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RESEARCH ARTICLE

Quantifying and evaluating strategies to decrease carbon dioxide emissions generated from tourism to Yellowstone National Park

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Abstract

The tourism industry needs strategies to reduce emissions and hasten the achievement of global carbon dioxide (CO_2) emission reduction targets. Using a case study approach, we estimated CO_2 emissions related to park tourism in Yellowstone National Park (USA) generated from transit to and from the park, transit within the park, accommodations, and park operations. Results indicate tourism to Yellowstone National Park produces an estimated 1.03 megaton (1.03 billion kg) of CO_2-equivalent emissions annually, with an average of 479 kg CO_2 per visitor. Almost 90% of these emissions were attributable to transit to and from the destination, while 5% were from transit within the park, 4% from overnight accommodations, and about 1% from other park operations (e.g., visitor centers, museums, shops, restaurants, etc.). Visitors who fly only made up about 35% of all visitors, but produced 72% of the emissions related to transit to and from the park. Future scenarios that alter transit to and from the park can reduce emissions the most; this includes a greater proportion of local or regional visitors, fewer visitors flying, and increased fuel efficiency of vehicles. The method developed in this work, and applied specifically to Yellowstone National Park, can be adopted elsewhere and used to help decision makers evaluate the effectiveness of potential emission reduction strategies.

1. Introduction

Over the past century, the Earth has warmed by about 1.1˚C [1]. This has already changed ecosystems and negatively affected human health and livelihoods [2]. Global climate change is driven by an increase in anthropogenic greenhouse gases in the atmosphere, including carbon dioxide (CO_2), methane, and nitrous oxide. Due to increased use of fossil fuels and industrial processes over the last century, as well as other factors like land use change, anthropogenic greenhouse gas emissions rose 54% between 1990 and 2019 [3]. Carbon dioxide is currently considered the most influential greenhouse gas because it contributes about three-quarters of

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anthropogenic greenhouse gas emissions [3]. Recently, the United States made a goal to reduce annual greenhouse gas emissions to 50% of 2005 levels by the year 2030 [4]. To achieve this goal, many sectors, including the tourism sector, will need to cut CO_2 emissions.

Between 2009 and 2013, tourism contributed 8% of all annual global CO_2 equivalent emissions, with the United States having the highest total carbon footprint related to tourism [5]. By 2035, tourism-related emissions are expected to grow by 161% from 2005 levels, largely due to a projected growth in air travel and longer transit distances [6]. Although air travel volume decreased temporarily as a result of the COVID-19 pandemic, the number of annual global air passengers has been increasing since 2020 and is almost back to pre-pandemic levels [7]; thus far, there has been little evidence that the COVID-19 pandemic will substantially change tourism in the long-run [8]. Although the overall efficiency of transit has increased over time (i.e., increasing km/L of vehicles), CO_2 emissions per tourist are still rising in many places because tourists are travelling greater distances [9]. Due to the rising demand for tourism and increased CO_2 emissions per tourist, it is critical that strategies are adopted to help slow the rise in tourism-related emissions.

More research is needed on both the effect of climate change on tourism, and the effect of tourism on climate change, to inform policies and decision-making [10]. A recent multinational policy analysis found climate change is often not considered in tourism policies [11]. In many places, such as the United States, a large portion of tourism is related to visiting parks and protected areas [12] with the U.S. National Park System receiving over 300 million annual visits [13]. Although previous studies have investigated the effect of climate change on visitors to parks and protected areas [14–18], few studies have addressed if and how visitors are contributing to climate change [19]. There are a variety of potential approaches to reduce CO_2 emissions in parks and protected areas, such as increasing public transit, updating buildings to be energy efficient, switching to renewable energy, or encouraging local or virtual park visits [20]. Understanding how specific park tourism behaviors influence CO_2 emissions can help park managers and other tourism suppliers prioritize carbon-reduction actions.

Consequently, our goal is to understand and quantify the CO_2 emissions from a high-profile park, using Yellowstone National Park (Yellowstone NP) as a case study. Specifically, we ask:

(1) What are the estimated annual CO_2 emissions produced from visitors to Yellowstone NP from transit to and from the park, transit within the park, accommodations, and park operations?

(2) How would different scenarios affect CO_2 emissions (e.g., more people per vehicle, more visitors using buses, fewer visitors flying, increase in renewable energy use)?

We also aim to detail a methodology that could be replicated in other locations to understand the CO_2 emissions generated from nature-based tourism. By quantifying the estimated CO_2 emissions by source, park and tourism managers or policymakers can strategically use management or policy actions to reduce total CO_2 emissions.

1.1. Carbon dioxide emissions from tourism-related travel

Researchers can estimate CO_2 emissions from tourism using either bottom-up or top-down approaches [21]. In bottom-up estimation, emissions are calculated for different sectors (e.g., transit, accommodations) and types of tourists (e.g., based on home location or type of overnight accommodation), and extrapolated for the number of visitors to a destination. Top-down analysis analyzes tourism-related emissions in the context of the larger economy (e.g., estimating tourism emissions by using data from other sectors). The top-down approach often does not produce emissions estimates for different tourism sectors, types of visitors, or visitor behaviors [21]. In this paper, we take a bottom-up approach to understand the carbon emissions of specific aspects of park tourism in a single U.S. national park.

Tourists generate CO_2 emissions from transit to and from their destination, transit within their destination, overnight accommodations, and recreational activities [22]. Transit contributes the largest portion of tourism-related CO_2 emissions [22–25]. For example, in Barcelona it was estimated that 96% of tourism-related CO_2 emissions came from transit to and from the destination [25]. Globally in 2001, tourism-related CO_2 emissions from transport were estimated at 1.26 gigatons of CO_2, more than 15 times the 81 megatons from accommodations, and more than 20 times the 55 megatons from activities [24]. Global tourism has grown substantially since then, with 2.3 billion international travelers in 2019, up from 1.2 billion international travelers in 2001 [26]. A study on national parks in Taiwan found transportation-related tourist behaviors such as visiting places closer to home, switching from private vehicles to tour buses, and increasing the number of people in each vehicle, all had the potential to significantly decrease CO_2 emissions from national park visitation [19].

