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Exploring the role of forest resources in reducing community vulnerability to the heat effects of climate change☆

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ABSTRACT

While the growing literature on forest ecosystem services has examined the value and significance of a range of services, our understanding of the health-related benefits of ecosystem services from forests is still limited. To characterize the role of forest resources in reducing community vulnerability to the heat effects of climate change, a general index of heat vulnerability (HEVI) was developed through Principle Components Analysis (PCA) and subsequently used within ANVOA and Poisson regression to assess the relationship between the amount and type of forest resources (species, management regime, spatial pattern) and a county's vulnerability to the heat effects of climate change. Results of the ANOVA showed significant differences in the extent and characteristics of forests among counties experiencing different levels of heat vulnerability. The Poisson regression using county heat mortality as the dependent variable found forest characteristics to have a significant influence on heat mortality when other determinants of vulnerability were controlled. A negative and significant relationship was specifically found between forest area and heat related mortality, which supports the hypothesis that the extent of forest coverage helps to alleviate vulnerability associated with heat effects. These findings have important implications for understanding the role of forest ecosystem services in reducing a community's vulnerability to the heat effects of climate change. Findings will also be useful in guiding land use planning and preserving desirable forest characteristics to help communities adapt to climate change.

1. Introduction

The emerging literature on ecosystem services has quantified and evaluated a variety of services from forests, including provisioning, regulatory, economic, and cultural benefits (Farber et al., 2002; Costanza et al., 2006; Vihervaara et al., 2012; Amacher et al., 2014). However, as climate change is expected to increase human exposure to heat and consequently vulnerability to the negative health effects of heat ("heat effects"), investigations of the characteristics and benefits of health-related ecosystem services derived from resources that mitigate heat, e.g., forests, is warranted (Myers et al., 2014). Increased heat effects are predicted to increase a community's vulnerability due to increased heat-related morbidity and health care costs, as well as energy consumption. The incremental increase in temperature associated with climate change acts at such a slow rate that the dangers associated with the overall trend are often unappreciated. However, the Center for Disease Control and Prevention (2009) advises that extreme heat events are responsible for more deaths annually than any other natural disaster in the United States. Further, the Intergovernmental Panel on Climate Change (IPCC, 2007) warns that the world will observe increased heat waves in the future. Considering the significance of heat vulnerability as a public health issue (Luber and McGeehin, 2008), there is a need for research to explore more carefully the links between forest cover and heat mitigation.

The literature on social vulnerability[1] indicates that the resiliency of human life and community structure depend both on the socioeconomic characteristics of households and features associated with the natural environment (Reid et al., 2009; Wilhelmi and Hayden, 2010; Uejio et al., 2011). Indeed, a growing number of empirical studies suggest human health benefits for urban residents living proximal to city trees and other green spaces (Donovan et al., 2011). Likewise, the literature on public health suggests that human communities in areas with less green space are more vulnerable to the heat effects of a warming planet (Reid et al., 2012). In terms of mitigation, however, ecological studies have also demonstrated that vegetation can help alleviate heat in urban areas (Akbari et al., 1997; Susca et al., 2011); and economics studies have characterized the value of residential energy savings related to forest

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[1] Social vulnerability here refers to marginalization, characterized by the lack of ability to assertively navigate social systems or to move progressively towards higher living standards in terms of material wealth and influence (Gaither et al., 2011, p.27).

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vegetation (Donovan and Butry, 2009; Pandit and Laband, 2010). However, whether and to what extent forest resources can be managed to increase the resiliency of local communities to the health effects of climate change remains almost unknown (Wilhelmi and Hayden, 2010). So far, studies on community vulnerability to natural disasters and risks have focused mostly on flood and wildfire (Cox et al., 2006; Zahran et al., 2008; Poudyal et al., 2012). The recognition of community vulnerability to climate-induced temperature increases is a relatively new phenomenon. As such, it has only recently started to receive attention from the social and economic sciences (Reid et al., 2012).

A handful of studies have examined community vulnerability in the context of green or vegetated areas in general. For example, Reid et al. (2009) showed non-vegetative areas (i.e. built up areas) to be an important component of vulnerability at the census tract level. Uejio et al. (2011) examined the relationship of heat-related mortality and morbidity with heat exposure, socioeconomic conditions, and the built environment for census block groups (CBG) in Philadelphia, PA and Phoenix, AZ. They found that heat mortality and heat distress incidents were higher in CBGs with low housing value, and higher proportion of black residents in Philadelphia, and in CBGs with sparse and less healthy vegetation in Phoenix. A similar study by Harlan et al. (2006) examined the correlation of heat index with population characteristics, environmental characteristics, and coping resources, respectively, in eight Phoenix neighborhoods. Results showed that neighborhoods with high housing density, sparse vegetation, and no open space had higher heat index ratings. Yet, these studies did not assess how vulnerability may be related to variations in characteristics of forest vegetation.

Variations that could determine a forests' ability to counteract heat effects include the extent of forest coverage, species composition, difference in major management regime, and the spatial pattern of forest patches. The tree physiology and landscape ecology literature suggests that a community's vulnerability to heat may also depend on the amount and composition of forests in the surrounding area. For instance, forest canopy density determines the amount of shade and cooling ability (Akbari et al., 1997). The species of a forest can also influence shade provision and therefore aid in cooling. Deciduous (hardwood) and mixed (deciduous and evergreen) species canopies typically contain larger leaves and wider canopies, and therefore offer wider shaded area than their evergreen counterparts (Akbari et al., 1997). The larger leaves and higher amount of shade per tree provides the potential for equivalent shading of forests with lower density.

