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Research article

Benefits of the fire mitigation ecosystem service in The Great Dismal Swamp National Wildlife Refuge, Virginia, USA

Bryan Parthum [a], Emily Pindilli [a, *], Dianna Hogan [b]

[a] U.S. Geological Survey, Science and Decisions Center, 12201 Sunrise Valley Dr. MSN 913, Reston, VA, 20192, United States
[b] U.S. Geological Survey, Eastern Geographic Science Center, 12201 Sunrise Valley Drive, MSN 521, Reston, VA, 20192, United States

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ABSTRACT

The Great Dismal Swamp (GDS) National Wildlife Refuge delivers multiple ecosystem services, including air quality and human health via fire mitigation. Our analysis estimates benefits of this service through its potential to reduce catastrophic wildfire related impacts on the health of nearby human populations. We used a combination of high-frequency satellite data, ground sensors, and air quality indices to determine periods of public exposure to dense emissions from a wildfire within the GDS. We examined emergency department (ED) visitation in seven Virginia counties during these periods, applied measures of cumulative Relative Risk to derive the effects of wildfire smoke exposure on ED visitation rates, and estimated economic losses using regional Cost of Illness values established within the US Environmental Protection Agency BenMAP framework. Our results estimated the value of one avoided catastrophic wildfire in the refuge to be $3.69 million (2015 USD), or $306 per hectare of burn. Reducing the frequency or severity of extensive, deep burning peatland wildfire events has additional benefits not included in this estimate, including avoided costs related to fire suppression during a burn, carbon dioxide emissions, impacts to wildlife, and negative outcomes associated with recreation and regional tourism. We suggest the societal value of the public health benefits alone provides a significant incentive for refuge mangers to implement strategies that will reduce the severity of catastrophic wildfires.

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1. Introduction

Ecosystem Services are the benefits provided by the natural environment that are of value to human populations. Ecosystem services are threatened by development, pollution, fragmentation, overexploitation of resources, and climate change. As part of a multi-year study on the ecosystem services of the Great Dismal Swamp (GDS) National Wildlife Refuge, the U.S. Geological Survey, in coordination with the U.S. Fish and Wildlife Service, examined the economic implications of health effects related to a catastrophic peat fire. The GDS is a highly-altered system that has been ditched, drained, and logged, all of which may be increasing the frequency and severity of wildfires (Reddy et al., 2015). Sleeter et al. (2017) provides an in depth discussion of the current and desired states of carbon stock/flow, vegetation, and soil moisture in the GDS. A series of water control structures were installed in the GDS's ditches which allow refuge managers to actively manage water levels and potentially optimize soil moisture. This hydrologic management is expected to result in multiple benefits including additional carbon sequestration, restoration of desired vegetation communities, and reduction of the duration and severity of wildfires (Reddy et al., 2015).

Benefits of a fire mitigation ecosystem service are closely linked to the health and hydrology of the soils within a peatland ecosystem. Periodic surface wildfires play a critical role in healthy peatland vegetation communities by helping perpetuate native trees including Atlantic White Cedar and pond pine (Sleeter et al., 2017; Reddy et al., 2015; Laderman et al., 1989). Conversely, catastrophic wildfire in a peatland is often associated with low water levels, and characterized by long-burning ground fires deep within the peat (>0.5 m) that release large quantities of carbon into the atmosphere (Reddy et al., 2015). Fire events of this magnitude are considered extremely damaging to the ecosystem; it is in this context that we describe these fires as 'catastrophic'. The GDS has experienced low water levels due to centuries of drainage and human disturbance. In this paper, we investigate the public health

* Corresponding author.
E-mail addresses: bparthum@usgs.gov (B. Parthum), epindilli@usgs.gov (E. Pindilli), dhogan@usgs.gov (D. Hogan).

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benefits of avoided catastrophic peat wildfires through improved hydrologic management, and the implication for adjacent human populations. We used the cost of illness (COI) as a lower bound indicator of the economic value of reducing wildfire severity and frequency.

In recent years, two catastrophic wildfires burned large areas within the refuge, producing dense smoke plumes that moved into neighboring communities. The South One Fire of 2008 (SOF) was ignited by heavy machinery, burning from June 9th through October 13th and spanned an estimated 1976 ha. During the 121-day burn, the cost of fire suppression exceeded twelve million dollars and distributed smoke into the popular Hampton Roads area of southeastern Virginia, home to an estimated two million people (US Census, 2010). In 2011, the Lateral West Fire, ignited by a lightning strike, swept through the same footprint as the SOF burning an estimated 2630 ha over the course of 111 days. Both fires quickly destroyed aboveground vegetation, while concurrently burning deep into the organic peat soils with an average fire depth of 0.8–1.1 m (Reddy et al., 2015). Under current conditions, fires similar to this magnitude and duration are expected to recur twice every 100 years - an annual probability of 2% (MTBS, 2014). Our analysis focused on the SOF due to the availability of emergency department data; we considered the SOF economic costs as a proxy for avoiding similar catastrophic events in the GDS.

Peat soils, such as those in the refuge, have been shown to produce a unique composition of emissions when ignited (Blake et al., 2009). This combustion results in the intermittent release of dense plumes containing volatile organic compounds, PM2.5 (particulate matter with a diameter of <2.5 μm), and PM10 (particulate matter with a diameter of <10 μm), which are considered particularly threatening to the cardiorespiratory health of exposed communities (Geron and Hays, 2013; Blake et al., 2009; Hinwood and Rodriguez, 2005; Joseph et al., 2003).