Air travel in particular contributes significantly to tourism-related carbon emissions. Previous research found domestic and international visitors used about the same amount of energy per day within New Zealand, but CO_2 emissions from transit to destinations were much higher for international visitors, both because they travel longer distances and because almost all international visitors must fly to reach the country [23]. Emissions of CO_2 at higher altitudes (e.g., flight level) have a larger effect on warming than emissions emitted at ground level [27,28], and some studies use a multiplier to account for this [22,24]. While longer flights emit more CO_2 in total, shorter flights emit more CO_2 per km because the take-off is energy intensive [9].

1.2. Other tourism-related CO_2 emissions

Although transit contributes the majority of tourism-related emissions, overnight accommodations also contribute CO_2 emissions. Previous studies have estimated energy use, which relates to CO_2 emissions, from different types of accommodations (e.g., hotel, bed and breakfast, motel, hostels, campgrounds) [29,30]. Generally, hotels and resorts use the most energy per visitor night, while camping uses the least energy [29,30]. However, there is large variability in the amount of energy used per visitor night, even within the same type of accommodation [31,32]. Variation in energy use across businesses is partially due to varying energy-savings measures and energy sources used by individual businesses [31,33].

Visitors' activities while at the destination also contribute CO_2 emissions, but less than transit and accommodations, and motorized activities contribute the most (e.g., scenic flights, motorized boating) [34]. In general, tourists visiting attractions (e.g., visitor centers, gardens, natural features, etc.) have lower emissions than visitors participating in activities (e.g., motorized water activities), but there is high variability in the emissions by activity [34].

Although park tourism produces CO_2 emissions, parks and protected areas also remove CO_2 from the atmosphere through carbon sequestration. Within the United States, the total value of vegetative carbon sequestration on National Park Service (NPS) lands is $707 million annually (assuming a social cost of carbon price of $40.45 per metric ton of carbon), but there is a projected drop in future sequestration due to climate change and the increasing prevalence of forest fires [35]. Previous research found Yellowstone NP had the second highest carbon sequestration of NPS units and is a net carbon sink, with -1.5 megatons of CO_2 annually [36]. However, even with a substantial increase in terrestrial sequestration (i.e., land use change), terrestrial carbon sequestration alone could not offset current global emissions [37]. Therefore, understanding and reducing total CO_2 emissions remains critical.

2. Methods

2.1. Study site

Located in the northwestern corner of Wyoming and crossing into both Idaho and Montana, Yellowstone NP is the largest national park in the Continental United States (Fig 1). It is a predominantly forested park that sits atop an active volcano and contains many hydrothermal features and geysers [38]. The park had over four million visitors annually between 2015 and 2019, with the vast majority of visitation occurring in the summer [39]. Yellowstone NP is a large park, totaling 8,991 km^2, with 727 km of roads and around 1,609 km of hiking trails [38]. Given the size of the park and the fact it is not close to any major metro areas, visitors often travel long distances to reach the park and drive many kilometers once inside the park.

The park gets very cold in the winter and most roads close due to snow, making snowmobiles and snowcoaches the primary modes of winter transit within the park [44]. There are nine hotels and lodges (>2,000 rooms), 12 campgrounds (>2,000 sites), and 11 visitor centers/museums within the boundaries of Yellowstone NP [38]. Additionally, many visitors stay overnight outside the park in West Yellowstone, a town directly to the west of the park's border.