Policy makers may be interested in knowing how factors that are beyond an individual's control, such as existing natural resources and community land use practices, could be used effectively to mitigate climate effects and what kind of low-cost options might be available for local communities to cope with the negative outcomes related to increasing temperatures. For example, some communities face more intense ambient temperatures due to the greater density of the built environment, and the lack of vegetation. This phenomenon, which is characteristic of many urban areas, is known as the Urban Heat Island Effect (UHI) (Environmental Protection Agency, 2014). Communities facing the intense effects of UHI may benefit from appropriate land use planning and urban tree management if they know whether and what kind of forest characteristics might help the community mitigate the negative effects of heat stress. Two otherwise identical communities may experience or have the ability to withstand different levels of heat stress simply because of the difference in the way forests and other green vegetation are managed. For example, if increasing canopy coverage could reduce the vulnerability of poor communities in treeless urban areas, community or urban forestry programs could be a favorable policy intervention. Therefore, understanding whether and what kind of roles forests of different characteristics play in reducing the heat effects of climate change not only increases our understanding of the full benefits of forest ecosystem services but also sheds light on the feasibility of expanding forestry programs as a means of climate mitigation and adaptation.

To fill this gap in knowledge, our study examined whether and how communities with different forest characteristics (i.e. amount of forest, species composition, management regime, and spatial configuration) might have different levels of vulnerability to the heat effects of climate change. We anecdotally know that increases in vegetation help mitigate heat (Akbari et al., 1997; Rosenfeld et al., 1995), but our goal is to understand (after controlling for all other factors) whether the species composition (e.g. deciduous, evergreen), broader management regime (protection, production), and spatial configuration (i.e. aggregate vs. fragmented) would significantly correlate to heat-related health outcomes of affected communities (i.e. an observable indicator of community vulnerability to heath effect). We hypothesize that increases in forest cover will significantly decrease the community's vulnerably to heat effects, but the contribution will vary across the type of dominant forest species, the way forests are managed, and the way they are distributed across the landscape.

2. Conceptual framework

The IPCC definition recognizes climate vulnerability as a multidimensional concept measuring "the degree to which geophysical, biological, and socio-economic systems are susceptible to, and unable to cope with, adverse impacts of climate change" (IPCC, 2010). Vulnerability has been previously identified using socio-economic, demographic, and hazard specific indicators to estimate the resilience of a human population to the heat effects of climate change prior to an extreme heat event (Cutter et al., 2003; Cox et al., 2006; Reid et al., 2009). That is, different communities will possess different capabilities of coping with heat based on differences in their levels of exposure, sensitivity, and adaptive capacity (Wilhelmi and Hayden, 2010; Eq. (1)).

$$\text{Vulnerability} = f(\text{exposure}, \text{sensitivity}, \text{adaptive capacity}). \tag{1}$$

This model is referred to as a "vulnerability framework" where, conceptually, vulnerability is a function of the level of exposure, sensitivity, and adaptive capacity of a community (IPCC, 2014). In the case of heat effects from climate change, exposure encompasses the climate-related risks in regard to both longer term and episodic climate changes that a community experiences. Sensitivity is the predisposed risk associated with both the social and demographic characteristics of a community, and adaptive capacity is the ability of a community to adapt to or recover from stresses created by extreme heat (Wilhelmi and Hayden, 2010). The influences of extreme heat may be place-specific and path-dependent, meaning that the vulnerability of a community will depend on both the physical and social characteristics of place (e.g. the surrounding environment specific to the community), and the series of attributes and/or actions that make community members sensitive to extreme heat (e.g. lack of household financial resources and information, age, and physical ability).

In a recent work, Myers et al. (2014) presented a schematic of the complex relationships between altered environmental conditions and public health. The framework essentially shows that population-level vulnerability is affected by various social and infrastructure barriers that could either buffer or eliminate the impacts of an altered environment. We extend Myer's et al.'s thesis to posit that the characteristics of natural surroundings, including amount of forestland, species composition of a given forest, and the forest's spatial arrangement could make a difference in a proximal community's resiliency. If certain characteristics of forest and natural vegetation correlate positively with lower heat vulnerability within the landscape, such natural assets may be considered adaptive resource to offset the heat effects.

There are two primary approaches to operationalizing community vulnerability (Zahran et al., 2008). The first is a generic index approach using a combined index of vulnerability, where a large set of socio-demographic data, economic conditions, and other known risk factors are combined to represent the exposure, sensitivity, and adaptive capacity of a community. This approach has widely been used in empirical analysis (Cutter et al. 2003, Cox et al., 2006, Wood et al., 2010, Gaither et al., 2011). These studies typically use factor analysis or principal components analysis to aggregate large numbers of selected risk-predicting variables into fewer factors for modeling the vulnerability of human populations. However, the resulting index is too general to make interpretations for any specific policy or management recommendation. Nevertheless, if the purpose is only to compare vulnerability across communities, this could still be a reliable approach to classify communities according to vulnerability levels (e.g. low and high) (Gaither et al., 2011). The second approach is an inductive approach where observation data on community vulnerability, such as number of fire incidences, number of accidents, deaths, or illness (Luber and McGeehin, 2008; Zahran et al., 2008; Reid et al., 2012) is related to specific attributes of the community. Compared to the generic approach discussed above, this approach is considered a more precise and direct determination of a community's vulnerability to a specific threat.