The health effects of wildfire emissions have been assessed using a number of different approaches and vary based on geographic location, ignition source, fuel, atmospheric conditions, topography, duration, season, and other physical variations of wildfires (Tse et al., 2015; Youssouf et al., 2014; Kochi et al., 2010, 2016; Rappold et al., 2011; Vora et al., 2010). Johnston et al. (2012) emphasize the substantial contribution of landscape fires to harmful global emissions and provide annual mortality estimates resulting from such fires. These estimates are substantial (200k-600k deaths per year globally); however, Kochi et al. (2016) recommends that mortality should not be considered for individual fire events that are: in the lower quartiles of susceptible area, short lived, or infrequent. Wildfires in the GDS are estimated to be both infrequent and on the lower quartiles of susceptible area (<4k hectares) (MTBS, 2014). Following this recommendation we examined effects related to morbidity and assume mortality is not a primary outcome of GDS wildfires. This assumption is supported by the fact that there was no recorded loss of life directly or indirectly attributable to either the 2008 or 2011 GDS wildfires (communication with GDS staff). We focused on morbidity symptoms experienced in nearby populations resulting from brief exposure to dense wildfire smoke plumes (EPA, 1999; 2004).

Rappold et al. (2011) examined the effect of peat fires on emergency department (ED) visitation rates in 42 North Carolina counties during a 2008 catastrophic fire in the Pocosin Lakes National Wildlife Refuge, a peatland with similar vegetation and hydrologic characteristics as GDS. Rappold et al. (2011) provided the estimates of cumulative Relative Risk (cRR) used in our analysis. cRR measures the ratio of the probability of a given occurrence over a discreet timeframe; for our purposes, the occurrence ratio is defined as those at risk of an ED visit in the absence of harmful smoke exposure, to observed visits during exposure. Johnston et al. (2014) employed a similar approach over an eleven-year time period in Sydney, Australia. Using ground-based PM sensors, Johnston et al. (2014) examined the relationship between harmful PM levels due to confirmed fire events and ED visitation. Although the fuels in the Australian study were very different to those of the present study (litter and grass fuels versus organic peat soils), Johnston et al. (2014) found a significant relationship (measured in cRR) between ED visitation and smoke exposure days. Due to the likeness of fuel source in Rappold et al. (2011) to that of the SOF and the GDS in general, we robustly applied and extended their methods for this analysis.

The valuation literature on the economic costs of wildfire is largely focused on geographic areas dissimilar to the GDS (Moeltner et al., 2013; Richardson et al., 2012). Richardson et al. (2012) employed a defensive behavior valuation method to derive willingness to pay (WTP) to avoid smoke exposure during a 2010 California wildfire. When compared to values derived using COI methods, WTP is considered a more appropriate measure of the true value of fire mitigation services (EPA, 2007; Hanemann and Kanninen, 2001; Loomis et al., 1991). The authors estimated a WTP/COI ratio of 9:1, suggesting the true value of fire mitigation could potentially be as much as, or more than, nine times higher than COI estimates. Moeltner et al. (2013) conducted an intertemporal analysis of wildfires in the western United States and found the marginal effects of wildfires on public health to have a lower-bound of $150-$200 per 40 ha of wildfire, aggregated to approximately $2.2 million over the course of a fire season in their study area.

Our analysis adds to the literature by exploring the economic cost of wildfire through localized outcomes on public health, attributable to wildfire smoke emissions from a nearby forested peat wetland. We extend the wildfire literature by providing unique estimates of the ecosystem services benefits resulting from a change in refuge management regimes. Using spatially targeted COI estimates we provide a local measure of the potential benefits to public health as a result of improved hydrology and wetland restoration. This study also contributes to a growing body of literature exploring the versatility and applicability of remote sensing methods by using high-frequency satellite data as a foundation for our analysis. Lastly, we propose that the methods described may provide a concise and systematic process for researchers and land managers to employ when more in-depth studies are not feasible. Our estimates of the benefits of avoided fire on an annual basis rely heavily on fire probabilities and the expected reduction in these probabilities as a result of management actions, which are highly uncertain. To this end, we offer a hypothetical damages avoided estimate based on the reduction of catastrophic fires by 50% in either severity or duration. The ecosystem services benefit estimates are unique to this refuge, and researchers should consider the similarity of their study area to ours before performing any direct transfer of these estimates.

2. Study area

The GDS encompasses approximately 54,000 ha of protected habitat located in southeastern Virginia and northeastern North Carolina. Similar to other southern swamps in the eastern United States, the wetland provides a unique habitat for a variety of flora and fauna, and numerous opportunities for recreational activities. However, the GDS is highly disturbed due to centuries of drainage, logging, and human encroachment, which together have led to drier and less-desirable conditions within the refuge (Reddy et al., 2015). This has shifted fire dynamics within the GDS by exposing organic peat soils to a higher probability of catastrophic wildfire and increasing the frequency and intensity of large fire events

(Frost, 1987). In an effort to restore the conditions of underlying hydrology and vegetation, GDS refuge management have installed water control structures. We don't estimate the costs of restoration or opportunity costs of the land which is protected within the refuge; the objective of the current analysis is to estimate a subset of the benefits of a restored system. The refuge sits 40 km inland from the Atlantic coastline, and experiences a west to east atmospheric current. This current typically carries smoke plumes originating from the GDS out to sea; however, eight Virginia counties (Chesapeake, Franklin, Isle of Wight, Norfolk City, Portsmouth City, Southampton, Suffolk, and Virginia Beach) surrounding the refuge are prone to smoke exposure from these plumes before they are eventually carried off the coast. These counties lie within the Tidewater region of Virginia (Fig. 1). Five counties in northern North Carolina are suspected to have been exposed to plumes from the SOF as well - Gates, Camden, Currituck, Pasquotank, and Perquimans. However, due to a wildfire in the Pocosin Lakes National Wildlife Refuge during our study period, it is difficult to determine the origin of the smoke over these counties. In addition, emergency department data for Franklin County in Virginia was unavailable. To avoid over-estimation of the fire mitigation service and due to limitations in data availability, we limit our study to the seven Tidewater counties.