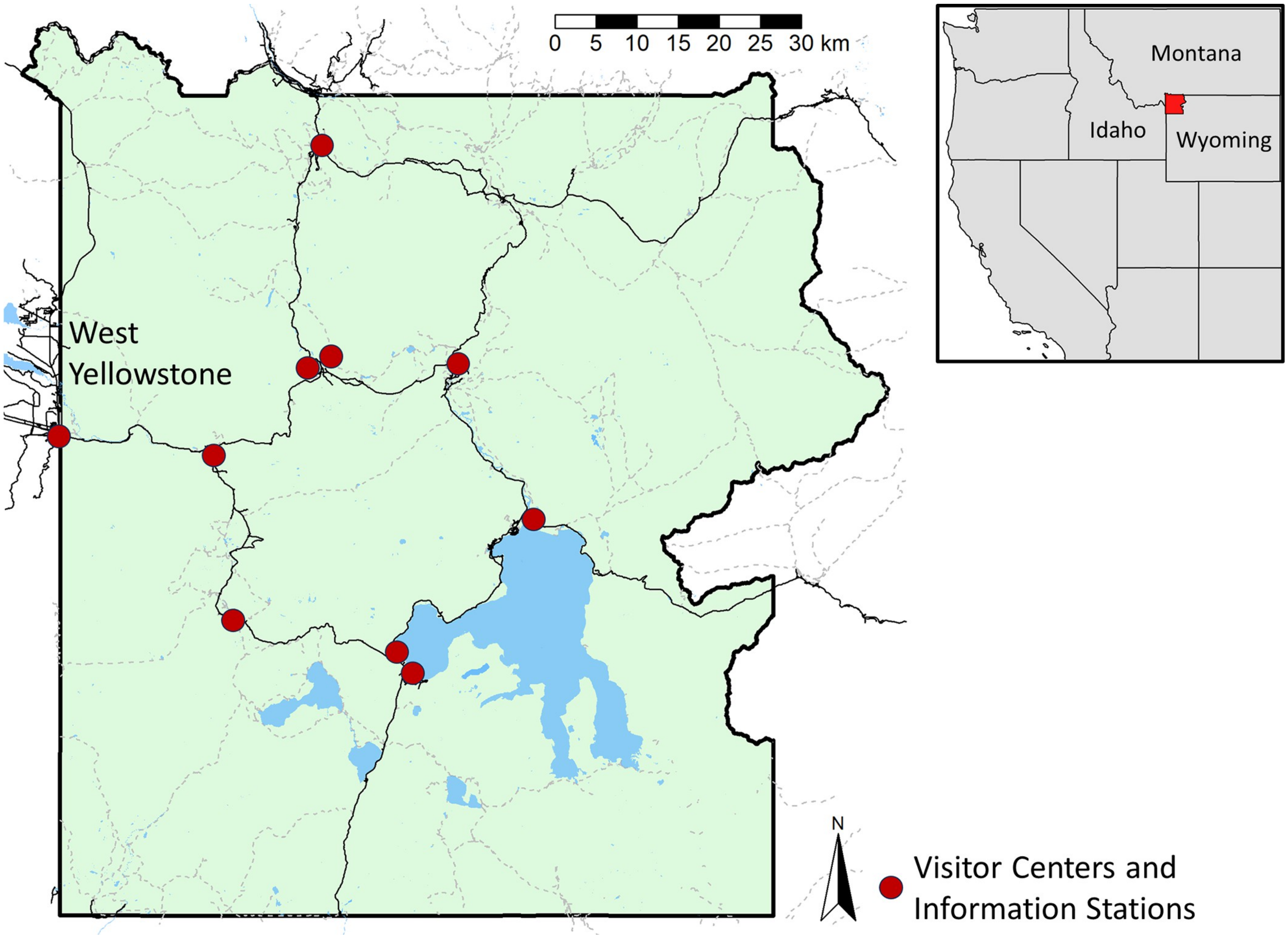

Fig 1. A map of Yellowstone National Park. Solid black lines represent roads; dashed grey lines represent trails. Maps created by the authors in R with the tmap and osmdata packages [40,41] using road, trail, and waterbody data from OpenStreetMap under the Open Database License [42]. Park boundaries are from the National Park Service [43].

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Yellowstone NP consumes the most energy of all National Park Service units and has goals to become more energy efficient [45].

2.2. Equations and variables for estimating CO_2 emissions from tourism

We calculated CO_2 emissions from transit to and from the park, transit within the park, and overnight accommodation using the equations in Table 1. We did not estimate CO_2 emissions related to non-transit recreational activities in Yellowstone NP because emissions from non-motorized activities are insignificant in the context of all tourism-related emissions [34]. Motorized recreational activities in Yellowstone NP, apart from transit, are uncommon; we consider snowmobiling to be a form of transit within the park rather than a recreational activity. Further, we do not have data regarding motorized recreation to make accurate estimates.

Equations for transit adapted from Gössling and colleagues [22].

The equations for calculating CO_2 emissions from transit to and from the park were adapted from Gössling and colleagues [22] (note that we use updated and more relevant data sources in the equations, which are described in section 2.3). One notable difference in the equations is in how we calculated the weight factor (WF, Table 1), which represents the proportion of flight emissions attributable to a single destination during a multi-destination trip.

Table 1. Equations used for calculating carbon dioxide emissions from transit and accommodation at Yellowstone National Park.

Category	Equations	Levels of *i*
Transit to and from the park	$CO_2\ (kg) = \sum_{i=1}^{n}(V_i*\beta_i*e_i)$ i = transit mode V = total transport volume (pkm) (see equation below) β = CO_2 emissions factor: $\frac{CO2\ per\ liter\ of\ fossil\ fuel\left(\frac{kg}{l}\right)}{fuel\ efficiency\left(\frac{km}{l}\right)*Load\ factor(people)}$ e = equivalence factor $V_i(pkm) = 2*(\sum_{oi=1}^{n}P_{oi}*D_{oi}*DF_i)*WF$ i = transit mode o = origin of visitor P = total number of passengers D = transport distance (km) DF = detour factor (for airplanes) WF = weight factor	• Automobile • Airplane If airplane, then add transportation after flying as: • Automobile, from airport to Yellowstone NP entrance, where *o* represents the different airports visitors fly into.
Transit within park	$CO_2(kg) = \sum_{i=1}^{n}(P_i*D_i*\beta_i*e_i)$ i = transit mode P = total number of passengers D = transport distance (total road km driven during trip) β = CO_2 emissions factor: $\frac{CO2\ per\ liter\ of\ fossil\ fuel\left(\frac{kg}{l}\right)}{fuel\ efficiency\left(\frac{km}{l}\right)*Load\ factor(people)}$ e = equivalence factor	• Automobile • Tour bus • RV • Motorcycle • Snowmobile • Snowcoach
Accommod-ation *(both inside and outside the park)*	$CO_2(kg) = \sum_{i=1}^{n}(N_i*EN_i*C)$ i = accommodation type N = visitor nights (total visitors * average length of stay in nights) EN = energy per visitor per night (MJ) C = CO_2 emissions factor (kg/MJ), calculated based on proportions of each energy source used in Yellowstone and in the local area: $C(kg/MJ) = \sum_{i=1}^{n}(CO_2\ Emissions_i*Proportion_i)$ Where i = energy source	Accommodation types: • Hotel (in park) • Hotel (outside park) • Camping (in park) • Camping (outside park) • Backcountry (in park) Energy sources: • Propane • Diesel • Electricity: Coal • Electricity: Natural gas • Electricity: Renewables

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Gössling and colleagues [22] calculated this weight factor by dividing the average length of time at a particular destination by the total trip length, while we used the percentage of visitors who indicated Yellowstone NP was their primary reason for visiting (71%) in a 2012 visitor study [46]. About 29% of respondents indicated that Yellowstone NP was not their primary destination, so we assume they would have travelled to the area even if they did not visit the park; thus, their emissions related to transit to the destination should not be attributed to Yellowstone NP tourism.

In addition to the weight factor, other variables to note in these equations include transport distance, detour factors, equivalence factors, and load factors. Transport distance for airplanes was calculated by using the geodesic distance, which is the shortest distance between two points on the surface of the Earth. However, detour factors adjust for the fact that transportation to and from a destination is rarely the shortest distance between two points. For flights, the flight path between two cities is not a straight line, and sometimes people have multiple flights with layovers to get to a single destination. Both of these factors must be accounted for when estimating air transit distances and ultimately CO_2 emissions. For transit to the destination in automobiles, we used road km as estimated from Google Maps, which does not require a detour factor. Equivalence factors adjust CO_2 emissions to be CO_2 *equivalent* emissions (e.g., emissions at flight level contribute more to warming than ground level). Additionally, load factors represent the average number of passengers per vehicle.