The heat vulnerability analysis framework presented by Wilhelmi and Hayden (2010) provides a conceptual model to investigate relationships between observed data on mortality and variables representing: 1. exposure (climate, heat), 2. sensitivity (socioeconomics, demographics) and 3. adaptive capacity (personal and household resources, social and community capital) of a population. The framework also emphasizes the fact that external drivers, including change of climatic condition and other macro-level stressors can increase the vulnerability of a community but proper land use management, urban design, and public health education can help communities adapt to the heat effects. Based upon the conceptual foundation of these two frameworks, the study presented in this current paper evaluates whether and how vulnerability to heat effect relates with the extent and type of surrounding forests.

3. Method

In this study, we took both the generic and specific approach of characterizing community vulnerability to the heat effects of climate change. We then explored the relationship between community vulnerability to heat with various characteristics of forest resources at the county level. It should be noted that counties are not necessarily the optimal representation of a “community” because counties are political entities whereas communities are social. However, we relied on county level analyses for several reasons. First, some level of aggregation was necessary to capture the characteristics of a “population,” and counties were the smallest unit at which data required for this analysis were available. Second, county boundaries are more stable over time than other smaller census units. Hence, results from our study will serve as baseline to compare against future assessments of vulnerability at the county level. Third, counties have been the most commonly used unit of analysis in previous social vulnerability research (Cutter et al., 2003, Zahran et al., 2008, Reid et al., 2009). Our study area encompassed the contiguous United States, which includes 48 states and 3142 counties.

3.1. Multivariate analysis and vulnerability index

Following Cutter et al. (2003), Cox et al. (2006) and Reid et al. (2009), we used exploratory factor analysis (EFA) to analyze a comprehensive set of socio-economic, climatic, and built environment variables. The EFA was run in SPSS 21 to reduce the number of variables (39) initially considered as individual indicators of vulnerability. These variables were selected based the literature and included indicators representing the broader categories of age, lack of material resources, race and ethnicity, urban environment, cultural or language barrier, and exposure to heat (Table 1). Variables with loadings below 0.5 and those with significant cross-loadings were removed from the analysis (Costello and Osborne, 2005; Hamilton, 2013). A total of five factors represented the original set of variables, which operationalized the vulnerability as expressed in Eq. (1). Since the cumulative index of the weighted factors provided a more meaningful interpretation than the relative contribution of factors in overall vulnerability at the county level (Cox et al., 2006), the predicted regression scores of the five factors were weighted by the variance explained and then summed for each county to create a cumulative Heat Effects Vulnerability Index (HEVI),

Table 1
List of sociodemographic, environmental, and climate risk variables initially considered in developing HEVI.

Variable	Source	Range
Age		
% under 5 years	ACS estimate	2006–2010
% over 65 years		
Median age of population in the county		
Lack of material resources		
% females	ACS estimate	2006–2010
% single parent households with one or more people under 18		
% civilian population in labor force 16 years and over: unemployed		
% households with self-employment income		
% households with social security income (SSI)		
% households with supplemental security income		
% households with public assistance income		
% households with retirement income		
% households with other types of income		
% occupied housing units: renter occupied		
Average house size		
% owner-occupied housing units: housing units with a mortgage: 50% or more		
% families: income in 2010 below poverty level		
% population over 25 with less than a high school education		
Percentage of households with air conditioning	AHS	2009
Race or ethnicity		
% Black or African American alone	ACS estimate	2006–2010
% Hispanic		
% some other race alone (non-white)		
Urban environment		
Population density: population/mi^2	ACS estimate	2006–2010
% total population in group quarters or consolidated housing (e.g. condominiums, apartments and dorms)		
% occupied in agriculture, forestry, fishing and hunting, and mining		
% occupied in construction		
% occupied in transportation and warehousing, and utilities		
% housing units: mobile home		
% housing units: boat, RV, van, etc.		
Median year structure built		
% means of transportation to work for workers 16 years and over: public transportation (includes taxicab)		
% means of transportation to work for workers 16 and over: motorcycle		
% means of transportation to work for workers 16 and over: bicycle		
% means of transportation to work for workers 16 and over: walked		
% means of transportation to work for workers 16 and over: other		
% not working at home		
Cultural or language barrier		
% total moved from different states	ACS estimate	2006–2010
% total moved from abroad		
% foreign born: not a citizen		
% naturalized citizens		
% foreign born		
Exposure to heat		
Average number of days with Heat Index in the extreme caution, danger, or extreme danger range (HI ≥ 91)	CDC	2006–2010
Number of cooling degree-days (June–August)		

ACS: American Community Survey, AHS: American Housing Survey, CDC: Center for Disease Control and Prevention.

using Eq. (2).

$$\text{HEVI} = \text{sum(factors of vulnerability created from EFA)}. \quad (2)$$

The final value of the index represents the relative vulnerability of counties to heat effects of climate change, such that a county with a higher value is considered more vulnerable than its lower value counterpart. To evaluate whether the counties with various levels of predicted vulnerability to heat effects were different in terms of forest resource characteristics, HEVI was first ranked in ascending order, and then classified into five equal quintiles. These groupings were labeled as very low (0–20%), low (21–40%), moderate (41–60%), high (61–80%), and very high (81–100%). Analysis of variance (ANOVA) tests were then conducted on each forest characteristic variable (e.g., forest extent, species composition, management regime, and spatial pattern) to test for statistical differences among county groups.