3. Materials and methods

Our methodology to estimate the benefits of a fire mitigation ecosystem service in GDS was performed in four distinct stages: 1) determined geographic area and populations vulnerable to dense smoke plumes originating within the refuge; 2) applied measures of cRR to health outcomes attributable to wildfire smoke exposure; 3) estimated the economic cost of a wetland wildfire using localized values for COI and lost wages; and 4) applied site specific fire probability and forecasted reductions through proposed management actions. The resulting avoided cost estimate is what we consider to be the public health benefit of a fire mitigation ecosystem service.

3.1. Area of impact

We determined geographic area and temporal exposure to SOF smoke plumes using a combination of remote sensing techniques, ground-level sensors, and air-quality indices. We examined daily geostationary aerosol smoke product (GASP) satellite readings acquired from the National Environmental Satellite Data and Information Service for the Tidewater region. These data provide high-resolution measures of aerosol optical depth (AOD) at 4 km square grids collected in 30-min intervals during daytime hours. AOD is a unitless measure ranging from 0 to 2; higher values indicate dense atmospheric conditions and are considered a good predictor of harmful PM2.5 concentrations (Al-Saadi et al., 2005; EPA, 2009). We generated daily 24-h averages of AOD measurements for the seven Tidewater counties.

In addition to smoke plumes, AOD can also be influenced by ambient air pollution. To help distinguish between pollution and wildfire contributions to AOD measurements, we examined historical levels within the region during both fire and non-fire years. In 2008 during those months that there were no fires (January to June; November and December), the daily AOD average for the Tidewater region was 0.33 with a standard deviation of 0.22. Similarly, during non-fire years (2005-07; 2009-10) AOD averages in the study area were 0.34 with a standard deviation of 0.26 (Table 1). The dense nature of the SOF plumes can bring these levels up to 2.0. As such, we determined a threshold for harmful smoke exposure to be in excess of 1.25 (consistent with assumptions in Rappold et al., 2011), and require at least 10% of a county be exposed above this level to be considered. Our estimates rely on these thresholds to be conservative and consistent with the literature to avoid overestimation in the results. During the 121-day period we found that each of the seven Tidewater counties examined was exposed between one and six days, with a total of 14 days when at least one county was exposed to harmful smoke.

Satellite-sourced AOD may not always be an appropriate measure of ground level conditions. However, peat wildfires typically result in low-lying smoke plumes, supporting the use of GASP readings when determining human exposure to wildfire smoke plumes (Rappold et al., 2011). An alternative to GASP AOD is to utilize ground level particulate matter measurements from devices in the region. A benefit to ground level monitors is that their elevation is closely representative of human exposure to PM2.5 (Boyouk et al., 2010). However, there are several limitations with these monitors including reduced ability to accurately determine readings across a given region due to their fixed location and the frequency of readings (Youssouf et al., 2014). For example, some monitors produce values once per day while others are as infrequent as once every four days. Twenty-four hour averages of these readings are a good estimate of high exposure levels at a given location, but weather patterns may prevent the monitors from detecting high levels of PM2.5 due to wildfire smoke plumes (Youssouf et al., 2014). The National Aeronautics and Space Administration Langley Research Center is the only ground monitor in the seven-county study area providing daily PM2.5 levels. 7 of the 14 exposed days determined using GASP AOD were also days that the ground monitor provided readings. We used these data and the resulting Air Quality Index (AQI) measures of the region to compare estimates of heavy exposure determined by the GASP data (see Table 1).

While the 14 GASP AOD high-exposure days also received high PM2.5 estimates from the ground monitor when available, the standard errors are much larger for the Langley Research Center ground monitor and AQI. When smoke plumes reach the monitor, this provides a good measure of local air quality; however, much of the Tidewater region is not captured by these readings and results in a much larger estimation error for the region. GASP high exposure days have an average AOD of 1.45 and a notably tighter deviation from the mean as they provide a much more spatially and temporally targeted reading derived through the satellite measurements. During the same months as the SOF in the five non-fire years, the 24-h AQI average for this region was 46.98. Daily levels of AQI above 63 are considered moderate to unhealthy, and correspond with measured PM2.5 conditions in excess of 35 μg/cm.[1] The AQI and PM2.5 levels included in Table 1 are produced using the U.S. EPA AirData archives.[2]

3.2. Health outcomes

We examined the incidence of five cardiorespiratory related illnesses during the SOF. Periods of brief yet heavy exposure to wildfire smoke have been widely recognized to have negative impacts on five specific diagnoses: asthma, chronic obstructive pulmonary disease (COPD), pneumonia/acute bronchitis, congestive heart failure (CHF), and miscellaneous cardiopulmonary symptoms (EPA, 2004; 1999). These outcomes can by identified by using the International Classification of Diseases, Ninth Division, Clinical

[1] Additional information regarding the AQI can be accessed through the U.S. EPA and/or AirNow.gov.

[2] EPA AirData archives: https://www.epa.gov/outdoor-air-quality-data/download-daily-data.