We also calculated total CO_2 emissions from energy use from park operations, including visitor centers, museums, gift shops, restaurants, medical clinics, convenience stores, offices, lodging, etc., which are operated by the NPS and concessionaires within the park. NPS provides energy use values within Yellowstone NP by source (e.g., propane, electricity) [45], which we converted into CO_2 emissions by multiplying the energy values by conversion factors (noted in the section below on values and data sources) to convert MJ of energy to kg CO_2. We subtract estimated CO_2 from lodging within the park to get the remaining CO_2 emissions within the park, which we refer to as "park operations."

2.3. Data sources for estimating CO_2 emissions from tourism to Yellowstone NP

All the data used in this analysis are purposefully from secondary sources. This makes the methodology more feasible to replicate in other parks and locations that may already have similar data.

2.3.1. Visitor behavior and trip characteristics. To understand Yellowstone NP visitors' home locations and modes of transport to the park, we used data from a 2016 visitor survey [47]. Printed visitor surveys were distributed in August 2016 at the five main entrance roads in Yellowstone NP with instructions on mailing back the physical survey. The five main entrance roads were chosen by the researchers as locations for surveys to be representative of all park visitors. In total, 2,030 visitors completed an on-site survey, and 1,257 of those completed an additional mail-back survey, for an overall response rate of 55% for completion of both [47]. Given the total number of annual visitors, this would produce a margin of error between 3–5% (depending on the question at the 95% confidence level [47]. The researchers on the 2016 study also were only aiming to capture peak season visitors (the survey was conducted in August), so although this is a representative sample of peak season visitors, characteristics of visitors and their visits may be different in other seasons. However, peak season visitors represent the majority of visitors in Yellowstone NP; in recent representative years (i.e., 2019, 2021), visitors between June–September comprised around 80% of the annual visitors, while visitors between November–February only represent around 3% of annual visitors [39]. The questionnaire contained questions on visitors' home locations, how they travelled to Yellowstone NP (e.g., mode of travel, arrival airport), transit type used within the park, and other information. The resulting data contains visitors' home state or country, but because we did not have data on visitors' cities of origin, we used the distance between Yellowstone NP and the most populous city in each state or country of origin to calculate transit distance.

To convert total visits (e.g., counting a person each time they re-enter the park) to total visitors, or unique trips, we obtained the total number of monthly and annual visits from the National Park Service [39] and the mean number of days entering Yellowstone NP during a single trip from the 2016 visitor survey [47]. NPS reports 4,860,242 visits in 2021, but the mean number of re-entries per trip is 2.27. Dividing the number of total visits by the mean number of re-entries results in an estimated 2,141,076 unique trips to the park from a home location. We used this number to scale up the survey percentages to represent all Yellowstone NP visitors in a single year. For instance, 7% of visitors were from California, so we multiply 2,141,076 unique trips by 0.07, resulting in 149,875 unique trips by visitors from California. We used 2021 visitation numbers for these estimates as visitation in 2020 was abnormally low due to the COVID-19 pandemic, and visitation numbers were also affected in 2022 due to historic flooding, which limited access to the park [48].

For calculating transit to and from the park, we know that roughly 35% of visitors flew to Yellowstone NP or the surrounding area, while 65% of visitors arrived in automobiles and did not fly [47]. From the 2016 visitor survey [47], we also know what percentage of visitors were arriving from each state (or region for international visitors). Based on these percentages, we assumed visitors from the closest states were driving (to total 65% of visitors driving), and visitors from the farthest states (e.g., East Coast) and international visitors were flying (to total 35% of visitors flying). Of course, it is possible that some visitors from the East Coast drove, while some visitors from closer states flew; however, this is the most reasonable assumption to produce CO_2 estimates.

2.3.2. Values and data sources. We used several data sources to assign values for CO_2 emissions, fuel efficiencies, load factors, detour factors, and equivalence factors (Table 2). We selected values from credible sources, including government agencies and peer reviewed scientific studies, when available; we also selected values that were specific to Yellowstone NP or the United States when available and appropriate (e.g., load factors vary by location, but CO_2 emissions from fossil fuels do not).

Additionally, we estimated the average total transit distance within the park and local area to be 274 km per trip for automobiles, buses, RVs, and motorcycles, and 102 km for snowmobiles and snowcoaches. This was calculated by summing the length of the Grand Loop Road in the park (230 km) and the additional 44 km between the entrance/exit and West Yellowstone (the most common entrance point [47]). Although we do not assume every visitor drove the entire road's length, this is a reasonable estimate for average distance driven (e.g., some visitors may have driven farther north to see other features or doubled back on some sections of the road). We estimated total transit distance of snowmobiles and snowcoaches to be 102 km, which is the round-trip distance of a common route from West Yellowstone to Old Faithful, one of Yellowstone NP's most iconic destinations. There is no dataset that we are aware of that contains average km driven within the park; these are also not common data other park units would likely have if this methodology were to be replicated in other locations. These data could be collected through giving GPS units to visitors during their trips or through mobile device data, however, both options would require significant costs.

To estimate CO_2 emissions related to overnight accommodations, we first calculated the number of visitor-nights by accommodation type by multiplying the percentage of visitors who reported staying overnight in hotels, campgrounds, or backcountry camping, and their

Table 2. Data sources and values used to calculate carbon emissions from transit. YELL = Yellowstone National Park.

