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The Value of US Urban Tree Cover for Reducing Heat-Related Health Impacts and Electricity Consumption

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Abstract

High air temperatures are a public health threat, causing 1300 deaths annually in the United States (US) along with heat-related morbidity and increased electricity consumption for air-conditioning (AC). Increasing tree canopy cover has been proposed as one way to reduce urban air temperatures. Here, we assemble tree cover and developed land-cover information for 97 US cities, housing 59 million people, and use regression relationships to analyze how much current urban tree cover reduces summer (JJA) air temperatures and associated heat-related mortality, morbidity, and electricity consumption. We find that 78% of urban dwellers are in neighborhoods with less than 20% tree cover. Some 15.0 million people (25% of total) experience a reduction of 0.5–1.0°C from tree cover, with another 7.9 million (13% of total) experiencing a reduction of greater than 1.0°C. Current relationships between temperature and health outcomes imply that urban tree cover helps avoid 245–346 deaths annually. Heat–mortality relationships in the 1980s, when a smaller fraction of US households had AC, imply a greater role in the past for urban tree cover in avoiding heat-related mortality. As AC availability has increased, the value of tree cover for avoiding heat-related mortality has decreased, while the value of tree cover for reducing electricity consumption likely has increased. Currently, for the 97 cities studied, the total annual economic value of avoided mortality, morbidity, and electricity consumption is an estimated $1.3–2.9 billion, or $21–49 annually per capita. Applying our results to the entire US urban population, we estimate urban tree cover annually supplies heat-reduction services worth $5.3–12.1 billion.

Key words: air temperature; energy use; heat waves; morbidity; mortality; United States.

Highlights

- We studied 97 U.S. cities, and our results imply that urban tree cover saves 245–346 lives annually.
- Urban tree cover helps avoid more than 50,000 doctor's visits due to heat annually.
- Heat-related benefits from trees are $1.3–2.9 billion annually, or $21–49/capita.

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Author's contribution The group jointly designed the research. RIM coordinated data analysis and wrote the paper with the help of the other coauthors. PZ assembled the information on air temperature and land cover, while PH worked on the methodology for estimating heat-related impacts. TK led the economic valuation analysis.

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Introduction

High air temperatures are a significant public health threat, killing an estimated 12,000 people annually worldwide in a typical year (McMichael and others 2004), with one heat wave in Europe in 2003 estimated to have killed more than 70,000 people (Robine and others 2008). Higher air temperatures increase mortality and morbidity by causing heat stroke and exhaustion, as well as by exacerbating existing cardiovascular, pulmonary, and renal diseases (McMichael and others 2004; McDonald and others 2016). Higher air temperatures also increase the need for indoor cooling of air, with temperature spikes being associated with a significant rise in electricity use for air-conditioning over daily, monthly, and annual time steps (Santamouris and others 2015). Climate change is projected to increase average air temperatures, as well as the frequency and severity of heat waves, thus potentially leading to large increases in mortality (Hales and others 2014) and electricity demand (McFarland and others 2015). Cities are increasingly focused on strategies that can minimize the impact of high air temperature on both their residents' health and the demands on their electric utilities (McDonald and others 2016).

The challenges posed by high air temperatures are even greater in urban areas, where the urban heat island (UHI) effect can significantly increase air temperatures compared to temperatures in nearby rural areas. Urban air temperature can be understood as the outcome of an energy balance equation (Oke 1982):

$$Q^{*} + Q_{F} = Q_{\mathrm{H}} + Q_{\mathrm{E}} + \Delta Q_{\mathrm{S}} + \Delta Q_{\mathrm{A}}$$

There are two inputs of energy into the urban atmosphere, Q^{*} (the net amount of energy from solar radiation) and Q_{F} (waste heat emitted by machines). There are four places that energy can go: it can get stored locally, e.g., in concrete or asphalt (ΔQ_{S}); it can be carried away through advection (ΔQ_{A}); it can increase sensible heat, Q_{H}, which increases air temperature; or it can increase latent heat, Q_{E}; the energy water needs to change from its liquid to its vapor phase (evapotranspiration). The UHI occurs primarily because cities contain materials like concrete and asphalt, which can absorb energy from incoming solar radiation (ΔQ_{S}) and later emit this energy as thermal radiation. There are two primary strategies for reducing the UHI: by shading these surfaces or increasing their albedo, thus reducing the storage of solar energy (ΔQ_{S}), or by increasing evapotranspiration, thus increasing latent heat storage (EPA 2014), Q_{E}.