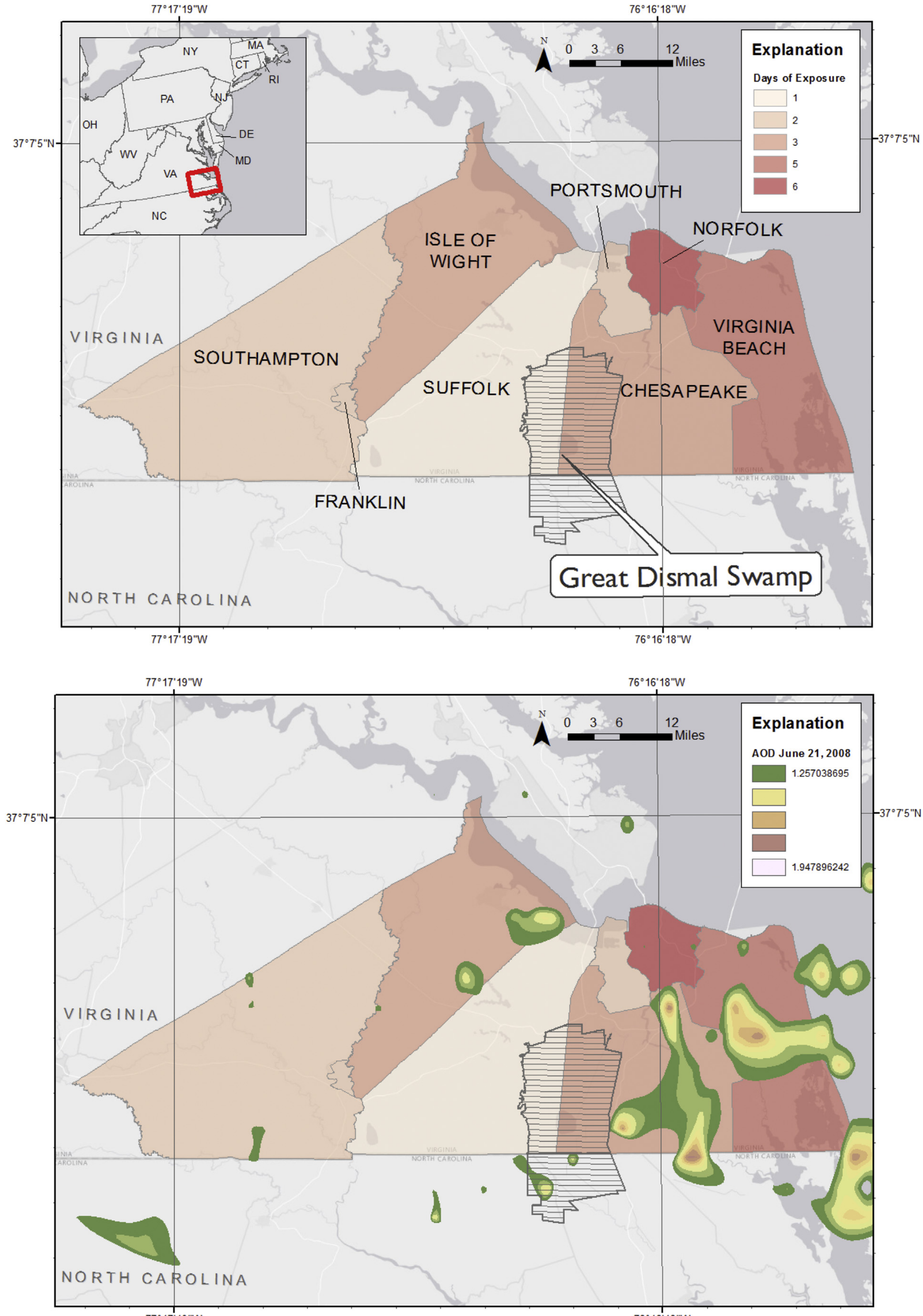

Fig. 1. Study Area. Top panel provides total number of days VA counties were exposed to heavy smoke plumes during the Great Dismal Swamp South One Fire (at least 10% of county above daily Aerosol Optical Depth (AOD) average of $\geq$1.25). Bottom panel provides a snapshot of AOD readings for June 21, 2008 when Chesapeake and Virginia Beach were both above the exposure threshold due to heavy smoke plumes from the SOF.

Table 1
Exposure metrics.

	Timeframe	AOD	AQI	LRC-PM2.5
Non-fire years	Annual	0.34 (0.26)	41.79 (18.58)	10.90 (6.11)
	SOF months	0.37 (0.24)	46.98 (20.43)	12.67 (7.16)
2008	Non-fire months	0.33 (0.22)	38.09 (17.40)	9.75 (5.53)
	SOF months	0.39 (0.24)	56.76 (34.81)	17.51 (15.93)
	Exposed days	1.45 (0.19)	112.42 (59.92)	46.83 (32.75)

Note: Mean values displayed with standard errors in parentheses. Non-fire months refers to the months outside of the 121-day SOF. burn. Non-fire years include '05-'07 and '09-'10. SOF months of non-fire years are provided for seasonal reference. Exposed Days are those that have 24-h averages ≥ the AOD threshold of 1.25. AQI = Air Quality Index; LRC = Langley Research Center Monitor; PM2.5 = particulate matter ≤2.5 μg. AOD = aerosol optical depth.

Table 2
Disease classifications.

Symptoms	ICD-9-CM
Asthma	493
C.O.P.D.	491,492
Pneumonia	466; 481-82; 485-86
C.H.F.	428
Cardiopulmonary	786

ICD-9-CM = International Classification of Diseases, Ninth Division, Clinical Modification system; COPD = chronic obstructive pulmonary disease; CHF = congestive heart failure.

Modification (ICD-9-CM) system, which are used by emergency departments (ED) to classify patient diagnoses for symptoms of morbidity. Ten ICD-9-CM codes fall under the five symptoms identified above, and are used in our analysis. In cooperation with Virginia Health Information[3] we explored daily ED visits in each of the seven Tidewater counties. Table 2 provides a summary of the symptoms and corresponding ICD-9-CM codes.

Smoke exposure might not result in an immediate visit to the ED (Pope et al., 2008; Braga et al., 2001); as such we considered a window for ED visitation due to a single initial day of heavy smoke exposure. Rappold et al. (2011) employed a distributed lag model (Peng et al., 2009) to determine a 5-day lag period in which those who have been exposed to heavy smoke plumes may experience symptoms related to exposure. Following Rappold et al. (2011), we defined the visitation window to be the initial day of exposure plus a 5-day lag period. During the SOF there were 548 total ED visits for the ten ICD-9-CM codes throughout the seven Tidewater counties.

