Title:

Benefits of a Fire Mitigation Ecosystem Service in The Great Dismal Swamp National Wildlife Refuge

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Abstract

The Great Dismal Swamp (GDS) National Wildlife Refuge delivers multiple ecosystem services, including 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 use 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 examine emergency department (ED) visitation in seven Virginia counties during these periods, apply measures of cumulative Relative Risk (cRR) to derive the effects of wildfire smoke exposure on ED visitation rates, and estimate economic losses using regional Cost of Illness (COI) values established within the US Environmental Protection Agency BenMAP framework. Our results estimate the value of one avoided wildfire within the refuge to be $3.96 million (2015 USD), or $306 per hectare of burn. Reducing the frequency or severity of unexpected and uncontrolled peatland wildfire events has additional benefits not included in this estimate, including 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.

Keywords

Ecosystem services, fire mitigation , wildfire, human health, geospatial information, Great Dismal Swamp National Wildlife Refuge, remote sensing

1. Introduction

Ecosystem Services (ES) are the benefits provided by the natural environment that are of value to human populations. ES are threatened by development, pollution, fragmentation, overexploitation of resources, and climate change. As part of a multi-year study on the ES of the Great Dismal Swamp (GDS) National Wildlife Refuge, the U.S. Geological Survey (USGS), in coordination with the Fish and Wildlife Service (FWS), examined the economic implications of health effects related to 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). The GDS is currently undergoing active hydrologic management designed to rewet the peat soils and provide refuge managers with the ability to actively manage soil moisture using a series of water control structures. These structures are expected to result in multiple benefits including additional carbon sequestration, restoring desired vegetation communities, and reduce the duration and severity of wildfires (Reddy et al., 2015). Sleeter et al. (2017) provides an in depth discussion of the current and desired states within the GDS across multiple dimensions including carbon stock/flow, vegetation, and soil moistures.

Benefits of a fire mitigation ecosystem service are closely linked to the health and hydrology of the soils within a peatland ecosystem. Catastrophic wildfire in a peatland is often associated with low water levels, and characterized by long-burning ground fires deep within the peat (>0.5m) that release large quantities of carbon into the atmosphere (Reddy et al., 2015). Within the GDS, low water levels due to centuries of drainage and human disturbance can be worsened in drought years, emphasizing the importance of control and versatility in hydrological management regimes. Conversely, periodic surface wildfires play a critical role in healthy peatland vegetation communities to help perpetuate native trees including Atlantic White Cedar and pond pine (Sleeter et al., 2017; Reddy et al., 2015; Laderman et al., 1989). In this paper, we investigate the public health benefits of avoided catastrophic peat wildfires through improved hydrological management, and the implication for adjacent human populations. These benefits are identified as a cost of illness (COI) measure, and are assumed to be a lower bound in the true economic value of reducing wildfire severity and frequency. This assumption is explained in sections 3.2 and 3.3.

In recent years, two catastrophic wildfires burned large areas of vegetation 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 spanning an estimated 1,976 hectares. During the 121-day burn, the cost of fire suppression exceeded twelve million dollars and distributing 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 footprint of the SOF burning an estimated 2,630 hectares over the course of 111 days from August 4th to December 1st. Both fires quickly destroyed the aboveground vegetation, concurrently burning deep into the organic peat soils with an average fire depth of 0.8 meters to 1.1 meters (Reddy et al., 2015). Fire events of this magnitude are considered catastrophic and extremely damaging to the ecosystem, and under current conditions are expected to recur twice every 100 years, or an annual 2% probability (MTBS 2014). Emergency department data was made available for high exposure days (explained in section 3.1) during the 2008 SOF, and will be the fire examined within this analysis.

Peat soils, such as those within the refuge, have been shown to produce a unique composition of emissions when ignited (Blake, 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, 2013; Blake, 2009; Hinwood, 2005; Joseph, 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, 2015; Youssouf, 2014; Kochi, 2010 & 2016; Rappold et al., 2011; Vora, 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. While in aggregate these estimates are substantial (200k-600k deaths per year globally), Kochi (2016) recommends that mortality should not be considered for individual fire events in the lower quartiles of susceptible acreage, short lived, or infrequent. Wildfires within the GDS are estimated to be both infrequent and on the lower quartiles of susceptible acreage (< 4k hectares) (MTBS, 2014). Following this recommendation we examine 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 and FWS staff). Our focus therefore is on symptoms related to morbidity in nearby populations resulting from brief exposure to dense wildfire smoke plumes (EPA, 1999 and 2004).