3.2. Forest resource variables

Five different variables were used to characterize the amount, species composition, spatial pattern of forest resources, and management regime at the county level. Forest area as a percentage of county area (measure of extent), and percentage of forest in evergreen, deciduous, and mixed species (measure of forest composition) were computed by overlaying county polygon maps on land cover datasets obtained from the 2006 National Land Use Cover Database (US Geological Survey, 2006). The NLCD classifies forests based on the Anderson Land Classification System which designates "areas dominated by trees at least 5 m tall and greater than 20% of total vegetation cover" of a one-tenth hectare (0.10 ha) plot as forest (US Geological Survey, 2006). The percent forest area in a given county represents the extent of forest cover in that county, with the associated benefits of shade cooling, pollution reduction, and other ecosystem services that can arguably alleviate stresses induced by extreme heat. For example, evergreen forests help maintain lower temperatures, while providing shade in urban environments (Leuzinger et al., 2010), while deciduous and mixed forest canopies provide cooler shaded environments than coniferous forest canopies (Renaud and Rebetez, 2009).

The spatial pattern of forest resources was measured in terms of forest patch density (number of patches/total forest area), which was calculated in Fragstats 3.4 (McGarigal et al., 2012). Patch density is commonly used in characterizing forest fragmentation at the landscape level. Further, percentage of forest area managed as public land was used to broadly characterize the dominant management regime associated with forestland in a given county. Admittedly, ownership type alone cannot precisely capture differences in management regime, but it does capture relative differences among counties in terms of the relative dominance of the primary management type. While some non-industrial private forest landowners do practice preservation-oriented sustainable forestry, other private landowners, especially industry, corporations, and companies often manage their forests more intensively, under mono-cropping systems (e.g. fast growing pine only) for profit with periodic harvesting and thinning. Such practices could make those forests different from forests in public parks, reserves, and recreation areas that are typically managed for biodiversity, recreation, and other non-consumptive uses. The ownership status of forest patches was determined using Protected Areas Database of the United States PAD US 1.1, part of the US Geological Survey's GAP Analysis program. On average, counties included in our study area had 29.83% land in forests, 7.45% of county area as publicly owned forests, 8.84% as evergreen forests, and 21% as deciduous or mixed forests with an average patch density of 0.75.

3.3. Regression analysis

In another effort to explore the association between community vulnerability to heat and forest resources, we followed Harlan et al. (2006) and Reid et al. (2009)'s approach and modeled heat-related human mortality as a function of socio-economic factors identified to be key components of vulnerability (from the EFA analysis discussed earlier) and forest characteristic variables (amount, species composition, spatial pattern of forest resources, and management regime). The idea was to evaluate whether and to what extent the variables characterizing forest resources at the county level are related to heat-related human mortality, after controlling for other factors believed to determine heat-related vulnerability. Reported mortality per capita (i.e. count of the number of heat-related deaths per thousand persons in the county) data was acquired from the National Vital Statistics Multiple Cause of Death Mortality file from the Center for Disease Control and Prevention's National Center for Health Statistics (NCHS) database. The NCHS database classified deaths in the U.S. by multiple cause of death and underlying cause of death based on International Classification of Disease codes.

Since the outcome variable (i.e. deaths) is a count data of non-negative integers, we employed a Poisson regression[2] estimator to explain mortality as a function of both the forest and control variables. Control variables in this case are all the components of HEVI. As identified in the process of the HEVI development earlier, these variables relate to physical exposure to heat, income, age, race, and built environment factors. By including these factors, we hope to control for non-forest related factors that might influence the outcome variable. The Poisson regression model (Greene, 2003, pp. 740) assumes that each y_i is drawn from a Poisson distribution with parameter λ_i, which is related to the independent variables x_i. Hence, it takes the following form (Eq. (3)):

$$Prob(Y_i = y_i / X_i) = \frac{e^{-\lambda_i} \lambda_i^{y_i}}{y!}, for\ y = 0, 1, 2, \ldots \quad (3)$$

where y_i is the number of deaths in the ith county, and e is the exponential function. Accordingly, the expected number of deaths in the ith county, conditional upon x_i is given by (Eq. (4)):

$$\frac{\partial E[y_i / x_i]}{\partial x} = \lambda_i \beta \quad (4)$$

where, x_i represents the vector of explanatory variables in the model, and includes five control variables and four forest-related variables (model 1). Another model (model 2) included all control variables but only one forest variable. Consistent with the vulnerability analysis framework presented by Wilhelmi and Hayden (2010, pg 3), the conceptual model of the regression equation had the following form (Eq. (5)):

$$\begin{aligned}&\text{Heat related mortality}\\ &= \text{f(Poverty, Age, Race, Urban, Exposure, Forest Resources)}.\end{aligned} \quad (5)$$

As discussed above, forest variables capture the extent of forest coverage, species composition, management regime, and spatial pattern of forest in the county. General Linear Modeling (GLM) functions in SPSS were used for regression analysis. Total forest as a percent of county area was removed from inclusion in the GLMs because it was strongly correlated with the variables representing species type. However, a separate regression model (model 2) with forest area, in addition to control variables, was estimated. A set of regional dummy variables were initially included in the model but were removed because of their

[2] A negative binomial regression is typically estimated in case of over-dispersion of data. However, in our case the variance (1.13) was not greater than mean (2), indicating that the over dispersion was not an issue.

correlation with several components of HEVI. We decided to the drop regional dummies and keep the HEVI components mainly because these components extracted from PCA represent a more comprehensive set of variables in accounting for differences in exposure, sensitivity, and adaptive capacity among counties.