Not all the ED visits during the visitation window are a result of the wildfire. A background rate of ED visits for the same symptom classifications would occur regardless of smoke exposure. Rappold et al. (2011) produced estimates of cRR for ED visits associated with brief but heavy exposure to wildfire smoke using a quasi-poisson generalized linear model. Daily estimates of relative risk were then used to determine a measure of cRR over the visitation window. In addition to a point estimate, they established statistically significant bounds for each symptom. The point estimate and corresponding bounds provide the upper and lower bounds for our valuation estimates. Rappold et al. (2011) explicitly states measures of relative risk to be:

$$Daily\ RR : exp\left(\beta_{ijt}\right) = \frac{\mu_{ijt}^{Exposed}}{\mu_{ijt}^{Not\ Exposed}} \tag{1}$$

Equation (1): β is determined through the quasi-poisson regression described above; μ denotes the observed/expected number of visits conditional on exposure; i, j, t denote the symptom i in county j on day t.

$$Cumulative\ RR : exp\left(\sum_{t=0}^{5}\beta_{ijt}\right) \tag{2}$$

Equation (2): β_{ijt} is determined through the distributed lag model (Peng et al., 2009); t denotes the days of visitation from $t = 0$ (day of exposure) to $t = 5$ (lagged exposure days); symptom i in county j. This is the coefficient we use in the following equation to determine excess visits due to the SOF. By applying estimates of cRR for each ICD-9-CM code to the observed visitation during the SOF, we statistically identified the counterfactual - visits not due to the wildfire. Explicitly stated:

$$Excess\ Visits = \mu_{ijt}^{Exposed} - \frac{\mu_{ijt}^{Exposed}}{\exp\left(\sum_{t=0}^{5}\beta_{ijt}\right)} \tag{3}$$

3.3. Economic valuation

The final step in our analysis was to associate an economic cost with each excess visit from equation (3). We used regional COI values highlighted within the BenMAP model framework (EPA, 2007). BenMAP provides COI by zip code; however, while the estimates vary by diagnosis they remain consistent throughout the Tidewater region. These data are available through www.epa.gov/benmap. While the BenMAP COI estimates incorporate all direct costs of hospitalization associated with each ED visit by ICD-9-CM diagnoses, they should be considered a lower bound estimate as they do not account for the disutility associated with symptoms or lost leisure and do not reflect the expenses incurred to avoid exposure. We used local estimates of symptom days for each hospitalization diagnoses (EPA, 2007) in conjunction with median daily income for each county to estimate opportunity costs of illness. We assumed individuals to be out of work for the extent of the symptom days. These symptom days do not include time lost during the recovery after the hospital visit, lost productivity, or lost recreation, which have all been shown to significantly increase traditional COI estimates (Chestnut et al., 2006).

The likelihood of ED visits and their associated COI are known to vary by age (EPA, 2007), so we considered COI and symptom-day estimates of two age categories. For asthma, COPD, and pneumonia diagnoses, the first age category falls between 18 and 64, and the second is above 64 years of age. For CHF, only groups above 65 years of age are considered, and for miscellaneous cardiopulmonary all patients over 18 are a single COI group. These age categories are determined within the BenMAP framework to have different costs and symptom days associated with each diagnoses. We used wages as a proxy to determine the value of time lost during the ED visit. As recommended by the EPA (2007), daily per-capita median income is applied to the number of symptom days associated with each diagnosis. This data is derived from the Bureau of Labor Statistics[4] for each of the seven Tidewater counties. While any group

[3] ED visits during the duration of the SOF burn were made available to the researchers through Virginia Health Information for the current analysis and under privacy agreements cannot be released.

[4] Bureau of Labor Statistics provides wage data by county: https://www.bls.gov/data/#wages.

Table 3
Tidewater ED visits during the SOF.

Diagnoses	cRR	Total Visits	Excess Visits
	(95% C.I)	(Age)	(95% C.I)
Asthma	1.65	53	20
	(1.25–2.17)	(18 ≤)	(11–38)
C.O.P.D.	1.73	83	35
	(1.06–2.83)	(18 ≤)	(5–53)
Pneumonia	1.59	112	41
	(1.07–2.17)	(18 ≤)	(7–60)
C.H.F.	1.37	119	32
	(1.01–1.85)	(65≤)	(1–54)
Cardiopulmonary	1.23	181	33
	(1.06–1.43)	(18 ≤)	(10–54)

Note: Total Visits are observed over the duration of the SOF for the 7 counties exposed to heavy plumes from the burn. Excess Visits are determined using equation (3). The age of patients whose visits were considered is consistent with Rappold et al. (2011). Final valuation uses these EV and COI varies by age group within BenMAP framework: www.epa.gov/benmap.

categorized above 64 years of age is assumed to be out of the work force, wages are used as a proxy for opportunity costs during an ED visit for groups above this age threshold. We aggregated the direct costs of hospitalization (COI) with the opportunity costs (lost wages: LW). The total benefit of avoiding these costs for one catastrophic wildfire in the GDS is calculated using equation (4), an aggregate of values across all seven counties:

$$\textit{Cost of One Fire} = \sum_{j=1}^{7} \left[EV_{ij} * \left(COI_{ij} + LW_{ij} \right) \right] \tag{4}$$

4. Results

Our analysis indicates that a single catastrophic wildfire event in the GDS results in an estimated 161 excess ED visits throughout the seven Tidewater counties. For each symptom, Table 3 provides a summary of measures of cRR, total ED visitation, and ED visitation attributable to the wildfire. The majority of symptoms that resulted in excess ED visits were for morbidity diagnoses surrounding pneumonia, totaling 41. An estimated 35 visits were related to COPD, in addition to considerable ED visits for asthma, C.H.F., and other cardiopulmonary symptoms.