Rappold et al (2011) examined the causal 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 those of the GDS. Rappold et al (2011) provide 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 emergency department visit in the absence of harmful smoke exposure, to observed visits during exposure. These calculations are explained in detail in section 3.3. Johnston et al. (2014) employ a similar approach over an eleven-year time period in Sydney, Australia. Using ground-based PM sensors they examine the relationship between harmful PM levels due to confirmed fire events and ED visitation. Although the fuel source of the fires in their study is largely dissimilar to the organic peat soils in our region, they also find a significant relationship (measured in cRR) between ED visitation and smoke exposure days. The likeness of fuel source in Rappold et al (2011) to that of the SOF, and the GDS in general, provides the opportunity for a robust application and extension of their methods.

The valuation literature on the economic costs of wildfire is largely focused on geographic areas dissimilar to the GDS (Moeltner, 2013; Richardson, 2012). Richardson et al (2012) employs a defensive behavior method during a 2010 California wildfire to derive willingness to pay (WTP) to avoid smoke exposure. 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, 2001; Loomis, 1991). The authors estimate 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 hectares 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 ES 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 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 in the following sections may provide a concise and systematic process for researchers and land managers to employ when examining the many benefits of a fire mitigation ecosystem service when larger more in-depth studies are not feasible. Our final estimates rely heavily on the managers' ability to provide accurate fire probabilities and estimate the reduction in these probabilities as result of their management actions. We recommend the methods in this paper, not the estimates, offer external validity for additional research. The ES 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 hectares 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 addition to actively managed vegetation through mechanical removal of debris and controlled burns, GDS refuge managers have been developing a grid of culverts and water control structures to aid in the distribution of wetland hydrology with the intent to restore peat moisture to more optimal levels. Our intent is not to provide a full cost/benefit analysis for these management actions, but instead to estimate the benefits of their proposed design. Refuge managers are expected to weigh these benefits with the costs when making their decisions. The refuge sits 40 kilometers inland from the Atlantic coastline, and experiences a west to east atmospheric current. This current typically carries smoke plumes originating from within the GDS out to sea; however, seven Virginia counties (Chesapeake, 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. Franklin county was omitted due to limitations in acquiring emergency department data. These counties lie within the Tidewater region of Virginia (Appendix I, Figure 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. As such, we limit our study to the seven Tidewater counties to avoid over-estimation of the fire mitigation service.

3. Materials and Methods

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

3.1. Area of impact

We determine geographic area and temporal exposure to SOF smoke plumes using a combination of remote sensing techniques, ground-level sensors, and air-quality indices. We examine daily geostationary aerosol smoke product (GASP) satellite readings acquired from the National Environmental Satellite Data and Information Service (NESDIS) for the Tidewater region. These data provide high-resolution measures of aerosol optical depth (AOD) – at four kilometer square grids - and are collected in 30-minute 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, 2005; EPA, 2009). We generate daily 24-hour 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 examine historical levels within the region during both fire and non-fire years. In 2008 during non-fire months (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 plumes during the SOF can bring these levels up to 2.0. As such, we determine 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 the county be exposed above this level. Our estimates rely on these thresholds, we have chosen conservative exposure levels, consistent with the literature, to avoid overestimation in the resulting benefits. Using these parameters, over the 121-day period 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 received harmful smoke exposure.

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 within the region. A benefit to ground level monitors is that their elevation is closely representative of human exposure to PM2.5 (Boyouk, 2010); however, there are several limitations associated with these monitors. They have less ability to accurately determine readings across a given region due to their fixed location and the frequency of readings (Youssouf, 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

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)
	S.O.F. 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)
	S.O.F. 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 erros in parentheses. Non-fire months refers to the months outside of the 121-day S.O.F. 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-hour averages ≥ the AOD threshold of 1.25. AQI = Air Quality Index; LRC=Langly Research Center Monitor; PM2.5 = particulate matter ≤ 2.5 μg. AOD = aerosol optical depth.

