activity coincides with the typical recreation months, occurring in May and June (Coleman, Graves et al. 2023).

Figure 2 illustrates annual acres impacted by state that had a NPU with a defoliation event. Acres impacted included all recorded spongy moth-related events, such as mortality, defoliation, crown dieback and discolouration. We found that West Virginia had the highest level of acres impacted, with over 840,000 acres (339,935 hectares) in 2001, 93,000 (37,635 hectares) in 2008, and 126,000 (50,990 hectares) in 2016. Virginia and Maryland had the second highest level of acres impacted, with between 20,000 and 126,000 acres (8,093 and 50,990 hectares) during outbreak years. Other states in the dataset had infestation events during this time period; yet those events did not occur in any NPU.

Eight NPUs had defoliation events between 1993 and 2019.[2] Yet, two were excluded from the study (Harriet Tubman National Park and Appalachian National Scenic Trail) because total recreation visitor data was not available. We also made the decision to exclude the National Capital Parks, since this was a combined variable in the NPS recreation visitor database. Thus, six NPUs that were

Table 2. National Parks with recorded spongy moth defoliation and tree mortality events from 1993 to 2019.

National park name (*State(s)*)	Number of high defoliation events from 1993 to 2019	Number of low defoliation events from 1993 to 2019
1. Catoctin Mountain Park (*M.D.*)	2	5
2. Chesapeake and Ohio Canal National Historical Park (*D.C., M.D.*)	1	2
3. George Washington Memorial Parkway (*V.A., D.C., M.D.*)	1	1
4. Harpers Ferry National Historical Park (*W.V., M.D., V.A.*)	3	5
5. Monocacy National Battlefield (*M.D.*)	2	1
6. Bluestone National Scenic River (*W.V.*)	0	2

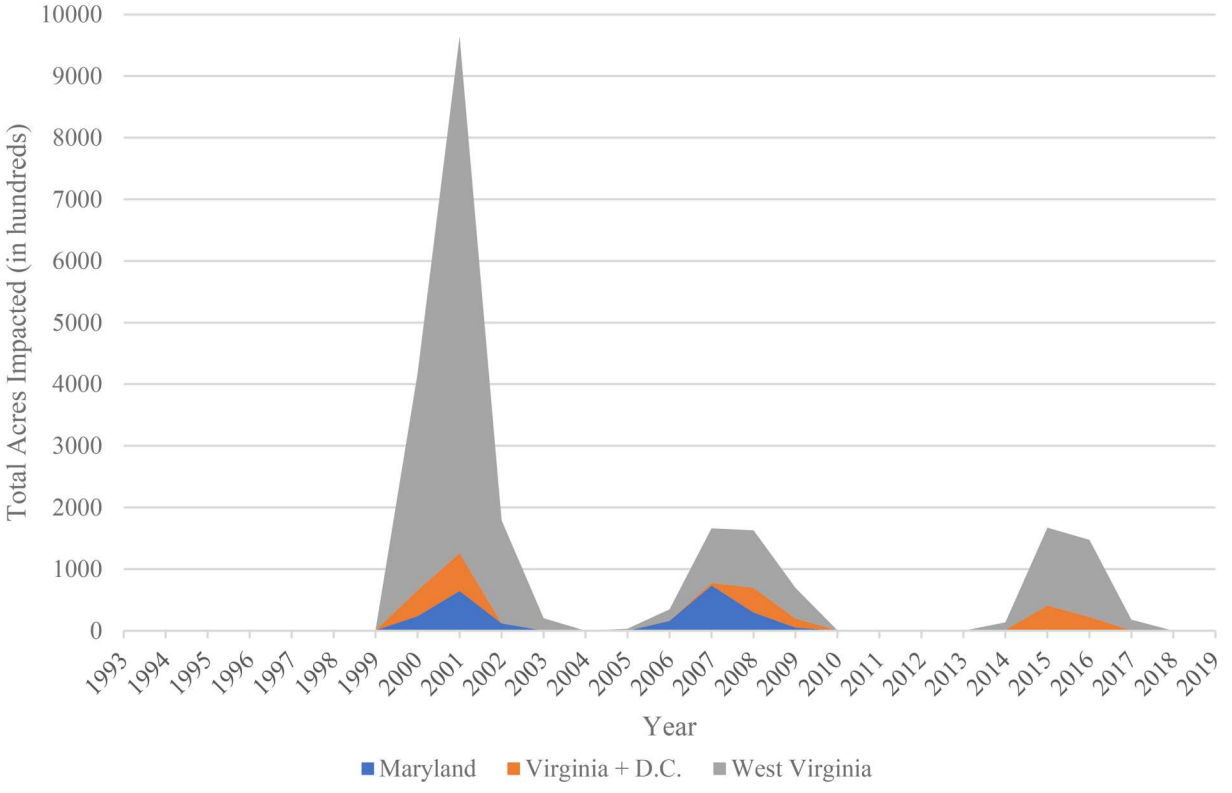


Figure 2. Annual acres impacted by spongy moth from 1993 to 2019 in states with defoliated National Parks. Total acres impacted for the entire state depicted here include recorded events, such as mortality, defoliation, crown dieback and discolouration. Approximately 16 acres were impacted by the moth in Washington D.C. in 2006 and are combined with Virginia.