The economic cost associated with these health effects is an estimated $3.69 million. The upper and lower bounds surrounding our estimate range from $696,475 to $5.73 million, and are a direct result of the 95% confidence interval of the cRR estimates.[5] Table 4 summarizes the direct COI, opportunity costs, and total costs associated with the health outcomes attributable to the SOF. These are conservative estimates and only include the cost of hospitalization and lost wages during the visit. It is important to note that our analysis does not attempt to quantify the total economic or public health costs associated with a wildfire in the GDS. It is likely that additional, or less-severe, symptoms were experienced by people within the exposure area who did not seek medical attention from the emergency departments examined within our study. The expenses and/or disutility that these people incurred are not accounted for in our estimates. Additionally, this analysis does not include the real costs associated with fire suppression, the social losses of carbon dioxide emissions from wildfire, the impacts to wildlife, or the lost opportunities associated with recreation and tourism during a fire event. Our values should therefore be considered a conservative estimate of total losses to social welfare from one wildfire.

Table 4
Endpoint Valuations for one Wildfire in the GDS.

	South One	Annualized Costs	Annualized Benefits
	Fire	(Current Hydrology)	(Improved Hydrology)
Cost of Illness	$ 3,575,000	$ 71,511	$35,756
Opportunity Cost	$ 116,605	$ 2332	$ 1166
Total	$ 3,692,000	$ 73,843	$36,922
Per Hectare	$ 306	$ 8	$ 3.75

Note: MTBS estimates the current annual probability of a catastrophic fire within the GDS is 2%. With improved hydrology this estimate may fall to 1%. Per hectare estimates are specific for peat wetland environments containing dense organic soils and medium-dense above ground biomass with nearby populations. All values are reported in 2015 U.S. Dollars.

When considering fire mitigation as an ecosystem service, it is useful to assess the annual cost associated with a wildfire. Under current (disturbed) conditions, the Monitoring Trends in Burn Severity estimates that the GDS is expected to experience a catastrophic wildfire like the SOF twice every 100 years - a 2% annual probability.[6] In terms of the health effects that we considered, this translates to an annual risk of $73,843 in total costs (Table 4). A peat wetland that was functionally restored would likely experience fewer and/or less severe catastrophic fires. GDS land managers estimate that implementation of proposed management actions such as completing the system of water control structures and restoring soils could reduce frequency or duration of expected annual fire incidence by as much as an annual probability decrease from 2% to 1%, and potentially reduce the duration of catastrophic wildfires by 50%. A reduction of this magnitude would be associated with a $36,922 savings in expected annual costs to public health.[7] This ecosystem service value, along with other costs associated with wildfires, could be considered in cost-benefit analyses of hydrologic restoration.

Evaluation of the costs of wildfires on a per hectare basis is another way we considered how the magnitude of such a fire alters economic losses. To estimate values by total area burned, we examined the size and scope of the SOF. The SOF burned 1976 surface hectares. On a per hectare basis, we estimated the health costs associated with the SOF to be $306.

5. Discussion

The dangers of public exposure to wildfire smoke, such as the plumes generated during the SOF, can be costly. This analysis indicates that a single catastrophic fire within GDS has potential costs to public health ranging from $696,475 to $5.723 million. In terms of ecosystem services, the functionality of the ecosystem is of interest when studying a fire mitigation service. For every catastrophic fire event that is avoided or for every fire that has a shortened duration, the value is gained by society. Under current conditions, fire events of this magnitude recur twice every 100

[5] These confidence intervals are listed in Table 3 under the point estimate for each estimate of cRR. To create the upper and lower bounds in our valuation, these values were used in equation (3).

[6] Monitoring Trends in Burn Severity (MTBS) provides 30 years of historical data to determine fire probabilities for the GDS. Recent scenarios suggest annual probabilities could in fact be larger, especially when coupled with climate change projections.

[7] Peat wetland hydrologic restoration and water control structures are expected to contribute to the reduced magnitude of impacts (especially duration) of wildfires and potentially reduced incidence; however, the precise effects are not fully understood. Therefore, we use 50% reductions in duration and/or incidence as a hypothetical to illustrate the potential value of avoided health effects.

years, or an annual 2% probability (MTBS, 2014). On an annual basis, we estimate the public health costs attributable to wildfire in the GDS to be between $13,930 to $114,446. If management actions could reduce the recurrence of catastrophic fire to one event every 100 years, or if the severity/duration of each fire were decreased by 50%, the annualized savings would be between $6965 to $57,233. It is important to consider the true underlying costs of wildfires by exploring the use of ratios such as those developed in Richardson et al. (2012), EPA (2007), and Dickie and Messman (2004). These ratios are indicative of how high the true value of avoided wildfires could potentially be. If we were to adopt the WTP/COI ratio developed by Richardson et al. (2012) of 9:1, our results translate to a WTP on the order of $6.27 million to $51.51 million to avoid a single catastrophic wildfire event or $62,700 to $515,100 annually.

The values estimated by this analysis are a conservative, partial estimate. The true costs remain unknown, and the intent of this study is to further refine estimates of just one of the many costs the public experiences during a wildfire event. Valuation of this ecosystem service does not account for avoidance behavior for those at risk of smoke exposure, changes to economic activity resulting from wildfires, the costs to suppress or extinguish the fire, the value of carbon emissions (lost carbon stock), or impacts to wildlife and biodiversity on the refuge as a result of the event. We provide a conservative value estimate for the public health parameter intended to provide support to management decisions within the GDS. A shortcoming of this study, and similar studies, is the limited size and scope of historical wildfires within the GDS, in addition to the limited access to emergency department visitation data. We propose the true underlying relationship between wildfire size and emergency department visitation to be non-linear and highly dependent on proximity and density of communities to the fuel source. Factors other than wetland hydrology that likely contribute to this relationship include public air quality notices and the greater atmospheric patterns which distribute smoke plumes upon various populations. This is an area for future research and we propose this analysis will partner well with studies which examine other factors contributing to the relationship between public health and wildfire or wetland management. Public land managers outside the GDS might find these estimates useful, especially for peat wetland areas susceptible to wildfire, and for management actions aimed at reducing the probability of wildfire for these areas.