4. Results

4.1. HEVI index from multivariate analysis

The final varimax rotation of EFA produced five factors,[3] which explained approximately 91% of the variance in heat vulnerability. The five variables represented poverty, exposure to heat, age, race, and urbanization (Table 2). Following Cox et al. (2006), the five factors were then combined to generate the cumulative vulnerability index at county level using Eq. (6).

$$\text{HEVI} = (\text{Poverty} * 24.28) + (\text{Exposure} * 19.60) + (\text{Age} * 19.13) + (\text{Race} * 18.21) + (\text{Urbanization} * 10.03). \qquad (6)$$

The estimated HEVI value from the above equation was mapped in Fig. 1 to visualize relative vulnerability at the county level across the conterminous states. The HEVI was positively and significantly ($p < 0.05$) correlated with the county-level record of observed heat-related mortality, which is a more direct indicator of heat-related vulnerability (Zahran et al. 2008, Reid et al. 2012). This finding supports the reliability of HEVI to assess a human population's vulnerability to heat effects. Fig. 1 shows the quintile classification of cumulative HEVI at the county level for the entire conterminous United States (Very Low, Low, Moderate, High, and Very High). The intensity of vulnerability was greatest in the Southeast region, extending from the coastal plain region in North Carolina to Florida, east through Louisiana and into Texas with slightly lower levels in the Appalachian Mountains. Similar clusters of population vulnerability to climate change were found by Wilson et al. (2010) in the Southern region. Vulnerability accrued less so in the southwest along the Mexican border and part way up the Pacific Coastline. The Northern and Central United States showed slight elevations in vulnerability and along the Canadian border from Washington to the Great Lakes. Along with the regional variation, the HEVI pattern also showed dissimilarity between urban counties and rural counties escalating in large cities and decreasing in rural settings. The lowest levels of HEVI were observed in the far Northeast from New York to Maine.

Results from the ANOVA analysis comparing forest resource variables among quintile grouping of counties according to HEVI show that each of the forest variables differed significantly ($p < 0.05$) among the groups (Table 3). In particular, percentage of public forest exhibited its highest levels in counties with the lowest level of HEVI, which appeared to be significantly higher in counties of lower percentage of public forest, suggesting an inverse relationship between the extent of county area in publicly managed forests and the vulnerability of county population to heat effects. Further, HEVI was significantly different among counties with different proportions of forest in evergreen species. Percentage of total forest and the share of deciduous and mixed forests were significantly different among county groups of HEVI, but the pattern was less revealing. However, the highest level of HEVI was observed in counties that contained higher forest patch density, suggesting that counties that had forests in more fragmented patterns had higher vulnerability to heat effects than those with similar amounts of forests in less fragmented pattern.

4.2. Poisson regression

Regression estimates for models 1 and 2 are presented in Table 4. Most of the control variables were statistically significant ($p = 0.10$). Considering the non-linear nature of the model, the marginal effects[4] are also reported along with coefficients to facilitate interpretation. Factors representing the sensitivity of the population, including age, race and ethnicity, and urban are all positively and significantly related to mortality at the county level. This finding suggests that counties with a higher proportion of elderly people, racial and ethnic minority groups, higher population density and impervious surfaces had higher heat-related mortality, and these results corroborate the findings of several recent studies. For example, Harlan et al. (2006) found communities with a higher proportion of poor, and ethnic minority groups to have higher levels of heat stress. Similarly, a multivariate modeling of heat mortality by Uejio et al. (2011) showed a positive relationship of heat mortality with proportion of black population, level of exposure to the heat, and percentage of people older than 65 years. The negative relationship between the exposure factor and mortality in our results was counter to our expectation, but this coefficient stayed constant across all specifications attempted. While the exposure factor controls for differences across counties in climatic conditions, it is possible that cooling degree days and the summer heat index are not the best metrics of climate to relate with the mortality measure we used. It is also arguable that the marginal impact of extreme heat may be higher in areas that are newly experiencing high levels of extreme heat due to lack of knowledge and experience. Coefficients on variables representing forest characteristics were significant, suggesting that after controlling for all other determinants of vulnerability, forest variables also have a significant role to play.

Similar results were found in model 2 for age, poverty, and exposure variables but the sign on the urban variable was opposite, which is partly attributable to some interaction between the urban component and forest area variable. This is probably because a lot of the variables representing population density and amount of impervious surface at the county level were represented by the urban component. In model 2, which included forest area only to characterize forest resources at the county level, a negative and significant relationship was found between forest area and heat related mortality. This supports our hypothesis that the extent of forest coverage helps alleviate vulnerability to heat effect. The marginal estimated for total forest suggests that assuming everything else constant, a 10% point increase in proportion of forest in county decreases the heat-related mortality per capita by 0.02.