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 2014). The NASA Langley Research Center (LRC) 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 use 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 LRC 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 isn't 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. Over the same months as the SOF in the five non-fire years, the 24-hour 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.[i] The AQI and PM2.5 levels included in Table 1 are produced using the U.S. EPA AirData archives.[ii]

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 and 1999). These outcomes can by identified by using the International Classification of Diseases, Ninth Division, Clinical Modification (ICD-9-CM) system, which are used by emergency departments to classify patient diagnoses for symptoms of morbidity. Eleven ICD-9-CM codes fall under the five symptoms identified above, and are used in our analysis. In cooperation with Virginia Health Information[iii] (VHI) we explore daily ED visits in each of the seven Tidewater counties. Table 2 provides a summary of the symptoms and corresponding ICD-9-CM codes.

Table 2: Disease Classifications

Symptoms	ICD-9-CM
Asthma	493
C.O.P.D.	491-492
Pneumonia	481-487
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.

Smoke exposure might not result in an immediate visit to the ED (Pope, 2008; Braga, 2001); as such we consider a window for ED visitation due to a single initial day of heavy smoke exposure. Rappold et al. (2011) employ a distributed lag model (Peng, 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 define 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 eleven 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) produce 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 are then used to determine a measure of cRR over the visitation window. In addition to a point estimate, they establish 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:

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

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.

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

Equation (2): β_{ijt} is determined through the distributed lag model (Peng, 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 identify the counterfactual - visits not due to the wildfire. Explicitly stated:

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

3.3. Economic Valuation

The final step in our analysis is to associate an economic cost with each excess visit from equation 3. We use 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 and the program 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 fail to account for the disutility associated with symptoms or lost leisure, and expenses incurred relating to defensive or avoidance behavior. We account for a portion of these costs by using local estimates of symptom days for each hospitalization diagnoses (EPA, 2007) in conjunction with median daily income for each county. We assume 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, 2006). To keep our estimates conservative, we only consider lost time during the hospital visit.

The likelihood of ED visits and their associated COI are known to vary by age (EPA, 2007), so we consider 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 use 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[iv] for each of the seven Tidewater counties. While any group categorized above 64 years of age is assumed to be out of the work force, wages are still used to estimate a portion of the disutility during an ED visit for groups above this age threshold. We aggregate the direct costs of hospitalization (COI) with the opportunity costs (lost wages: LW). Total valuation for the benefits of avoided wildfires in the GDS is calculated using equation (4), an aggregate of values across all seven counties:

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

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 34 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.[v] 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 active 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 3: Tidewater ED visits during the SOF

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

When considering fire mitigation as an ecosystem service, it is necessary to assess the annual cost associated with a wildfire. Under current (disturbed) conditions, the Monitoring Trends in Burn Severity (MTBS) estimates that the GDS is expected to experience a catastrophic wildfire like the SOF twice every 100 years - a 2% annual probability.[vi] 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 restored soils could reduce expected annual fire incidence 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.[vii] This ecosystem service value, along with other costs associated with wildfires, should be considered in cost-benefit analyses of hydrologic restoration within the GDS.

Evaluation of the costs of wildfires on a per hectare basis is another way we consider how the magnitude of such a fire alters economic losses. To estimate values by total acreage burned, we examine the size and scope of the SOF. The SOF burned 1,976 surface hectares within the refuge. On a per hectare basis, we estimate the health costs associated with the SOF to be $306.

Table 4: Endpoint Valuations for one Wildfire Within the GDS

	South One Fire	Annualized Costs (Current Hydrology)	Annualized Benefits (Improved Hydrology)
Cost of Illness	$ 3,575,000	$ 71,511	$35,756
Opportunity Cost	$ 116,605	$ 2,332	$ 1,166
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 is believed to fall by 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.

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 ES, 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 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 $6,965 to $57,233.

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 ES 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 which are likely contribute to this relationship might 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. When doing so, it is important to consider the true underlying costs of wildfires by exploring the use of ratios such as those developed in Richardson (2012), EPA (2007), and Dickie (2004). These ratios are indicative of how high the true value of avoided wildfires could potentially be. Assuming a WTP/COI ratio of 9:1 (Richardson, 2012), our results translate to a WTP in the order of $6.27 million to $51.51 million to avoid a single catastrophic wildfire event.