A growing body of evidence shows that high air temperatures are associated with increases in mortality and morbidity, with numerous papers examining the functional form of the dose–response relationship between increases in air temperature and the relative risk of negative health impacts (Kalkstein and others 2011; Guo and others 2014; Wu and others 2014; Gasparrini and others 2015; Gasparrini and others 2016; Kingsley and others 2016; Son and others 2016). Studies have used different measures of air temperature over different time periods (Davis and others 2016), or have used indices of thermal comfort (Davis and others 2016). The heat–mortality dose–response curves vary among cities globally (Guo and others 2014; Gasparrini and others 2015; Gasparrini and others 2016) and in the United States (US) (Davis and others 2003; Anderson and Bell 2011; Kalkstein and others 2011; Bobb and others 2014; Nordio and others 2015), with cities in hotter climates having lower slopes, presumably because residents in these climates are better adapted to living with high air temperatures.

Reports of heat-related mortality may significantly underestimate total mortality, since often another more proximate cause of death is listed in medical records. For instance, the Centers for Disease Control in the US for 2006–2010 reported an average of 620 deaths per year from excess heat exposure (Berko and others 2014), whereas epidemiological studies that use statistical methods to estimate excess deaths above baseline mortality levels found around 1300 deaths per year from excess heat exposure (Kalkstein and others 2011). This paper focuses on cities in the US, where a few studies (e.g., Anderson and Bell 2011; Bobb and others 2014) have quantified city-specific mortality risk due to excess heat.

Multiple studies have shown that the dose–response curve between air temperature and mortality has changed over time, and for any given increase in air temperature there are now lower levels of mortality and morbidity (Davis and others 2003; Nordio and others 2015; Barreca and others 2016). For instance, in the US the mortality effect from a hot day declined by approximately 75% between 1900–1959 and 1960–2004 (Barreca and others 2016). This decrease in the population's mortality from excess heat has been shown to be correlated with increased air-conditioning (Hondula and others 2015; Nordio and others 2015). As the prevalence and use of air-conditioning has increased, people in the US have decreased their health risks from heat but have increased their electricity use (Hondula and others 2015).

Cities have multiple ways to reduce risk during periods of high air temperature. To reduce the risks of heat waves to public health, cities use heat action plans that formulate strategies to reduce exposure to extreme temperatures and to treat those who are experiencing heat-related illness (Matthies and others 2008; Boeckmann and Rohn 2014). Increasingly, urban trees are mentioned as one potential solution that can reduce ambient air temperatures (Stone Jr and others 2014; Middel and others 2015; Coutts and others 2016; Declet-Barreto and others 2016; Jenerette and others 2016; Kroeger and others 2018). Trees cool the air primarily by shading surfaces such as concrete and asphalt, thus preventing heat storage and reducing the UHI. Trees can also reduce the UHI by transpiring water, increasing the fraction of heat going to latent rather than sensible heat (EPA 2014). Urban tree cover can reduce surface temperature by 10–20°C on a summer day (EPA 2014). Effects on air temperatures are more modest, with a row of urban street trees on average lowering summertime air temperatures by 0.5–2.0°C (1 SD range) (McDonald and others 2016). Larger forests in parks have been reported to reduce nearby downwind peak air temperatures by up to 5°C, and their cooling effect can extend several hundred meters downwind (Kroeger and others 2018).

Cities and electric utilities can decrease electricity use by, among other things, implementing energy efficiency programs, reducing building albedo (''cool roofs''), and creating incentives to conserve electricity (EPA 2014). Trees near homes and other buildings can be another, complementary strategy to decrease electricity use. They reduce ambient air temperature and in some cases shade buildings from solar insolation, both of which reduce the need for indoor cooling. For instance, Santamouris and others (2015) found an average increase of 0.45–4.6% in peak electricity load for each 1°C increase in air temperature. Air-conditioning use is highly correlated with cooling degree days (CDD), the annual or monthly sum of the number of degrees by which a day's temperature is above some baseline comfortable temperature. E.g., one recent climate change modeling study by McFarland and others (2015) found that a 32–43% increase in CDD would result in a 1.6–6.5% greater annual electricity demand.