Results from model 1 show that after taking into account of all other factors, counties with a higher percentage of land in public forest are likely to have a significantly lower number of heat-related mortalities per capita than those with a lower proportion of public forest. Marginal estimates for the public forest variable suggest that a 10% increase in proportion of public forest decreases heat-related mortality per capita by 0.08, ceteris paribus. The negative and significant coefficient on the evergreen forest variable revealed that counties with higher proportions evergreen forest are likely to have a lower level of heat related mortalities, when all other factors are taken into account. More specifically, the estimated marginal for this variable suggests that a 10% increase in proportion of evergreen forest in the county decreases the heat-related mortality per capita by 0.04, ceteris paribus. The coefficient of the percentage of deciduous and mixed forest revealed that counties with higher proportions of land in primarily deciduous and mixed forest correlated positively with a higher number of heat related mortalities per capita, with all other variables in the model held constant. Assuming all other factors constant, a 10% increase in proportion of deciduous and mixed forests increases heat-related mortality per capita by 0.02. This observation is different from what we had seen from the ANOVA

[3] Detail descriptive statistics of these components are not reported here for brevity but are available from authors upon request.

[4] Marginal effects were estimated following Cameron and Trivedi (2005, p. 576) and Ferreira and Ghimire (2012).

Table 2
List of variables represented by factors retained in the final varimax rotated principal components analysis (PCA) solution.

Common theme	Justification	Factor loading	Variance
Poverty			24.3%
% households with supplemental social security income (SSI)	Communities with higher proportions of households depending on social services are already economically, socially, or functionally marginalized and are at a higher risk (Morrow, 1999).	.898	
% families with income below poverty level	Populations in poverty typically live in lower quality/more exposed residences and may lack the resources to prepare, receive warnings, or recover from disasters (Fothergill et al., 1999).	.853	
% population over 25 with less than a high school education	The lack of knowledge of hazards in an area can create risks associated with the inability to cope with, or adapt to extreme heat events (Cutter et al., 2003).	.847	
Exposure to heat			19.6%
Average number of dangerous heat index days (HI ≥ 91)	Exposure to excessive heat creates potential for human health hazards. These risks amplify for populations predisposed by socio-economic, demographic, and environmental conditions (Reid et al., 2009; Smoyer, 1998).	.952	
Number of cooling degree-days	Cooling degree-days is an indicator of the necessity for air conditioning and economic stress associated with it.	.920	
Age			19.1%
% over 65 years	The intensity with which heat disorders affect the human body increases with age because of	.953	
Median age of population	thermoregulatory ability, and body condition (Cutter et al., 2003; FEMA, 2013).	.951	
Race			18.2%
% African American alone	Marginalized races/ethnicities are likely to face barriers created by language, experience, culture,	.911	
% White alone	stereotypes, discrimination and social isolation during disaster relief efforts (Enarson and Morrow, 1997).	.871	
Urbanization			10.0%
Population density: persons/mi^2	Increases in population density create increases in denser housing structures, congestion, and concentration of impervious surfaces, which all may relate to increased levels of heat stress (Cutter et al., 2003; Fothergill et al., 1999).	.99	
Total variance explained			91.2%

analysis earlier but the results from the regression analysis may be more reliable in understanding both the size and sign of the relationship.

This contrasting effect of evergreen and deciduous forests on vulnerability justifies our attempt to analyze both the generic index and a specific indicator of vulnerability. While it is not clear from our analysis why the proportion of evergreen and deciduous forest would have different relationships with heat stress mortalities, it is possible that these forest variables could to some extent also interact with socio-demographic variables in the model. For example, areas with deciduous forests are often selected for new residential development, and most