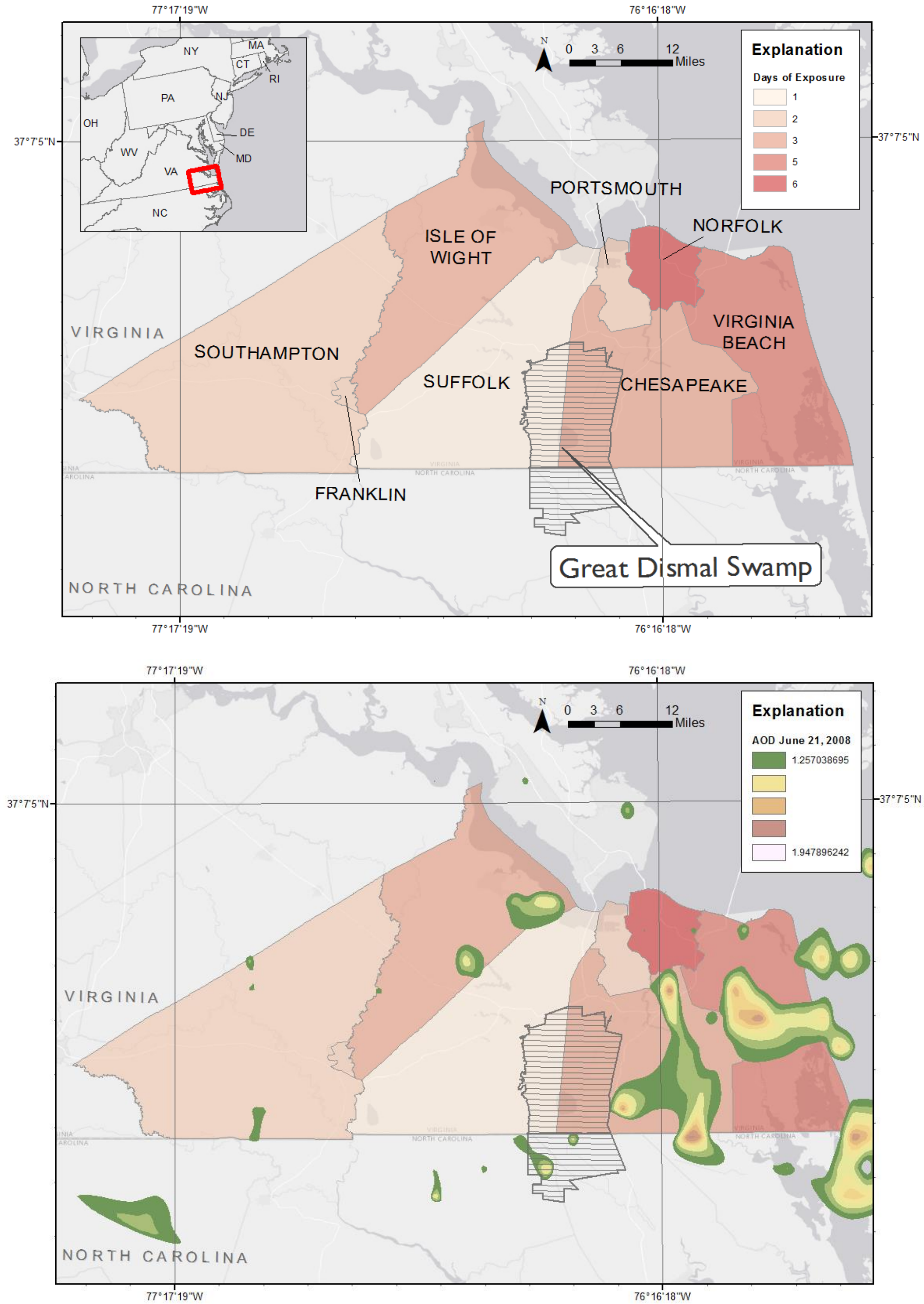
6. Conclusions

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 employ 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.

1 Appendix I

Figure 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 ≥ 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.



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

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

[iii] 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.

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

[v] 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.

[vi] 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.

[vii] 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.