Although there is scientific evidence that trees can play an important role in reducing urban air temperature and its impacts on human health and air-conditioning use, relatively few studies have attempted to quantify across a large sample of US cities the value of several heat-related ecosystem services trees provide. For instance, Akbari (2002), McPherson and others (2005), and Endreny and others (2017) each calculated the benefits of trees for reduced building energy use for selected cities, but did not model heat-related health benefits from trees. Nowak and others (2017) conducted a US study of building energy use reduction due to trees, but similarly did not model heat-related health benefits. Kroeger and others (2018) modeled the summer heat reduction that could be achieved through large-scale urban reforestation in 27 US cities and the number of people receiving different levels of heat mitigation, but did not estimate the size or economic value of associated avoided health impacts.

Here, we examine 97 US cities, integrating information on urban tree cover and developed land cover with information on summer (June, July, August) daytime air temperature to estimate maps of average air temperature anomaly due to land cover. This information is then combined with information on dose–response curves for US cities to estimate mortality and morbidity impacts that are avoided due to current urban tree cover. We also estimate the electricity demand for air-conditioning i.e., avoided due to the presence of current urban tree cover. Finally, we extrapolate results from our 97 cities to the entire urban population of the US. The goals of this paper are to:

- Quantify the effect of urban tree cover in US cities on summer daily mean air temperatures.
- Quantify the effect of this reduction in air temperature on heat-related mortality and morbidity, as well as electricity use for air-conditioning.
- Examine how the increase in air-conditioning penetration has changed the effect of urban tree cover on health.
- Economically value the effect of urban tree cover on reducing heat-related costs to society.

Methods

Our methodology has four main stages: First, we conducted a GIS analysis to measure the proximity of urban populations to tree cover and developed land cover and constructed a counterfactual scenario of tree cover loss, where urban tree cover is replaced by a representative mix of other land cover types found nearby. Second, we modeled the effects of urban tree cover and developed land cover on air temperature. Third, we modeled the impact of our counterfactual scenario of tree cover loss on air temperature, and the effect of this loss of heat mitigation on mortality, morbidity, and electricity consumption. Fourth, we estimated the economic value of avoiding these heat-related impacts on health and electricity consumption.

GIS Analysis and Counterfactual Scenario of Urban Tree Cover Loss

We assembled tree cover and land-cover data for 97 US cities. These cities were chosen to match the cities studied by Bobb and others (2014), although we excluded a few small towns due to concerns that population data were not spatially well-resolved in these urban areas. The 97 cities we studied had a combined total population of 59.1 million in 2010. For each city, we mapped tree canopy cover using the NLCD 2011 Continuous Forest Cover (%) product. Although this 30-m product is the best available data on forest cover for the entire continental United States, we acknowledge that it is likely an underestimate of the true urban forest cover. For instance, McDonald and others (2016) found that a 30-m forest cover product, although linearly correlated with tree cover measured with a finer-scale dataset ($R^2 = 0.62$, Fig. 39 in McDonald and others 2016), underestimated tree cover. Note, however, that as we developed in this manuscript empirical regressions that relate tree cover in the NLCD Forest Cover product to temperature, the estimated parameters will still allow for an accurate estimate of the effect of tree cover on temperature.

Categorical land-cover data, including developed land cover, were taken from the NLCD 2011 Land-use Land Cover (LULC) dataset (Homer and others 2015). We used these categorical land-cover data, rather than the available NLCD product for % impervious, because we wanted to statistically estimate the effect of all developed areas on temperature, not just the effect of impervious surfaces. Urban area boundaries follow those used by Bobb and others (2014) and are generally city proper (municipal) boundaries.

To understand the effect of proximity to different land covers on temperature at residential locations, we calculated the percent tree cover and developed land covers within a set of buffer distances (90 m, 200 m, 500 m, 1 km, 2 km, 5 km, 10 km) using Focal Mean commands in ArcGIS 10.4.1. These data were overlaid with information on population density from the Wildland/Urban Interface (WUI) dataset (Radeloff 2010), which downscales US census data using additional information such as the location of protected areas (Radeloff and others 2005). Then in our regression, described below, these data were used to explicitly examine the spatial scale at which land cover affects air temperature measured at air temperature sensors, and the results of our regression analysis were extrapolated to all residences in a city.