Measure	Values	Year of data	Location	Sources
CO_2 emissions from fossil fuels *(kg/L)*	Gasoline: 2.319	2020	Global	[49]
	Diesel: 2.692	2020	Global	
	Jet fuel: 2.576	2020	Global	
	Aviation gas: 2.198	2020	Global	
Average fuel efficiency *(km/L)* *	Cars: 11.496	2017	U.S.	Car, airplane, motorcycle, and bus data: [50] RVs: [51] Snowmobiles: [52] Snowcoaches: [53]
	Airplanes: 0.433 **	2017	U.S.	
	Motorcycles: 17.883	2017	U.S.	
	Buses: 1.601	2017	U.S.	
	RVs: 4.251	2018	U.S.	
	Snowmobiles: 5.667	2016	U.S.	
	Snowcoaches: 1.394	2006	YELL	
Load factors *(passengers per vehicle)*	Cars: 2.6	2017–18	YELL	Airplane and motorcycle data: [50] All other data: [54]
	Airplanes: 117.3	2017	U.S.	
	Motorcycles: 1.2	2017	U.S.	
	Buses: 31.3	2017–18	YELL	
	RVs: 2.6	2017–18	YELL	
	Snowmobiles: 1.4	2017–18	YELL	
	Snowcoaches: 9.1	2017–18	YELL	
Detour factors	Air travel (long flights): 1.05	2000s	Global	Air travel: [55,56] Air travel, connection correction: [56,57]
	Air travel (short flights): 1.15	2000s	Global	
	Air travel (all flights, connection correction): 1.10	2000s	Global	
Equivalence factors	All road travel: 1.05	2000s	Global	Road travel: [22] Air travel: [56]
	All air travel: 1.8 ***	2000s	Global	

* Fuel efficiency conversion factors from the U.S. Energy Information Administration [58]. For gasoline, 31,776.2 BTU/L; for diesel, 36,292.2 BTU/L. We assumed that buses and Recreational Vehicles (RVs) use diesel, airplanes use a 50/50 mix of jet fuel and aviation gas, while cars, motorcycles, snowmobiles, and snowcoaches use gasoline.

** Does not factor in cargo and thus may be slightly inflated for passenger transit.

*** Includes some variability and uncertainty due to radiative forcing from contrail-induced cirrus; this value represents the equivalence factor assuming average projected cirrus and a 100-year time frame[56]. A recent review indicates this value should be between 1.7 and 2.0 [28].

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trip lengths, in Resource Systems Group's Yellowstone NP visitor survey report [47]. Table 3 summarizes the values and data sources we used to calculate CO_2 emissions from accommodations. These include the proportions of different energy sources used in the local area, the CO_2 emissions per MJ of energy for different energy sources, and the estimated average energy use per visitor per night by accommodation type. We also used the CO_2 emissions from energy in Table 3 to convert energy used for park operations to CO_2 emissions.

A spreadsheet used to track all values and generate estimates presented in the results is available as a (S1 Data). All numbers for CO_2 emissions presented in this paper are best estimates based on the best available data; however, there is always uncertainty inherent in these types of analyses and these numbers should be treated as estimates rather than exact values.

2.4 Scenarios to reduce CO_2 emissions

To answer our second research question of how different scenarios would affect CO_2 emissions, we first determined scenarios that have been used in the prior literature and would be feasible to create estimates for. A similar study situated in Taiwanese national parks tested six

Table 3. Data sources and values used to estimate carbon dioxide emissions from accommodations at Yellowstone National Park.

Measure	Values	Year of data	Location	Sources
Proportion of total energy from each energy source	Propane (LPG): 0.384	2018	YELL	Ratio of propane, diesel, and electricity: [45] Proportions within electricity: [59]
	Diesel: 0.232	2018	YELL	
	Electricity: 0.383	2018	YELL	
	Coal: 0.200	2018	YELL	
	Natural gas: 0.190	2018	YELL	
	Solar, wind, hydro: 0.610	2018	YELL	
CO_2 emissions from energy *(kg CO_2/MJ)*	Propane (LPG): 0.060	2016	Global (U.S.)	Propane and diesel: [49] Electricity: [60]
	Diesel: 0.069	2016	Global (U.S.)	
	Electricity*:			
	Coal: 0.278	2019	U.S.	
	Natural gas: 0.115	2019	U.S.	
	Solar, wind, hydro: 0.0	2019	U.S.	
Energy per visitor per night ** *(MJ)*	Hotels: 172 ***	2004	Europe	Hotels: [61] Camping: [29]
	Camping: 25	1998–2000	New Zealand	
	Backcountry: 0	N/A	N/A	

* These represent 2019 averages in the United States for electricity-only power plants; actual values vary by day, month, time, and location.

** Presently, no studies situated in North America have investigated energy use per bed night at accommodations. We therefore consulted with a review of all energy use per bed night findings [32] and chose values based on what accommodations would be closest to what is found in Yellowstone NP.

*** Represents the mean of 111 mid-market hotels (i.e., not upscale, often older facilities) that typically have a kitchen and restaurant.

N/A = Not Applicable.

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different scenarios related to load factors increasing, home locations of tourists moving closer to their destinations (i.e., reduced transit distance to the park), and a larger percentage of tourists switching to tour buses rather than private cars for transit within the park [19]. We used these same general scenarios to understand how changes to transit would affect CO_2 emissions generated by visitors to Yellowstone NP. However, since our study does not focus only on transit, we also add three additional scenarios related to energy. This makes our scenarios inclusive of actions not reliant on changes in end-user behavior, and therefore more diverse in feasibility.

This aspect of the analysis is exploratory, and these are intended to be broad scenarios rather than specific policies or management actions. Since we are estimating CO_2 related to park tourism, which is broader in scope than emissions produced by the park itself, the scenarios are also broader in scope and not intended to be things the park alone could address. Because replicability is a significant aim in this paper, we also considered whether the percent change in CO_2 emissions could be estimated without using variables that are overly complex or could rapidly change (e.g., modeling a scenario where visitors switched to electric vehicles would require incorporating a value related to CO_2 emissions from production of new vehicles). The specific scenarios are described in the results section 3.4, and the reductions in CO_2 emissions, both as an absolute value and as a percentage, were calculated by adjusting values as described in the scenarios.

3. Results

3.1. Summary of estimated CO_2 emissions related to tourism

Overall, tourism to Yellowstone NP generates an estimated 1.03 megaton CO_2 annually, with an average of 479 kg CO_2 per visitor (Table 4). For a comparison, the average *annual* per capita

Table 4. Estimated CO_2 equivalent emissions related to Yellowstone National Park (NP) tourism. Total CO_2 equivalent numbers are based on 2021 visitation numbers.

Category	Total CO_2 (Thousands of kg)	Average CO_2 per visitor (kg)	Percent of total CO_2 emissions
Transit to/from Yellowstone NP	919,413.65	429.42	89.66%
Transit within Yellowstone NP	52,457.31	24.50	5.12%
Overnight accommodation (both inside and outside Yellowstone NP)	40,667.98	18.99	3.96%
Park operations (excluding overnight accommodation)*	12,952.94	6.05	1.26%
TOTAL	**1,025,491.88**	**478.96**	**100.00%**

* Includes visitor centers, museums, convenience stores, restaurants, gift shops, offices, medical clinics, etc. within park boundaries run by NPS or concessionaires.