impacted by spongy moth defoliation events were included in this analysis (Table 2), and the full set of NPUs included in the econometric model can be found in Appendix B. All impacted parks were in Maryland, Virginia, West Virginia, and/or the District of Columbia (D.C.). Only one NPU had a recorded tree mortality event, Harpers Ferry National Historic Park, which occurred in 2009. Notably, tree mortality resulting from defoliating insects is often difficult to detect during aerial detection surveys and is commonly not mapped. All high defoliation events occurred between 2000 and 2008, and low defoliation events occurred between 2000 and 2016. The year that defoliation events occurred can be found in Appendix D. Data transformations were conducted in ArcGIS Pro 3.3.6. Analyses were conducted in STATA 18.0.

3. Methods

In order to examine the impacts of the invasive spongy moth on recreation, we constructed a model of NPU visitation[3] across its infested range. There is well-established literature that examines NPU recreation, which suggests a wide variety of factors that may influence recreation visitation (Gosal et al. 2021). Many of these factors do not significantly vary through time (i.e. mountainous regions, size of the NPU, proximity to cities, and others), and so we used a panel fixed effects model to assess how recreation visitors responded to spongy moth defoliation events. The analysis was complicated by the fact that recreational areas have annual variation in levels of defoliation and that this defoliation can have effects that last several years. We included non-impacted parks to establish a counterfactual, or baseline, of what would have happened to recreation visitation if the spongy moth infestation had not occurred. While the fixed effects model controls for time-invariant factors such as park size, it does not control time-varying factors that impact parks at the same time (i.e. gas prices). Without including non-infested parks that could have reasonably had an infestation since they are located in infested areas, we may mistakenly attribute a drop in recreation visitation to other factors that are not spongy moth related.

A similar model in Lee, Suter, and Bayham (2023) quantified the impacts of wildfire on campground reservation demand in U.S. National Forests. Expanding on Lee, Suter, and Bayham (2023), we estimated a fixed effects model with weather controls and lagged metrics of infestation for U.S. NPUs in our study region (Equation 1).

$$ln(Y_{it}) = \sum_{j=0}^{8} \beta_j X_{it-j} + \gamma_1 PCTinterest_{it} + \gamma_2 PCTtrail_{it} + \gamma_3 \ln(precip)_{it} + \gamma_4 \ln(temp)_{it} + u_i + \delta_t + \varepsilon_{it} \quad (1)$$

Where Y_{it} is the log-transformed recreation visitation of each NPU (i) in year (t), X_{it-j} is the percentage of each park defoliated, β_j, is a series of lagged coefficients to account for the impact of defoliation events j years after the initial event, u_i is the park fixed effect, and δ_t is the time fixed effect. Control variables collected for all parks include the percentage of interest points within one mile of defoliation ($\gamma_1 PCTinterest_{it}$), percentage of trails within a defoliated area ($\gamma_2 PCTtrail_{it}$), precipitation ($\gamma_3 \ln(precip)_{it}$), and temperature ($\gamma_4 \ln(temp)_{it}$) averages. The control variables (interest points and trails impacted) were included in the model to account for visitor experience (i.e. if a portion of the NPU was defoliated but never visited, then it may not have an impact on visitation). The error term is given by ε_{it}. Standard errors were clustered at the NPU level to account for correlation within each a given park over time.