In all of our analysis, we tried to account for as many sources of uncertainty as possible, using standard propagation of error techniques (Taylor 1996). When errors are uncorrelated (i.e., the variables are independent), the error of the sum of two variables is simply:

$$\delta_x = \sqrt{\delta_a^2 + \delta_b^2}$$

where δ_a and δ_b are the errors of the two variables and δ_x is the error of the sum. Similar formulas can be derived for other arithmetic operations. In some cases, in our error propagation the assumption of uncorrelated errors seemed unlikely to be true, and, to be conservative, in those cases we assumed complete correlation of errors, essentially assuming that errors do not cancel each other out when summed (Taylor 1996). In general, for our analysis, calculations summing pixels within a city assume correlated errors, which seemed likely given the spatial autocorrelation in many driving variables at this scale, while calculations summing city values to a national figure assume uncorrelated errors.

Our methodology follows Imhoff and others (2010) and Zhang and others (2014), who classified areas (the size of MODIS pixels, 1 km^2) into four categories of urbanization intensity: heavily urban ($> 75\%$ developed land cover, DC), moderately urban (50–75% DC), lightly urban (25–50% DC), and less developed ($< 25\%$ DC). This classification is helpful because it captures two important gradients that occur in many but not all cities: a gradient toward higher population and DC in the urban core, and a gradient toward greater urban tree cover in less densely developed areas. Note that although we classified 1-km^2 blocks, the fine scale of the NLCD and (to a lesser extent) WUI data means we had information on the variability within these 1-km^2 blocks, which was important for error propagation.

The principal goal of this study was to estimate the total value of urban tree cover for reducing heat-related impacts. This required constructing a counterfactual scenario in which all urban tree cover is absent, which in turn necessitates an assumption about what land cover would be present instead. We assumed that if urban tree cover disappeared, the land cover present instead would be a representative mix of the other land-cover types (excluding urban tree cover) in each urbanization intensity category. For each (i) urbanization intensity category, we calculated the fraction of land use i.e., currently developed excluding tree cover, $Frac_{imp,i}$. This quantity is less in rural areas and greater in the urban core. If a given area of tree cover, $A_{FC,I}$, is lost, then the increase in the area developed is $A_{FC,i}$ x $Frac_{imp,i}$. It is important to note, therefore, that our counterfactual scenario can increase air temperature in two ways: via the direct loss of tree cover and via its partial replacement by developed land cover. Our regression approach, described in the next section, explicitly accounts for both effects.

Modeling the Effects of Land Cover on Temperature

In this paper, we developed a regression that relates land cover to air temperature. We acknowledge that there are numerous factors other than land cover that also impact temperature, and studies for small geographical extents often build and calibrate microclimatological, process-based models that attempt to account for these factors (e.g., Wouters and others 2013). However, several studies have shown that predictable statistical relationships exist between land cover and air temperature, and these relationships hold over the continental United States (Imhoff and others 2010; Zhang and others 2014). For the purposes of this paper, which is to estimate the effect of tree cover on air temperature for a large sample of US cities, the empirical, regression-based approach was more tractable and allowed a statistical quantification of the uncertainty in estimating temperature, which can then be used to quantify the uncertainty in estimating heat-related impacts.

The dependent variable in our regression is summer (June, July, August) average daily mean temperature. We chose to focus on daily mean air temperatures since they are often used in studies of heat-related mortality and morbidity (Knowlton and others 2011; Bobb and others 2014), as well as electricity consumption for space cooling (Santamouris and others 2015), and we wanted to match the predictions of our regression equation as precisely as possible to those studies. However, we acknowledge that other parameters such as nighttime temperatures and the duration of high air temperature also can affect health and electricity consumption.

Our regression directly relates summer average daily mean temperature with both tree cover and developed land cover. The air temperature data ($N = 994$) come from the same source as that of Zhang and others (2014), the Global Historical Climatology Network (NOAA 2017). Our predictor variables are calculated percentages of tree cover and developed land cover within different buffer distances of the air temperature sensor. We tested various buffer distances (90 m, 200 m, 500 m, 1 km, 2 km, 5 km, 10 km), selecting the spatial scale with the greatest explanatory power, as selected through a forward regression. We allowed for differences in regression slopes among biomes, only finding a significant difference in the case of developed cover. Our definition of biomes follows that used by Zhang and others (2014), although in our final regression we combined biome categories that did not have significantly different regression parameters, to increase the sample size and precision of parameter estimation within a category. Finally, we included a fixed effect for metropolitan area, which focused our regression on the remaining variance in temperature (the air temperature anomaly) due to land cover. We tested for interaction terms between all model effects, using forward regression.