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CO_2 equivalent emissions were 4,600 kg globally, or 14,700 kg for United States residents, in 2019 [62]. We calculated 2,141,076 unique trips to Yellowstone NP in 2021, which influences the total CO_2 output, but not per visitor estimates. For all per visitor estimates below, these represent one unique trip (e.g., one person visiting for multiple days during the same trip). Almost 90% of total emissions are from transit to and from Yellowstone NP, while 5% are from transit within the park and 4% are from overnight accommodations. Other park operations, excluding overnight accommodations, contribute slightly more than 1% of total CO_2 emissions related to Yellowstone NP tourism (Table 4, Fig 2).

3.2. Carbon dioxide emissions from transit

The majority of CO_2 emissions from transit come from transit between the park and visitors' home locations (Table 5). Flying to Yellowstone from an international home location resulted

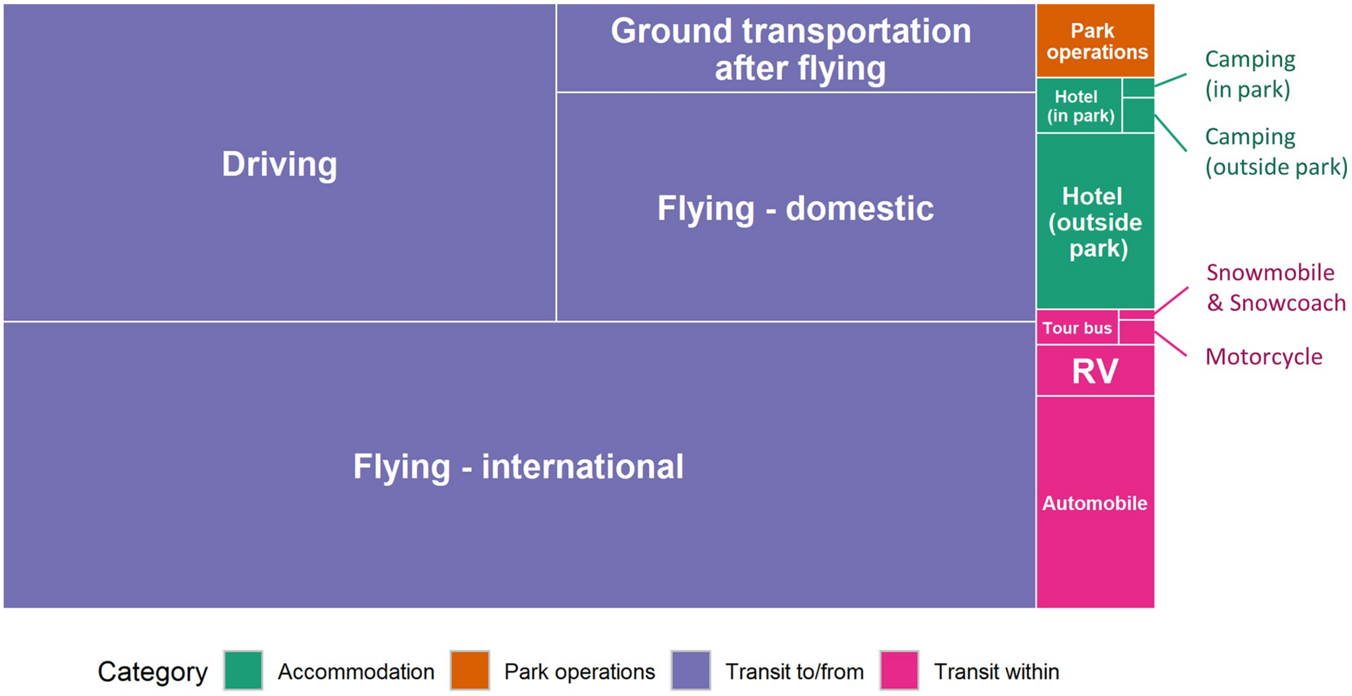

Fig 2. A visual breakdown of sources contributing to the estimated 1.03 megaton of CO_2 emissions related to Yellowstone National Park tourism. Figure created in R using the treemapify package with ggplot2 [63]. RV = Recreational Vehicle.

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Table 5. Total estimated CO_2 emissions and average CO_2 emissions per visitor resulting from each type of transit.

Category	Percent of visitors in this category	Total CO_2 (Thousands of kg)	Average CO_2 per visitor resulting from this type of transit (kg)
Transit to/from Yellowstone NP			
Driving–non-local/regional	50.8%	239,103.50	219.83
Driving–local/regional*	13.6%	19,541.43	67.11
Flying–domestic	18.6%	161,526.95	405.60
Flying–international	17.0%	436,455.96	1,199.11
Ground transportation after flying	35.6%	62,785.82	82.37
Transit within Yellowstone NP			
Automobile	78.0%	37,277.53	22.32
Tour bus	13.0%	4,301.84	15.46
Recreational Vehicle (RV)	6.0%	9,001.89	70.07
Motorcycle	2.0%	1,331.32	31.09
Snowmobile	0.5%	335.13	31.30
Snowcoach	0.5%	209.60	19.58

* Includes visitors from the surrounding states of Montana, Wyoming, Idaho, and Utah.

NP = National Park.

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in substantially more CO_2 emissions related to travel compared to other forms of transit to and from the park, while driving to and from the park resulted in the lowest CO_2 emissions per visitor. Visitors who flew only made up about 35% of all visitors, yet produced 72% of emissions related to transit to and from the park. For all CO_2 estimates related to transit to and from the destination, these estimates take into account the fact Yellowstone NP was not the primary tourism destination of all visitors. Approximately 29% of visitors indicated Yellowstone NP was not their primary destination, so 29% of transit-related emissions are not attributed to Yellowstone NP in these estimates for transit to/from Yellowstone NP.