Park managers coordinate aerial treatments and may put in place partial park closures in the years following defoliation events. To verify, we contacted all NPUs with spongy moth infestations in our dataset and received correspondence from every park. Park managers sent a variety of documents on recommended and planned treatment areas, environmental assessments, work plans, as well as community outreach and bulletins notifying the public and adjacent landowners. Most

documents we received were from the early 2000s.[4] Thus, we explored lags, and ultimately added lags for eight years post-defoliation, or two years after defoliation becomes statistically insignificant. The lags account for the impact of defoliation events in the years following a defoliation event, since community outreach, treatments, and successive defoliation events occur after initial infestation. The inclusion of eight lags is greater than those used in Lee, Suter, and Bayham (2023) for wildfire and provided a large enough time range to test whether the effect of the defoliation diminishes over time, and if so, how quickly.[5]

Finally, the Durbin-Wu-Hausman test (Hausman specification test) was used to assess the efficiency of the fixed effects estimator (Wu 1974). We found that the difference in coefficients was not systematic and could reject the random effects as inconsistent; thus, we interpret the fixed effects regression estimates. In addition, to address the concern regarding multicollinearity, we calculated Variance Inflation Factors (VIF) for all independent variables. The results show a Mean VIF of 1.93, with all individual VIFs falling well below the conservative threshold of 5 (the highest being 2.80 for percent of trails impacted). This evidence suggests that multicollinearity among defoliation metrics is not a significant concern for this model.

4. Results

On average, there were 842,588 recreation visits to NPs in the northeastern U.S.A. per year; the minimum average recreation visits were at Thaddeus Kosciuszko National Memorial and the maximum were at Gateway National Recreation Area (Table 3). Recreation visits for parks that were defoliated can be seen in Figure 3. The minimum average recreation visits in a year were to Monocacy National Battlefield (37,429 recreation visitors), although recreation visitors had trended up from about 11,600 in 1994 to almost 150,000 in 2019. Bluestone National Scenic River consistently had between about 40,000 and 60,000 recreation visitors over the 26-year period. The maximum number of recreation visitors was to George Washington Memorial Parkway (7,070,474 recreation visitors). The percentage of park area with defoliation for impacted parks was, on average, 0.075%, with a maximum of 0.356% and a minimum of 0.000023%. On average about 299 acres were impacted in defoliated years, with a maximum of 1,995 acres. In impacted parks, defoliation events impacted on average 49% of interest points, and 17% of hiking trails.

Using the fixed effects estimator, we explored the impact of defoliation events on recreation visits in the year that the defoliation event occurred, as well as the lagged effect on the years following infestation. Average temperature (degrees Fahrenheit), percent of interest points impacted, and percent of trails impacted did not significantly impact visitation. Average rain (inches) was not statistically significant at our modest cutoff level yet was significant at the 10% level with the expected negative sign. We found a strong correlation between recreation visits and the percent of the NPU defoliated in the year of the defoliation event, and up to five years after the initial event (Figure 4).

Findings indicate that as the percentage of an average NPU defoliated increases by 1 percentage point, recreation visits decrease by about 46.28%.[6] However, a defoliation event this large on a NPU is never observed. In terms of the amount of defoliation we observe in our dataset, on average, a park with 0.075% acres defoliated would result in a drop of 4.55% of recreation visitors in the

Table 3. Summary statistics of independent and dependent variables used in the regression analysis.

Total observations = 1741	Mean	Standard deviation	Min.	Max.
Recreation Visitors	842,588.300	1,543,668.000	425.000	10,300,000.000
Average Rain (Inches)	46.270	9.860	21.120	73.180
Average Temperature (Fahrenheit)	52.280	4.900	33.000	61.300
*Percent of Park Defoliated	0.075%	0.105%	0.000%	0.356%
*Percent Interest Points Damaged	49.01%	19.63%	16.67%	100.00%
*Percent Trails Damaged	17.27%	16.99%	0.47%	51.56%

*Indicates summary statistics for impacted parks only.