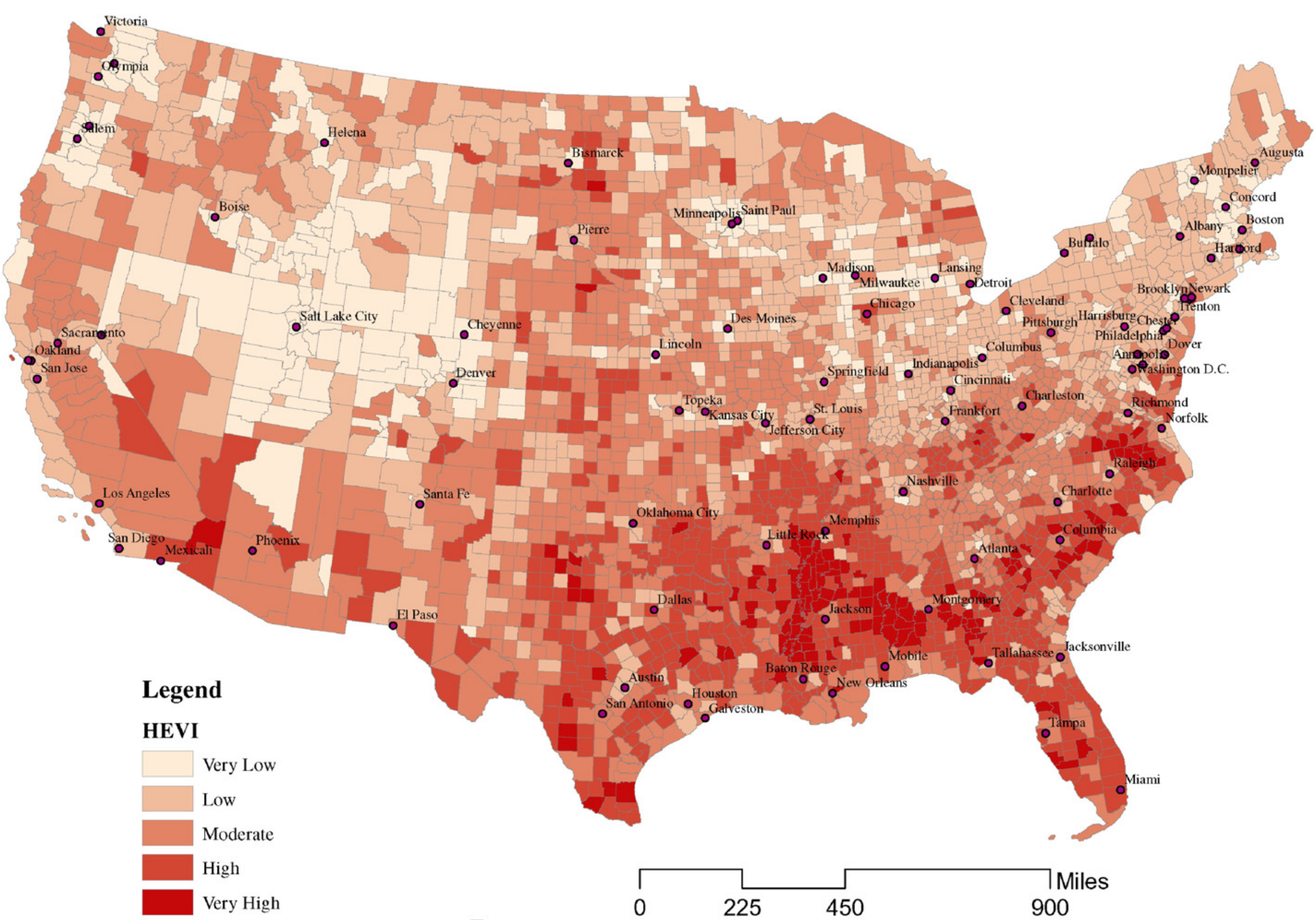

Fig. 1. Quintile map of cumulative HEVI index at the county level across the United States.

Table 3
ANOVA comparison of forest characteristic variables among counties of various HEVI levels.

Forest characteristics	HEVI					
	Very low (0–20%)	Low (21–40%)	Moderate (41–60%)	High (61–80%)	Very high (81–100%)	F-statistic
Forest area	26.29	30.81	32.21	31.36	28.51*	5.62***
Public forest	10.09	7.83	7.56	6.42	5.41**	12.21***
Evergreen forest	7.84	7.56	9.41	9.69	9.79	3.94***
Deciduous forest	18.45	23.25	22.81	21.67	18.71	6.16***
Forest patch density	0.77	0.71	0.76	0.72	0.82	3.58***
N	622	622	622	622	621	

*** $p < 0.01$.
** $p < 0.05$.
* $p < 0.10$.

ornamental trees (with attractive foliage color) are often planted in residential urban areas (Kleerekoper et al., 2012). Additionally, the resolution of the land cover is 30 m which limits the minimum patch size of forest that is mapped, leading to some underestimation of the amount of forest present in a county. Finally, forest patch density, a measure of the extent of forest fragmentation in the county, exhibited a positive and significant sign. This indicates that with all other variables in the model held constant, counties with more fragmented forests were associated with higher numbers of heat related mortalities than those with more aggregated forest. Marginal estimates for this variable suggest that assuming all other factors constant, one unit increase in number of patch relative to the area of forest in county would mean a 0.025 increase in heat-related mortality per capita. While there is no preceding literature to compare this result, it is reasonable to expect that fragmented forests could have a higher edge effect, smaller interior areas, and therefore lower capacity to absorb substantial amount of heat and solar radiation at a local level.

5. Discussion and conclusions

Despite the growth of literature on the quantification and valuation of ecosystem services, whether and how the cumulative benefit of forest ecosystem services contribute to positive health outcomes at the landscape level is not well-understood. The exploratory analysis used in this study presents some empirical evidence to characterize the role of forest resources in reducing a community's vulnerability to the heat effects of climate change. Results from this study have a number of management and policy implications related to the public health benefit of forest ecosystem services and to the integration of land use and forest management options that may benefit communities. First, the heat vulnerability index developed and mapped at the county level allows for comparison of regional patterns and variation in vulnerability across the nation so that appropriate climate education/outreach, adaptation, and mitigation programs could be targeted to areas predicted to be most vulnerable. Since the factors contributing to vulnerability vary

Table 4
Estimates from Poisson regression of heat-related mortality per capita against HEVI components and forest characteristics.