For transit within the park, Recreational Vehicles (RVs) had the highest estimated CO_2 emissions per visitor (70.07 kg), while tour buses had the lowest CO_2 emissions per visitor (15.46 kg) (Table 5). Only 6% of visitors travel by RV within the park, yet these visitors produce 17.2% of all emissions related to transit within the park.

3.3. CO_2 emissions from accommodation and other park operations

Although the average CO_2 per visitor for accommodations is estimated at 18.99 kg, when only considering those who stay overnight in the area (81%), it rises to 23.45 kg CO_2 per overnight visitor. Staying overnight in hotels outside the park had the largest CO_2 emissions per visitor of all accommodation types (35.69 kg), followed by staying at a hotel inside the park (28.95 kg) (Table 6). Differences in per visitor CO_2 from hotels inside and outside the park are attributable to different average lengths of stay (i.e., visitors who stayed outside the park had longer stays than those who stayed inside the park). Camping had substantially lower emissions, and CO_2 emissions from staying with friends/family or backcountry camping are negligible. All other park operations (excluding lodging) produced an estimated 6.05 kg CO_2 per visitor, which we calculated assuming all visitors use park operations.

3.4. CO_2 emission reduction scenarios

There are several ways CO_2 emissions related to park tourism could be reduced in the future. Management actions, marketing strategies, policy changes, and technological innovations

Table 6. Total estimated CO_2 emissions and average CO_2 emissions per visitor for specific types of overnight accommodations and all other park operations in Yellowstone National Park.

Category	Percent of visitors in this category	Average length of stay (nights)	Total CO_2 (Thousands of kg)	Average CO_2 per visitor who engaged in the behavior (kg)
Overnight accommodation				
Hotel outside of the park	40.5%	3.02	30,949.31	35.69
Camping outside the park	15.0%	3.08	1,697.49	5.29
Hotel inside the park	11.3%	2.45	7,030.21	28.95
Camping inside the park	8.0%	3.36	990.97	5.77
Staying with friends/family	5.2%	3.41	0.00	0.00
Backcountry inside the park	1.0%	2.29	0.00	0.00
Did not stay overnight in the area	19.0%	0.0	0.00	0.00
Park Operations				
All park operations excluding overnight accommodation	100%	N/A	12,952.94	6.05

N/A = Not applicable.

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could change emissions related to transit, types of tourists, and energy efficiency. We identified seven hypothetical scenarios that could reduce emissions without restricting visitor access. These are scenarios rather than specific policies or management actions; each scenario could be achieved through a mix of various policy and management actions, marketing strategies, and/or technological innovations. It is beyond the scope of this paper to fully evaluate individual strategies, and these alternatives should be further evaluated for feasibility, acceptability, limitations, and other outcomes. Further, some of the scenarios are entirely outside the control of park management (e.g., increasing fuel efficiency on vehicles, increasing proportion of electricity generated from renewable sources for accommodations outside the park), and the only scenario entirely under the control of park management would be facilities within Yellowstone NP taking energy-saving measures. For each scenario we calculated the percent reduction in total CO_2 emissions (Table 7). Notably, reducing emissions related to transit within Yellowstone NP has a relatively small effect on total CO_2 emissions. Although not within the control of park management, increased fuel efficiency for all vehicles and a changed composition of visitors (i.e., more visitors driving and fewer flying) would have the largest effect on CO_2 emissions due to its influence on emissions related to transit to and from the park.

4. Discussion

Nature-based tourism provides numerous personal and social benefits to tourists; it also plays an essential role in the economies of many municipalities, counties, states, and even countries. This is certainly true in the western United States, where many state governments actively promote outdoor recreation and tourism at national parks and other public lands to out-of-state and out-of-country markets [64,65]. However, focusing primarily on the social and economic benefits of tourism obfuscates the many environmental costs of tourism. Principal amongst these effects are CO_2 emissions, for which tourism contributes 8% globally [5]. Here we revive a line of research into quantifying the CO_2 emissions from nature-based tourism that has been relatively stagnant since the early 2000s. The work provides a methodological and data-driven approach that can be used to better understand CO_2 emissions in other types of park destinations. The work is intended to reinvigorate discussion on both the major role tourism plays in shaping the climate and the many ways tourism's effect can be mitigated through strategic

Table 7. Hypothetical scenarios and how they would affect average CO_2 equivalent emissions per visitor to Yellowstone National Park (NP). All scenarios hold the total number of visitors constant.

Hypothetical scenarios	Change in average CO_2 per visitor (kg) *	Percent reduction in TOTAL CO_2 emissions	Percent reduction in CO_2 emissions in the specific sector(s) this change affects
Transit within the destination			
Management and marketing strategies to increasing the use of private tour buses in the park, resulting in a doubling of visitors taking tour buses instead of private vehicles once at the destination (i.e., 13% to 26% on buses)	-0.90	0.19%	3.64% *(from transit within destination)*
Management strategies to implement public transit in the park during the summer, resulting in 25% of visitors taking public buses instead of private cars once at the destination	-1.72	0.36%	7.01% *(from transit within destination)*
Management strategies to increase the number of people per vehicle, resulting in the average load factor increasing by one within the destination (for all vehicle types except motorcycles and snowmobiles)	-6.08	1.27%	24.80% *(from transit within destination)*
Transit to the destination			
Marketing strategies change the composition of visitors: 20% of tourists who fly now come from closer distances and drive instead**	-47.26	9.87%	11.01% *(from transit to/from destination)*
Energy sources and efficiency			
Facilities within Yellowstone NP take energy-saving measures and decrease energy consumption by 20%	-1.21	0.25%	20.00% *(from park operations (excluding accommodations))*
The proportion of electricity generated from renewables increases from 61% to 100% for all overnight accommodation (electricity makes up 38.3% of all energy use in the area)	-8.20	1.71%	43.17% *(from accommodations)*
Average fuel efficiency on all vehicles (airplanes, cars, buses, Recreational Vehicles (RVs), motorcycles, snowmobiles, snowcoaches) increases 20%	-75.66	15.80%	16.67% *(from transit to/from)* 16.67% *(from transit within destination)*

* Change from the actual current estimate of 478.96 kg CO_2 per visitor (Table 4).