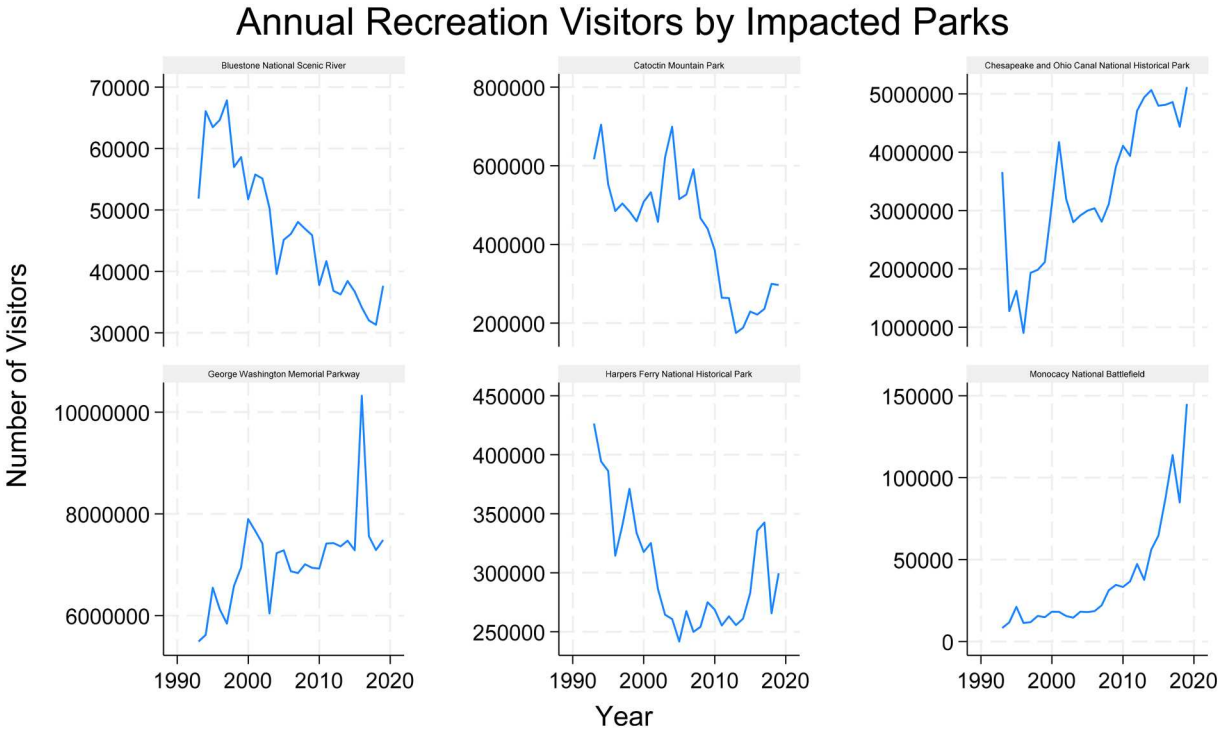


Figure 3. Annual recreation visitors by impacted NPUs from 1993 to 2019. Impacted NPUs from top left to bottom right include: Bluestone National Scenic River, Catoctin Mountain Park, Chesapeake and Ohio Canal National Historic Park, George Washington Memorial Parkway, Harpers Ferry National Historic Park, and Monocacy National Battlefield.

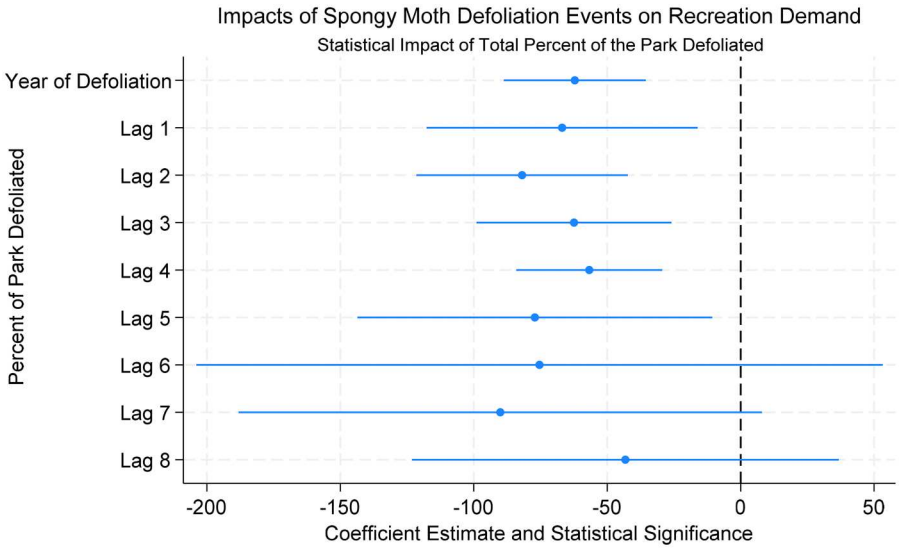


Figure 4. Impact of spongy moth defoliation events on recreation visitors at National Parks in the northeastern U.S. ($p < 0.01$).

year of the defoliation event, 4.89% in the year following the defoliation event, 5.96% two years after, 4.57% three years after, 4.16% four years after, and 5.62% five years after (Table 4). To illustrate this finding, the minimum number of visitors went to Monocacy National Battlefield (37,429 recreation visitors). Using the average park defoliation (0.075%) would result in a drop of 1,705 in the year of the defoliation event, 1,831 in the year after, 2,231 two years after, 1,712 three years after, 1,558 four years after, and 2,105 five years after, for a cumulative effect of 9,851 fewer visits over a six-year period.