Predictions for our regression were first calculated at the 1-km^2 level. These values were then summarized at the national level using a population-weighted average. Similarly, values were summarized at the city level using a population-weighted average. We used the population-weighted average to calculate the average reduction in temperature experienced by people due to current tree cover. As shown in Table S1, most urbanites reside in lightly urbanized or moderately urban neighborhoods, which have lower tree cover than the less developed parts of the city. When propagating uncertainty by summing from 1-km^2 level up to the city level, we made the conservative assumption that errors are correlated.

Heat-Related Impacts

We used the best available published dose–response curves relating air temperatures to human health and economic impacts, using as an input variable the calculated shift in air temperature from our tree cover loss scenario. In doing so, we make the assumption of linearity, that if a hypothetical tree cover decline leads to an average increase of 1°C in summer daily mean air temperature, that it will also lead to an increase of 1°C during smaller periods of time (e.g., during a heat wave). We acknowledge that this assumption of linearity is a simplification of the complex processes that determine urban air temperature (Oke 1982). For our calculation of heat-related impacts, we used information aggregated to the level of urbanization category within city, but we ensured that we used the population-weighted average developed and tree cover percentages. This is important, since it accounts for local-scale variability, and the trend (which exists even within an urbanization category) for sites with less tree cover to have more people nearby, and vice versa.

Details of our estimation of avoided heat-related impacts due to tree cover can be found in Supplementary Methods section (Electronic supplementary material 1). For mortality estimation, our analysis is based on Bobb and others (2014), who estimated heat–mortality relationship for 105 US cities. For morbidity estimation, our analysis is based on Gronlund and others (2014), who estimated heat-related hospitalizations as a function of air temperature for a large population in the US. For estimating the electricity consumption, we used two papers that used contrasting methods to estimate electricity consumption as a function of temperature, McFarland and others (2015) and Santamouris and others (2015).

Economic Valuation

Our analysis estimated the value of avoiding one unit of heat-related impact, expressed in 2015 US dollars (USD, $). Where studies listed values for other years, we adjusted to 2015 dollars using the Bureau of Labor Statistics' CPI inflator. In all calculations, we propagated uncertainty using standard propagation equations (Taylor 1996). We first estimated the economic value of mortality, morbidity, and electricity consumption for the 97 cities we studied. We then extrapolated our results to the total US urban population, assuming that the per capita rate of impact of our tree loss scenario would be the same in other cities as what we observed in our 97 cities.

Details of our valuation of avoided heat-related impacts due to tree cover can be found in Supplementary Methods section (Electronic supplementary material 1). Our estimation of the value of avoided mortality takes a value of a statistical life (VSL) approach, based on the work of Kniesner and others (2012), Berko and others (2014) and Murphy and Topel (2006). For estimating the value of avoided morbidity, we apply a cost-of-illness (COI) approach, quantifying the costs of emergency department (ED) and outpatient visits (Knowlton and others 2011), hospitalizations (Schmeltz and others 2016), and the lost work productivity associated with these events. For estimating the value of avoided electricity consumption, we used data on average household residential electricity consumption and average cost per KWh, by electric utility (EIA 2016).

Results

More than 28 million people (48% of the total population of 59 million) in the 97 cities we studied live in neighborhoods with less than 10% tree cover (Table S1 in Electronic supplementary material 4). Only 5.9 million and 7.1 million people live in neighborhoods with, respectively, 20–30% or more than 30% tree cover. This is important because for the heat-mitigation services of urban tree cover that are the focus of this paper, the higher the level of urban tree cover, the greater potential service provision.

There is an important variation in tree cover from the heavily urban core out to less developed suburbs and exurbs (Table S1 in Electronic supplementary material 4). To address this gradient in urbanization intensity, we mapped four urbanization categories, based on the percent of the neighborhood that was developed land cover (DC). Most urban residents, 44 million people, live in neighborhoods that are lightly urbanized (25–50% DC) or moderately urbanized (50–75% DC). Residents in the lightly urbanized category most frequently live in the 10–20% tree cover range, while the residents in the moderately urbanized category are most frequently in the 0–10% tree cover range. Conversely, although only 7.5 million people (13% of the total population) live in the less developed (< 25% DC) category, these residents most often have tree cover that exceeds 30%. Thus, the typical city resident lives in a neighborhood with relatively low tree cover, whereas less developed areas that house fewer residents contain the majority of a city's urban tree cover.