** For this scenario, we reduced the 20% evenly from each flying destination, and instead assumed these visitors were driving from the average distance of visitors who drive to the park (1,004 km) (i.e., some visitors from oversees would be replaced by domestic visitors for this scenario).

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interventions, such as marketing strategies that change the composition of visitors or regulations that improve the fuel efficiency of vehicles. Our work purposefully focuses on what is arguably America's most well-known national park to make the analysis as tractable as possible to the largest potential audience.

Like other studies [22–25], we find transit to and from the destination has a greater influence on CO_2 emissions than transit within the destination, overnight accommodations, and park operations. The amount of emissions from transit to and from the destination may be even greater for an iconic park like Yellowstone NP, where many visitors travel long distances to visit. A similar study found substantially different effects of scenarios on CO_2 emissions related to national park tourism in Taiwan compared to those found in this study; this is likely attributable to the fact that many of the visitors in that study were local and the average travel distance to the parks in Taiwan was much shorter compared to the average travel distance to Yellowstone NP [19]. This indicates the composition of tourists visiting a park, particularly the home locations of visitors, affects which scenarios would reduce emissions the most.

As transit to and from the destination produces the most emissions, the most effective strategies for reducing CO_2 emissions address transit to and from Yellowstone NP. Additionally, flying produces much higher per capita CO_2 emissions than driving. Therefore, actions that encourage tourists to take more local or regional trips, where they could drive rather than fly, could meaningfully reduce CO_2 emissions. For instance, tourism marketers could advertise more to regional audiences rather than audiences that would need to fly. At the site-level, managers could provide interpretive information about CO_2 emissions related to transit. However, some researchers suggest there may be cognitive dissonance when providing travelers with information on the negative environmental consequence of flying (i.e., attitudes and beliefs may be inconsistent with behavioral decisions), and that more research is needed on behavioral changes regarding air travel [66]. There are many benefits to nature-based tourism, and strategies could encourage more local or regional travel without reducing the total visitation to parks.

This paper evaluates the relative CO_2 emission contributions from distinct components of park tourism to identify priorities for reducing CO_2 emissions. However, this is not a comprehensive policy analysis, and other costs and benefits related to each scenario should be considered. For example, while tourism does contribute significantly to CO_2 emissions globally, tourism to parks like Yellowstone NP can lead to indirect environmental benefits. Visiting parks and protected areas can increase pro-environmental behaviors at home, some of which have been shown to reduce greenhouse gas emissions [67,68]. Therefore, the intended takeaway of this study is not that overall visitation must decrease to reduce CO_2 emissions. Instead of reducing visitation, strategically influencing aspects of park tourism can reduce emissions while still providing visitor enjoyment. Overall, tourism planners, park managers, and policymakers could use this approach to help make data-driven decisions for reducing carbon emissions. Specific options for reducing CO_2 emissions are outlined in other works, including options that focus specifically on parks and protected areas [20]. This paper adds a methodology for considering the level of impact of different scenarios.

4.1. Limitations and future research

For all calculations, the profile of visitors was based on a visitor study from August 2016, which only surveyed August visitors. However, it is possible that the visitor profile varies seasonally, as well as across years. For instance, the COVID-19 pandemic likely caused a temporary decline in the percentage of international visitors, and it is unknown whether visitor characteristics in Yellowstone NP have returned to pre-COVID levels. Additionally, most values used in the calculations have some degree of uncertainty. Data from the 2016 visitor survey have a margin of error between 3–5% depending on the question [47]. Detour factors, equivalence factors, and energy per visitor/night in overnight accommodations are all estimates based on the best available information and research. Fuel efficiency data are mostly from U.S. averages, but fuel efficiency within Yellowstone NP may be slightly lower, particularly in the summer when high visitation sometimes causes stop-and-go traffic, or slightly higher due to increased fuel efficiency at higher elevations. While this work is grounded in previous research, and reasonable assumptions, the results are still estimates.

Future research is needed to understand visitors' perceptions of CO_2 emissions related to parks and protected areas, and what they believe are the most appropriate actions to reduce tourism-related emissions. Additionally, virtually visiting a destination (e.g., watching recorded videos or live-streaming cameras) is becoming more common, and is already an option for Yellowstone NP [69]. This could enable some of the benefits visitors experience from in-situ tourism without the CO_2 emissions from travel, but more research is needed to better understand this option. Future CO_2 estimates may also integrate the carbon reducing function of parks and protected areas into the calculations. Previous research suggests that Yellowstone NP is a net carbon sink, with -1.5 megatons CO_2 annually [36]. This indicates that despite tourism-related emissions, Yellowstone NP is likely a net carbon sink. More research is needed to better understand carbon sequestration and net carbon emissions related to park tourism.

Finally, this type of analysis could be replicated in other parks and protected areas to understand how different park and tourism characteristics influence the composition of CO_2 emissions, as well as how effective different scenarios could be at reducing emissions. This study only analyzed a single park, but of course most parks exist in a larger system–in this case, Yellowstone NP is only one of over 420 units managed by the NPS. Analyses across a whole system would be useful to determine where might be the easiest or most viable places to target for CO_2 emission reductions. Some parks may have plentiful opportunities to reduce emissions, while others may have few opportunities to further meaningfully reduce emissions.

5. Conclusion

This study demonstrates and documents a process both for estimating CO_2 emissions related to tourism at an individual park, and for understanding how effective specific scenarios could be at reducing these emissions. These estimates and scenarios can help decision makers who aim to reduce emissions make more strategic decisions by weighing relative reductions in CO_2 against other constraints and concerns. When estimating CO_2 emissions, we aim to use the best available information, but there is always uncertainty and CO_2 emissions should be treated as estimates rather than exact values. Additionally, the results support the notion that for parks that receive many non-local visitors, travel to and from the destination produces the vast majority of CO_2 emissions. Therefore, scenarios targeting this category of behaviors for reductions are likely to be the most effective. Although tourism produces substantial CO_2 emissions, the scenarios we examine here show that it is possible to reduce emissions while maintaining current levels of access and visitation.

Supporting information

S1 Data. A spreadsheet used to track all values used as input data and generate estimates. (XLSX)

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