6. Conclusions

Our analysis adds to the existing literature exploring the economic cost of wildfire through outcomes on public health, attributable to localized wildfire smoke emissions from a nearby forested peat wetland. We extend these costs into management space by providing estimates of the benefits of land management aimed at reducing the duration or severity of wildfire. The methods described above provide a concise and systematic process for researchers and land managers to examine the benefits of a fire mitigation ecosystem service. For this study we were limited to select days of emergency department data during a single historical fire within the GDS. Clearly this is a shortcoming of this study; however, our estimates and methods provide an important contribution to this literature, and we encourage other researchers to replicate these methods in similar wetland areas to help uncover the true underlying relationship between wetland management and public health risks of peat wildfires. Emergency department data such as these are often difficult or costly to acquire. For this reason we propose that a statistically sound functional transfer of the measures of cumulative relative risk from Rappold et al. (2011) provides a feasible approach when larger, more in-depth studies are not practical. We also contribute to a growing body of literature exploring the versatility and applicability of remote sensing methods by using high-frequency satellite data as a foundation for our analysis. By using localized COI we propose that the end point estimates derived within our analysis are an accurate value for this region, and any similar research should explore the COI estimates corresponding to the same region as the study.

The GDS provides many ecosystem services and the current efforts to restore the wetland's hydrology could potentially increase the flow of these services. A reduction in the occurrence or severity of catastrophic wildfires in GDS would have multiple benefits including the potential avoidance of negative public health effects. Valuation of the fire mitigation ecosystem service as a part of a portfolio of services provides important information to refuge management about the total potential benefits associated with wetland restoration. Climate change and continued drying conditions could potentially increase the probability of catastrophic fire, and considering the full range of these valuations will be an important step in protecting the overall welfare of the public.

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References

Al-Saadi, J., Szykman, J., Pierce, R.B., Kittaka, C., Neil, D., Chu, D.A., Remer, L., Gumley, L., Prins, E., Weinstock, L., Macdonald, C., Wayland, R., Dimmick, F., Fishman, J., 2005. Improving national air quality forecasts with satellite aerosol observations. Bull. Am. Meteorol. Soc. 86, 1249–1261. http://dx.doi.org/10.1175/bams-86-9-1249.

Blake, D., Hinwood, A., Horwitz, P., 2009. Peat fires and air quality: volatile organic compounds and particulates. Chemosphere 76, 419–423. http://dx.doi.org/10.1016/j.chemosphere.2009.03.047.

Boyouk, N., Léon, J.-F., Delbarre, H., Podvin, T., Deroo, C., 2010. Impact of the mixing boundary layer on the relationship between PM2.5 and aerosol optical thickness. Atmos. Environ. 44, 271–277. http://dx.doi.org/10.1016/j.atmosenv.2009.06.053.

Braga, A.C., Zanobetti, A., Schwartz, J., 2001. The lag structure between particulate air pollution and respiratory and cardiovascular deaths in 10 US cities. J. Occup. Environ. Med. 43, 927–933. http://dx.doi.org/10.1097/00043764-200111000-00001.

Bureau of Labor Statistics, year. Modeled Wage Estimates. Available at: https://www.bls.gov/data/#wages.

Chestnut, L.G., Thayer, M.A., Lazo, J.K., Eeden, S.K., 2006. The economic value of preventing respiratory and cardiovascular hospitalizations. Contemp. Econ. Policy 24, 127–143. http://dx.doi.org/10.1093/cep/byj007.

Dickie, M., Messman, V.L., 2004. Parental altruism and the value of avoiding acute