Tree cover and developed land cover relate to air temperature in predictable patterns. Figure 1A shows an example for the Raleigh, NC area, where the air temperature sensors in developed areas, such as near the airport and in central Raleigh, have low tree cover and high DC in their surroundings and have the highest observed summer daily mean temperatures. In this case, sensors in these highly urbanized areas have a summer daily mean temperature around 1.5°C higher than sensors in more rural areas. This general pattern of a local air temperature anomaly due to land cover is common across the 97 cities we studied, although there are important other factors that cause regional and local gradients in air temperature. At the national level, of course, summer daily mean

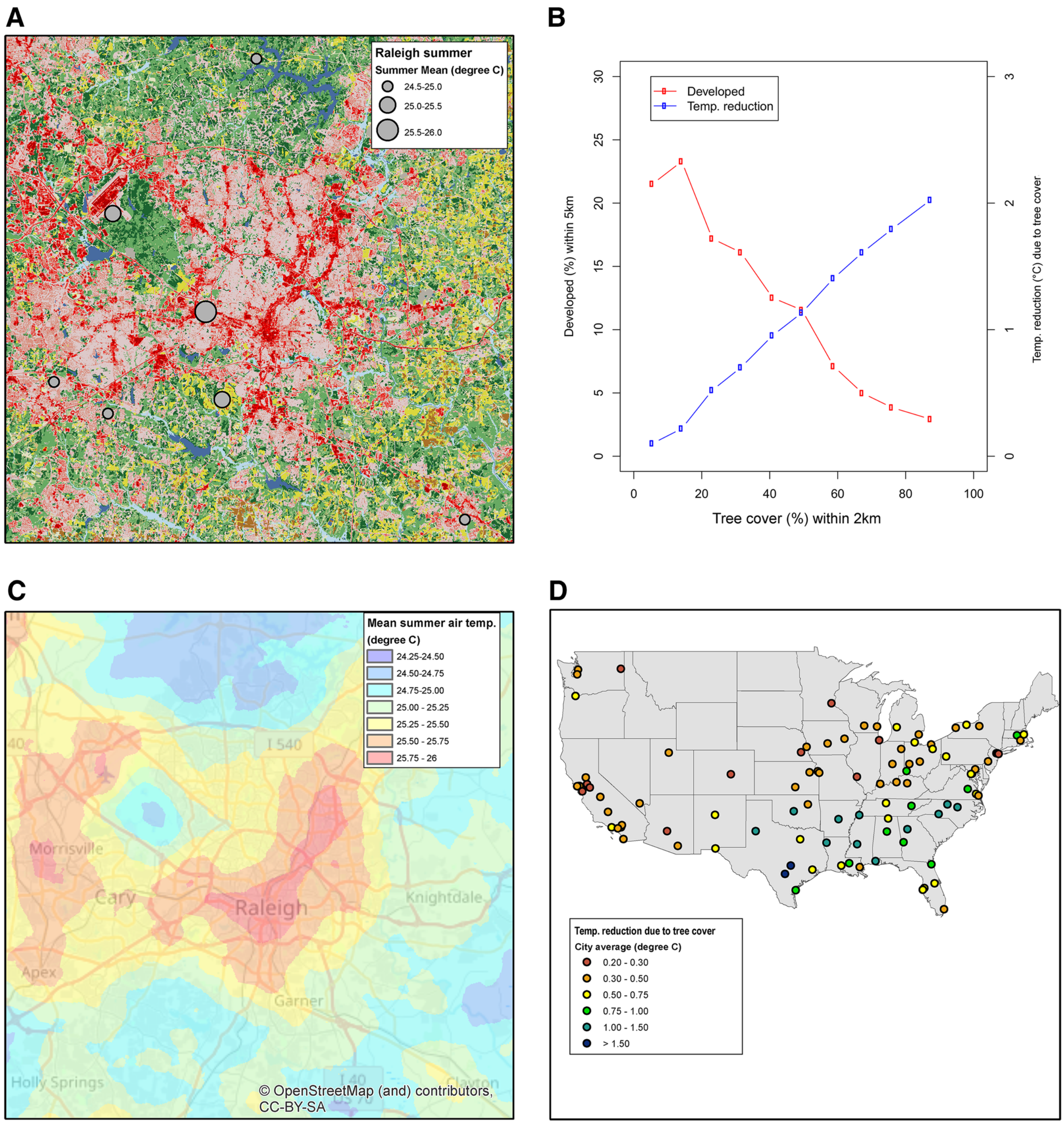

Fig. 1. Relationship between tree cover and air temperature. **A** Land cover and air temperature for one urban area, Raleigh, NC. Developed land covers are shades of red, whereas tree cover is shown in green, sparse vegetation in yellow, and water in blue. **B** Regression relating tree cover and developed land cover with summer daily mean temperature for cities in the forest biome. **C** Predicted air mean summer daily temperature due to the presence of tree cover in the Raleigh area. **D** The population-weighted average summer daily mean temperature reduction by current tree cover for the 97 cities studied.

temperatures vary regionally due to climatic factors, with the hottest temperatures observed in the Southwest, and the magnitude of this regional variation is often larger than the local air temperature anomaly due to land cover.

In this paper, we developed a regression directly relating nearby tree cover and developed land cover to summer daily mean air temperature observed at air sensors. We found that the 2-km buffer for tree cover (Figure S1 in Electronic supplementary material 2) and the 5-km buffer for developed land cover (Figure S2 in Electronic supplementary material 3) had the greatest explanatory power. Greater tree cover within 2 km of a sensor is significantly ($P < 0.001$) related to lower summer daily mean air temperature, while higher developed cover within 5 km is significantly ($P < 0.001$) related to higher summer daily mean air temperature (Table S2 in Electronic supplementary material 5). Note that the slope of the tree cover and developed cover effect varies significantly ($P < 0.001$) between arid and mesic regions. We find that in arid regions (desert and mediterranean biomes) an increase in air temperature is associated with a decrease in developed land cover, in contrast to mesic regions (grassland or forest biomes), where this correlation is positive or not significantly different than zero. In both regions, tree cover is associated with a decrease in temperature, and there is a statistically significant difference in the slopes. The predicted relationship between percent tree cover within 2 km of a sensor and the air temperature reduction is shown in Figure 1B, for a mesic region like Raleigh, NC. Also shown is the average amount of developed land cover (%) within 5 km of the sensor.