For George Washington Memorial Parkway, applying the average level of defoliation (0.075%) would result in a cumulative decrease of 1,860,695 visits; applying the average recreation visits from across all parks (842,588 recreation visitors), the cumulative decrease would be 221,769 visits. Further, for the average park (842,588 recreation visitors) at the maximum level of defoliation (0.356%), the cumulative effect would be 644,856 visits over a six-year period, and for the average

Table 4. Fixed effects regression estimates of spongy moth defoliation events that impacted National Parks in the northeastern U.S.

Dependent Var = Recreation visitors (ln)	Coefficient	Robust Std. error
Average Rain (ln)	−0.109	(0.070)
Average Temperature (ln)	0.297	(0.551)
Percent of Park Impacted	−62.143***	(13.40)
Percent of Interest Points Impacted	0.131	(0.375)
Percent of Trails Impacted	0.308	(0.560)
Lag 1 (Percent of Park Impacted)	−66.906*	(25.570)
Lag 2 (Percent of Park Impacted)	−81.892***	(19.960)
Lag 3 (Percent of Park Impacted)	−62.440**	(18.391)
Lag 4 (Percent of Park Impacted)	−56.710***	(13.780)
Lag 5 (Percent of Park Impacted)	−77.119*	(33.482)
Lag 6 (Percent of Park Impacted)	−75.372	(64.740)
Lag 7 (Percent of Park Impacted)	−90.05	(49.370)
Lag 8 (Percent of Park Impacted)	−43.196	(40.270)
Year fixed effects not reported in table		
R-sqr	0.066	
dfres	91	
BIC	648.7	

Note: The dependent variable is recreation visitors (natural log).

park at the minimum level of observed defoliation (0.000023%), the cumulative effect would be 79 visits over a six-year period.

According to the National Park Service, most NPU sites do not charge an entrance fee.[7] The typical fee, for those parks that do charge, is $10.00 per person or $20.00 per private vehicle. Of those parks observed to have been defoliated, the only park that charged a per person fee was Harpers Ferry National Historical Park. We used the per person dollar amount to proxy for visitor willingness to pay, or satisfaction from recreation. A decrease in recreation visitors suggests lower visitor satisfaction, and potentially lost opportunities to connect with nature, physical exercise, or other benefits of visiting NPs. From 2000 to 2002, Harpers Ferry National Historic Park had a multi-year outbreaking event resulting in cumulative defoliation of 0.004% of the park impacted.[8] Using the actual count of recreation visitors and defoliation levels from those years, we found that the compounded effect of the three-year outbreaking event resulted in a loss of 4,477 recreation visitors, or a decrease of $44,770 in entrance fees over this six-year period.

5. Discussion

The purpose of this research was to explore whether spongy moth impacts recreation and tourism in NPUs; and if so, does that impact persist over time. We showed that defoliation from spongy moth was associated with a decline in visitation, and a prolonged impact across 5 years following the defoliation event. For comparison, Goebl (1986), who disseminated a questionnaire, found that 27% of visitors who went to Allegheny National Forest reported that they would not return to the area in the following year if spongy moth was present. At that time, 16% of Allegheny National Forest was defoliated. Our data suggest that, on average, 142,000 recreation visitors frequent Allegheny Portage Railroad National Historic Site. If 27% of visitors who wanted to visit the NPU did not do so due to spongy moth infestation, that would be associated with a decrease of 38,000 recreationists. Our analysis suggests that if 16% of the NP was defoliated, then we would expect there to be an almost complete loss of recreation visitors, suggesting the relationship may be non-linear; in that the marginal effect of defoliation decreases as more acres are impacted. Yet, for the 26-year period, we did not observe over 0.36% of any NPU to be defoliated, suggesting that a 16% defoliation event is relatively infrequent for NPUs.

In addition, there is an important confounding factor regarding the mechanism by which defoliation impacts visitation. Invasive species are often managed using pesticide treatments that require temporary closures of recreation areas (Coleman et al. 2023b). Though outside the scope of this study, it is important to note that this might be a mechanism by which visitation is impacted, even with small spongy moth outbreaking events. Schlueter and Schneider (2016) assessed the impact of emerald ash borer in Wild River State Park, Minnesota, and found that recreationists considered chemical treatment an unacceptable management action. Thus, it is possible that the defoliation event may impact willingness to visit in the first year of defoliation, but there could be a compounded effect in future years that includes future defoliation events, subsequent tree mortality, and management actions (chemical or biological treatments).