Variables	Description	Model 1 Coefficient (Marginal effects)	Model 2 Coefficient (Marginal effects)
Control variables			
Age	Age component extracted from PCA analysis of HEVI, representing proportion of elderly population in county	0.144*** (0.300)	0.177*** (0.521)
Race	Race component extracted from PCA analysis of HEVI, representing proportion of racial and ethnic minorities in county	0.020** (0.041)	−0.010 (0.030)
Poverty	Lack of material resources and lifeline component from PCA analysis of HEVI, representing proportion of households depending on social security and public assistance income	0.016 (0.033)	0.028** (0.082)
Urban	Built environment component extracted from PCA analysis of HEVI, representing population density, and impervious surface	0.016*** (0.033)	−0.001*** (0.181)
Exposure	Climatic stress component extracted from PCA analysis of HEVI, representing number of cooling degree days and days with heat level in extreme danger range	−0.038*** (−0.079)	−0.251*** (0.738)
Forest characteristic variables			
Public forest	Proportion of county land that is covered by public forests	−0.004*** (0.008)	
Evergreen forest	Proportion of county land that is covered by evergreen forests	−0.002*** (0.004)	
Deciduous forest	Proportion of county land that is covered by deciduous forests	0.001** (0.002)	
Patch density	Number of forest patches in county divided by the area of forests	0.025* (0.052)	
Total forest	Proportion of county that is forested		−0.001*** (0.002)
Goodness of fit (R^2)		0.017	0.032

*** $p < 0.01$.
** $p < 0.05$.
* $p < 0.1$.

across the nation, it will also be possible for planners and managers to understand the underlying source of vulnerability (e.g. demography related, land use, landscape configuration, or climate) and target appropriate programs to address those deficiencies.

Second, our results confirm that a community's vulnerability to the heat effects of climate change may also depend upon the extent and characteristics of forests in the surrounding areas. Hence, managing forest resources at the landscape level may be a useful tool to reduce a community's vulnerability to the negative effects of heat. In light of predicted increases in unhealthy heat conditions with a changing climate, increasing public investment in green infrastructure like forests could be a cost-efficient public policy measure to address growing public health concerns in the long run. In urban areas, city planners may find expanding urban forestry programs through roadside and yard side plantation and community gardens more economical than offering subsidies or installation and maintenance services for air conditioning devices. Educating people on the benefit of trees may encourage more support of investment in urban forestry projects and motivate people to find creative ways of adapting to climate change impacts. It should be noted that the estimated marginal effects for forest variables are relatively smaller compared to those for control variables. However, considering that the dependent variable represents the number of mortality in per capita terms, the absolute size of these marginals is perhaps not trivial. Nevertheless, the relationship established in our exploratory study could be expanded in future research to further scrutinize the marginal effects of forest variables in more controlled experimental settings (e.g., finer scale analysis, high resolution data).

A third implication of our results is that the forest's ability to offset heat effects may depend on the species composition and the way they are managed or are configured in the landscape. For example, having evergreen species in public spaces seem to be more beneficial than deciduous trees as far as reducing heat-related mortality is concerned. These insights would be useful in the selection of appropriate tree species in plantation projects that are designed to enhance co-benefits of forest ecosystem services. Similarly, forests managed under public ownership with a conservation emphasis may be more effective than those managed under private ownership with intensive harvesting and production emphasis. This contrasting observation provides further support for acquisition and protection of natural areas to benefit the community. It will however, be more important to understand what specific management practices (e.g. silvicultural practice/system) make these two types of forests different in this regard.

Further, the spatial pattern of forest patches in the landscape appears to be important as well. Communities located in areas with lower heat vulnerability had less fragmented forests. As we see a nationwide trend in urban sprawl and seasonal housing surge, which are considered primary causes of forest fragmentation, appropriate land use planning may be needed to prevent forest fragmentation and maximize the landscape level benefit of forest ecosystem services. Studies have also claimed that forests in various parts of the country have fragmented over the years (Li et al., 2009), and the fragmentation is more likely to be in areas of lower land quality (Alig et al., 2005). The overall social benefits of forest ecosystem services can only be sustained by incentivizing landowners to protect forests located in marginal lands. Considering that some urban areas will also see higher levels of heat stress due to the urban heat island effect, implementing smart growth policies and urban forest protection programs should be a priority for helping to alleviate community vulnerability to heat. While poverty exists both in urban and rural areas, it appears that poor communities living close to federally protected public lands (national forests, national parks) may benefit more from those forests' potential to provide shelters and offset heat effects than communities living in central business districts of large cities. Regional disparities in the vulnerability to heat effects as well as the public health benefits of forest ecosystem services should be a part of the discussion while engaging communities for collaborative action towards mitigation and adaptation to climate change. Investment on innovative incentive mechanisms such as "agglomeration bonus" as opposed to "homogenous bonus" (Parkhurst and Shogren, 2007; Watzold and Drechsler, 2014) might be needed to slow forest fragmentation.

A few limitations of this study should be noted. First, because of data availability, our analysis used data summarized by county, which is more of a political entity than social entity. While some of the attributes of forest resources at the landscape level are better quantified at the county level, other social and cultural forces that define the community of people at the neighborhood level are not captured in our model. Second, while our analysis found some empirical evidence of correlation between vulnerability and forest resources, confirming the causation associated these correlations may require additional experimental studies or difference-in-differences modeling (Atreya et al., 2013) at a finer resolution than counties. Finally, the study did not account for some other potential variables (e.g. elevation, health care facilities that specialize in heat related-illness, and air conditioning facilities) that could be important predictors of health outcome at the county level. Future studies could focus on extending our model with addition of such variables measured preferably at household level, and with forest variables measured characterizing land use at finer scale (e.g. neighborhood level).

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