illness: are kids worth more than parents? J. Environ. Econ. Manag. 48, 1146–1174. http://dx.doi.org/10.1016/j.jeem.2003.12.005.
Frost, C.C., 1987. Historical Overview of Atlantic White-cedar in the Carolinas. A.D. Laderman, Atlantic White-cedar Wetlands. Westview Press, pp. 257–263.
Geron, C., Hays, M., 2013. Air emissions from organic soil burning on the coastal plain of North Carolina. Atmos. Environ. 64, 192–199. http://dx.doi.org/10.1016/j.atmosenv.2012.09.065.
Hanemann, M., Kanninen, B., 2001. The statistical analysis of discrete-response CV data. Valuing Environ. Prefer. http://dx.doi.org/10.1093/0199248915.003.0011, 302–441.
Hinwood, A.L., Rodriguez, C.M., 2005. Potential health impacts associated with peat smoke: a review. J. R. Soc. West. Aust. 88, 133–138.
Johnston, F., Henderson, S., Chen, Y., Randerson, J., Marlier, M., DeFries, R., Kinney, P., Bowman, D., Brauer, M., 2012. Estimated global mortality attributable to smoke from landscape fires. Environ. Health Perspect. 120 (5), 659–701. http://dx.doi.org/10.1289/ehp.1104422.
Johnston, F., Purdie, S., Jalaludin, B., Martin, K., Henderson, S., Morgan, G., 2014. Air pollution events from forest fires and emergency department attendances in Sydney, Australia 1996-2007: a case-crossover analysis. Environ. Health 2014 (13), 105. http://dx.doi.org/10.1186/1476-069X-13-105.
Joseph, A., Sawant, A., Srivastava, A., 2003. PM10 and its impacts on health - a case study in Mumbai. Int. J. Environ. Health Res. 13, 207–214. http://dx.doi.org/10.1080/0960312031000098107.
Kochi, I., Champ, P.A., Loomis, J.B., Donovan, G.H., 2016. Valuing morbidity effects of wildfire smoke exposure from the 2007 Southern California wildfires. J. For. Econ. 25, 29–54. http://dx.doi.org/10.1016/j.jfe.2016.07.002.
Kochi, I., Donovan, G.H., Champ, P.A., Loomis, J.B., 2010. The economic cost of adverse health effects from wildfire-smoke exposure: a review. Int. J. Wildland Fire 19, 803. http://dx.doi.org/10.1071/wf09077.
Laderman, Aimlee D., Brody, Michael, Pendleton, Edward, 1989. The Ecology of Atlantic White Cedar Wetlands: a Community Profile. U.S. Department of Interior, Fish and Wildlife Service, National Wetlands Research Center, Washington, D.C., 114pp. Biological Report.857.21. http://www.nwrc.usgs.gov/techrpt/85-7-21.pdf
Loomis, J., Hanemann, M., Kanninen, B., Wegge, T., 1991. Willingness to pay to protect wetlands and reduce wildlife contamination from agricultural drainage. Econ. Manag. Water Drain. Agric. 411–429. http://dx.doi.org/10.1007/978-1-4615-4028-1_21.
Moeltner, K., Kim, M.-K., Zhu, E., Yang, W., 2013. Wildfire smoke and health impacts: a closer look at fire attributes and their marginal effects. J. Environ. Econ. Manag. 66, 476–496. http://dx.doi.org/10.1016/j.jeem.2013.09.004.
Monitoring Trends in Burn Severity MTBS, 2014. Data Access: Fire Level Geospatial Data. US Department of Agriculture, Forest Service and US Department of Interior, Geological Survey. http://mtbs.gov/data/individualfiredata.html/. (Accessed 10 September 2015).
Peng, R., Dominici, F., Welty, L.J., 2009. A Bayesian hierarchical distributed lag model for estimating the time course of risk of hospitalization associated with particulate matter air pollution. J. R. Stat. Soc. Ser. C Appl.(Stat.) 58, 3–24. http://dx.doi.org/10.1111/j.1467-9876.2008.00640.x.
Pope, C., Renlund, D., Kfoury, A., May, H., Horne, B., 2008. Relation of heart failure hospitalization to exposure to fine particulate air pollution. Am. J. Cardiol. 102, 1230–1234. http://dx.doi.org/10.1016/j.amjcard.2008.06.044.
Rappold, A., Stone, S., Cascio, W., Neas, L., Kilaru, V., Carraway, M., Szykman, J., Ising, A., Cleve, W.E., Meredith, J.T., Vaughan-Batten, H., Deyneka, L., Devlin, R.B., 2011. Peat bog wildfire smoke exposure in rural North Carolina is associated with cardiopulmonary emergency department visits assessed through syndromic surveillance. Environ. Health Perspect. 119, 1415–1420. http://dx.doi.org/10.1289/ehp.1003206.
Reddy, A., Hawbaker, T., Wurster, F., Zhu, Z., Ward, S., Newcomb, D., Murray, R., 2015. Quantifying soil carbon loss and uncertainty from a peatland wildfire using multi-temporal LiDAR. Remote Sens. Environ. 170, 306–316. http://dx.doi.org/10.1016/j.rse.2015.09.017.
Richardson, L.A., Champ, P.A., Loomis, J.B., 2012. The hidden cost of wildfires: economic valuation of health effects of wildfire smoke exposure in Southern California. J. For. Econ. 18, 14–35. http://dx.doi.org/10.1016/j.jfe.2011.05.002.
Sleeter, R., Sleeter, B., Williams, B., Hogan, D., Hawbakaer, T., Zhiliang, Z., 2017. A carbon balance model for the great dismal swamp ecosystem. Carbon Balance Manag. 12, 2. http://dx.doi.org/10.1186/s13021-017-0070-4.
Tse, K., Chen, L., Tse, M., Zuraw, B., Christiansen, S., 2015. Effect of catastrophic wildfires on asthmatic outcomes in obese children: breathing fire. Ann. Allergy, Asthma & Immunol. 114 http://dx.doi.org/10.1016/j.anai.2015.01.018.
U.S. Census Bureau, Population Division. 2010. https://census.gov/.
U.S. Environmental Protection Agency EPA AirData archives: https://www.epa.gov/outdoor-air-quality-data/download-daily-data.
U.S. Environmental Protection Agency EPA, 1999. The Benefits and Costs of the Clean Air Act 1990 to 2010. US Environmental Protection Agency, Washington, DC.
U.S. Environmental Protection Agency EPA, 2004. Air Quality Criteria for Particulate Matter. US Environmental Protection Agency, Washington, DC.
U.S. Environmental Protection Agency EPA, 2007. Cost of Illness Handbook. US Environmental Protection Agency, Washington DC.
U.S. Environmental Protection Agency EPA, 2009. Air Quality Index, a Guide to Air Quality and Your Health. EPA-456/F-409-002. U.S. EPA, Research Triangle Park, NC.
Vora, C., Renvall, M., Chao, P., Ferguson, P., Ramsdell, J., 2010. How the october 2007 san diego wildfires affected asthmatics. J. Allergy Clin. Immunol. 125 http://dx.doi.org/10.1016/j.jaci.2009.12.811.
Youssouf, H., Liousse, C., Roblou, L., Assamoi, E., Salonen, R., Maesano, C., Banerjee, S., Annesi-Maesano, I., 2014. Quantifying wildfires exposure for investigating health-related effects. Atmos. Environ. 97, 239–251. http://dx.doi.org/10.1016/j.atmosenv.2014.07.041.