In contrast, studies have also examined the impact of not acting to remove invasive species (Schneider 2023). For instance, Rossiter-Rachor et al. (2023) showed that delayed management for the removal of an invasive grass resulted in a doubling of management costs. Thus, though closures might impact recreation for extended periods of time, as we show, costs of management might grow if no action is taken. Persistent infestation can result in reduced tree densities from tree mortality, and heavily impacted trees may be removed along trails and recreation facilities if they pose hazards to visitors (Arnberger et al. 2018). This may further reduce visitation to highly frequented locations if facilities are closed to conduct tree-removal. There are many studies that have shown a positive willingness to pay for invasive species removal and management in NPUs (see Levers and Pradhananga 2021). Though our study focuses on visitation and does not perform valuation, the negative impact to visitation implies that the willingness to pay for spongy moth management is positive, as in Levers and Pradhananga (2021) and other studies. Future work that examines cost

benefit analyses of treatments could consider tourism impacts as an important benefit category. Treatment costs associated with spongy moth vary depending on whether the treatment is a chemical application or hormone-based mating disruption. For chemical treatments, the average cost is $33.95 2020 USD per acre, whereas with mating disruption, it's $8.35 2020 USD per acre. In addition, monitoring costs can be high, with trapping costs for spongy moth averaging $57.98 2020 USD per trap (Slow the Spread Programme 2020).

Our study highlights the existence of feedback between recreation and invasive species. Previous work has shown that recreation plays a role in the spread of invasive species (Anderson et al. 2015). Individuals that travel between recreation sites can increase the risk that an invasive species is transmitted (Cole, Keller, and Garbach 2016). This can hold true for spongy moth, which has a high propensity to lay eggs and pupate on many surfaces (e.g. cars, trailers, outdoor equipment), during outbreaks. Thus, future work could assess how park closures impact the transportation of spongy moth between infested sites. In this paper, we also show that invasive species, either through their degradation of the natural environment or through necessary treatments and park closures, negatively impacts visitation. This indicates that modelling of invasive species and recreation could differentiate between the effect of the insect itself and the management and community outreach about the pest, which is beyond the scope of this analysis. Finally, since recreation visitors, in general, are not paying a recreation fee it is difficult to measure the impact on lost revenue to an individual park. It is likely that recreationists substitute to a different location within relatively close proximity (Schneider et al. 2019); thus, total recreation revenues through direct and indirect effects on the region may not be lost. However, satisfaction for the recreation visitor may decrease if they feel close place identity with a particular recreation location (Meitner, South, and Wieler 2011).

6. Conclusion

Previous literature on spongy moth outbreak events has typically used stated preference methods and found non-consensus on the impact to recreation visitor preferences. Some literature has suggested that defoliation events can spur understory growth, increasing visitor preference (Davidson, Gottschalk, and Johnson 1999; Twery 1990; Brock, Hollenhorst, and Freimund 1991), while other literature has suggested that spongy moth is a nuisance (Goebl 1986; Hollenhorst et al. 1993). This study investigated the impact of invasive species on recreation visitation to NPUs, and whether these impacts lasted beyond the initial defoliation event. Our results indicated that defoliation leads to statistically significant, yet a small-in-magnitude change to visitation, which is persistent over approximately 5 years. It is possible that educational programmes (such as impact on forest ecology, spongy moth life cycle and collapse, and management) could shape visitor experience, and their desire to return.

There are several limitations of this current work and areas for future research to expand upon. First, future work could address whether impacts on recreation seen in the visitation data are driven by the infestation event itself or by management related to invasive species. Second, we considered a limited number of sites in our study. There are many municipal, state-level and even some federal recreation sites that we do not consider. These sites might attract a diverse range of recreationists with varying preferences. Third, future research could examine the impacts of invasive species on substitution effects between recreation locations. Finally, research could quantify the consumer surplus lost due to an infestation event, since most NPUs were free to enter and use at the time of this analysis.

Notes

1. This buffer was chosen, since National Parks are relatively small, as compared to National Forests (which was the unit of interest in Lee, Suter, and Bayham 2023). If larger buffers were drawn for this analysis, they likely extended much outside the scope of the NP (See Appendix C for an example).

2. Forest Health Protection (FHP), '*conducts surveys to detect and appraise insect infestations, disease conditions, and man-made stresses affecting trees*'. We use the term, 'defoliation event', to discuss and assess the combination of both 'low' and 'high' defoliation designations, which are greater than 0% and up to 100% defoliation and excludes tree mortality. https://www.fs.usda.gov/science-technology/forest-health-protection/assessment-applied-sciences.
3. The definition of a recreation visitor, according to the National Park Service is, '*The entry of a person onto lands or waters administered by the NPS except as defined as non-reportable and non-recreation visits. Funeral parties at National Cemeteries, school groups, etc. are reportable as 'recreation' use since their use is for the purpose for which the park was established. Visits originating on surface vehicles (trains, boats, other) and aircraft may be counted if they stop and disembark passengers on NPS administrated territory. The applicable rule is that one entrance per individual per day is countable*' (National Park Service (NPS), Updated February 21, 2024).
4. We received many helpful documents from NPU managers. However, we were not able to reconstruct a census of all treatments and timing of treatments. In addition, our choice of a yearly model, as opposed to a monthly model, is motivated by the fact that spongy moth outbreaks and peak tourism season overlap, and by the fact that treatments are reported annually, not monthly. As such, a monthly model would likely confound the impacts of treatments while not providing sufficient differences in results.
5. With the addition of lags, missing values were generated for the initial eight periods in the dataset. Thus, the full dataset has 2,538 observations and the fixed effects estimation with eight lags has 1,741 observations.
6. We have used the exact formula: $\%\Delta = (e^{\beta^*\alpha}-1) * 100$, where β is the coefficient value, and α is the percent of the park defoliated.
7. https://www.nps.gov/aboutus/entrance-fee-prices.htm#what-private-vehicle-means.
8. Harpers Ferry National Historical Park; defoliation (year); 0.0020523% (2000), 0.0009456% (2001), 0.0006603% (2002).

Author contributions

Conceptualization, Data Curation, Formal Analysis, Investigation, Methodology, Visualization, Writing – original draft, review and editing. CRediT: Conceptualization, Investigation, Methodology, Visualization, Writing – review and editing. CRediT: Conceptualization, Data Curation, Visualization, Writing – review and editing. CRediT: Visualization, Writing – review and editing

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Appendices

Appendix A. Image of spongy moth frass (Coleman 2024).



Appendix B. National Parks (NPs) in the dataset.

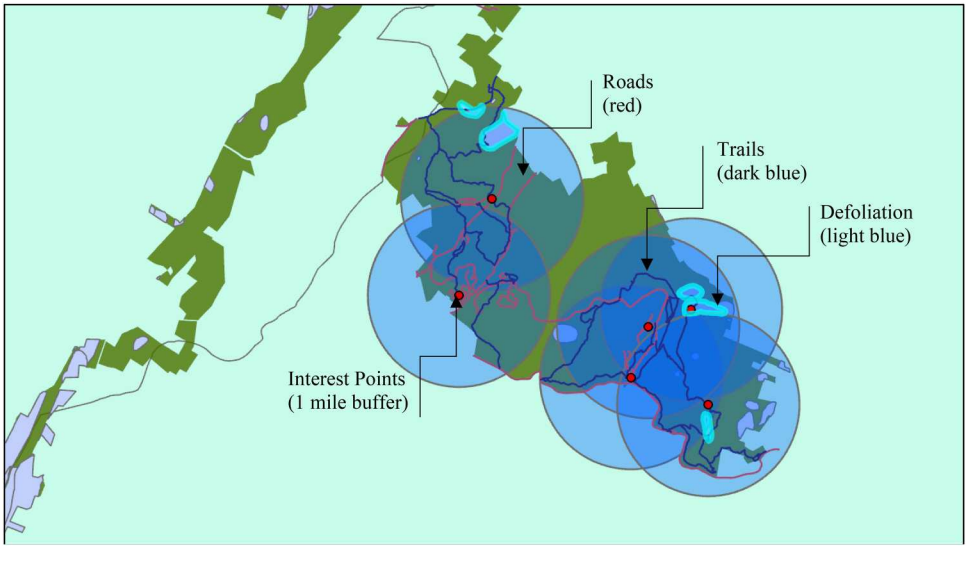
	National park name		
1	Abraham Lincoln Birthplace National Historical Park	48	Indiana Dunes National Park
2	Acadia National Park	49	Isle Royale National Park
3	Allegheny Portage Railroad National Historic Site	50	John Fitzgerald Kennedy National Historic Site
4	Antietam National Battlefield	51	Johnstown Flood National Memorial
5	Apostle Islands National Lakeshore	52	Lincoln Boyhood National Memorial
6	Appomattox Court House National Historical Park	53	Longfellow House-Washington's Headquarters National Historic Site
7	Assateague Island National Seashore	54	Lowell National Historical Park
8	Bluestone National Scenic River	55	Maggie L. Walker National Historic Site
9	Booker T. Washington National Monument	56	Mammoth Cave National Park
10	Boston African American National Historic Site	57	Manassas National Battlefield Park
11	Boston National Historical Park	58	Martin Van Buren National Historic Site
12	Cape Cod National Seashore	59	Monocacy National Battlefield
13	Castle Clinton National Monument	60	Morristown National Historical Park
14	Catoctin Mountain Park	61	New River Gorge National Park and Preserve
15	Chesapeake and Ohio Canal National Historical Park	62	Pennsylvania Avenue National Historic Site
16	Clara Barton National Historic Site	63	Perry's Victory and International Peace Memorial
17	Colonial National Historical Park	64	Petersburg National Battlefield
18	Cumberland Gap National Historical Park	65	Pictured Rocks National Lakeshore
19	Cuyahoga Valley National Park	66	Pipestone National Monument
20	Dayton Aviation Heritage National Historical Park	67	Piscataway Park
21	Edgar Allan Poe National Historic Site	68	Prince William Forest Park
22	Effigy Mounds National Monument	69	Richmond National Battlefield Park
23	Eisenhower National Historic Site	70	Rock Creek Park
24	Eleanor Roosevelt National Historic Site	71	Roger Williams National Memorial

(*Continued*)

Continued.

	National park name		
25	Fort Donelson National Battlefield	72	Sagamore Hill National Historic Site
26	Fort McHenry National Monument and Historic Shrine	73	Saint Paul's Church National Historic Site
27	Fort Stanwix National Monument	74	Saint-Gaudens National Historical Park
28	Fort Washington Park	75	Salem Maritime National Historic Site
29	Frederick Douglass National Historic Site	76	Saratoga National Historical Park
30	Frederick Law Olmsted National Historic Site	77	Saugus Iron Works National Historic Site
31	Fredericksburg and Spotsylvania County Battlefields Memorial National Military Park	78	Shenandoah National Park
32	Friendship Hill National Historic Site	79	Sleeping Bear Dunes National Lakeshore
33	Gateway Arch National Park	80	Springfield Armory National Historic Site
34	Gateway National Recreation Area	81	Steamtown National Historic Site
35	Gauley River National Recreation Area	82	Thaddeus Kosciuszko National Memorial
36	General Grant National Memorial	83	Theodore Roosevelt Birthplace National Historic Site
37	George Rogers Clark National Historical Park	84	Thomas Edison National Historical Park
38	George Washington Memorial Parkway	85	Thomas Jefferson Memorial
39	Gettysburg National Military Park	86	Thomas Stone National Historic Site
40	Grand Portage National Monument	87	Upper Delaware Scenic and Recreational River
41	Greenbelt Park	88	Valley Forge National Historical Park
42	Hampton National Historic Site	89	Vanderbilt Mansion National Historic Site
43	Harpers Ferry National Historical Park	90	Vietnam Veterans Memorial
44	Herbert Hoover National Historic Site	91	Voyageurs National Park
45	Home of Franklin D. Roosevelt National Historic Site	92	Weir Farm National Historical Park
46	Hopewell Culture National Historical Park	93	William Howard Taft National Historic Site
47	Hopewell Furnace National Historic Site	94	Women's Rights National Historical Park

Appendix C. Example of data manipulation in ArcGIS Pro for Catoctin Mountain Park. Image represents all defoliation events from 1993-2019, interest points, trails, and road networks.



Appendix D. Defoliation events by National Park and year. A '1' indicates that a defoliation event occurred in that year, and '0' otherwise. Data from Forest Health Monitoring Table 1 Source E.

	National parks impacted by spongy moth infestation events					
Year	Bluestone National Scenic River	Catoctin Mountain Park	Chesapeake and Ohio Canal National Historical Park	George Washington Memorial Parkway	Harpers Ferry National Historical Park	Monocacy National Battlefield
1993	0	0	0	0	0	0
1994	0	0	0	0	0	0
1995	0	0	0	0	0	0
1996	0	0	0	0	0	0
1997	0	0	0	0	0	0
1998	0	0	0	0	0	0
1999	0	0	0	0	0	0
2000	0	1	0	0	1	0
2001	0	1	1	0	1	0
2002	0	1	0	0	1	1
2003	0	0	0	0	0	0
2004	0	0	0	0	0	0
2005	0	0	0	0	0	0
2006	0	0	0	1	0	0
2007	0	1	1	0	1	0
2008	0	1	0	1	0	1
2009	0	0	0	0	1	0
2010	0	0	0	0	0	0
2011	0	0	0	0	0	0
2012	0	0	0	0	0	0
2013	0	0	0	0	0	0
2014	0	0	0	0	0	0
2015	1	0	0	0	0	0
2016	1	0	0	0	1	0
2017	0	0	0	0	0	0
2018	0	0	0	0	0	0
2019	0	0	0	0	0	0
Total Events by Park	**2**	**5**	**2**	**2**	**6**	**2**