The predicted temperature due to tree cover and developed cover can also be mapped spatially (Figure 1C). Because of the buffer distances involved (2 km for tree cover, and 5 km for developed land cover), the predicted temperature anomaly due to land cover looks like a smoothed-out version of the land-cover trends, with areas of high tree cover having higher estimated reductions in summer daily mean air temperature due to tree cover. Figure 1C shows the same geographic area in Figure 1A, allowing for comparison between the pattern of land cover and predicted air temperature.

At the city scale, the average population-weighted reduction in summer daily mean air temperatures, relative to our counterfactual scenario of tree cover loss varies greatly (Figure 1D), from less than 0.3°C (e.g., cities in the Southwest in arid biomes that often have little tree cover) to more than 1.5°C (e.g., cities in the Southeast in forest biomes that often have large tree cover). Note that these population-weighted figures represent the tree cover in the neighborhood of the median person in each city. Particular neighborhoods may experience much greater or lesser reductions in summer daily mean air temperatures due to tree cover. As noted in Table S1, although the majority of tree cover may be located in less developed areas, which have a large estimated reduction in temperature, the median household lives in lightly urbanized or moderately urban areas, with a smaller estimated reduction in temperature.

In our counterfactual scenario of tree cover loss, tree cover is replaced with a representative mix of nearby land-cover types (see ''Methods'' for details). The loss of tree cover will directly lead to an air temperature increase, although the partial replacement by developed land cover will lead to a further increase in temperature (Figure 2). Across urbanization categories, the direct impact of tree cover loss is estimated to have a greater impact on air temperature than the partial developed land-cover gain. However, the relative magnitude of the two varies, with more urbanized neighborhoods having a greater fraction of their temperature increase in the counterfactual scenario due to the partial developed land-cover gain.

The number of urban dwellers receiving different levels of temperature reduction, relative to our counterfactual scenario, varies across biome type (Table S3 in Electronic supplementary material 6). In our study cities in the forest biome, 8.2 million people (27% of urban dwellers in this biome) receive a 0.5–1°C reduction in summer daily mean

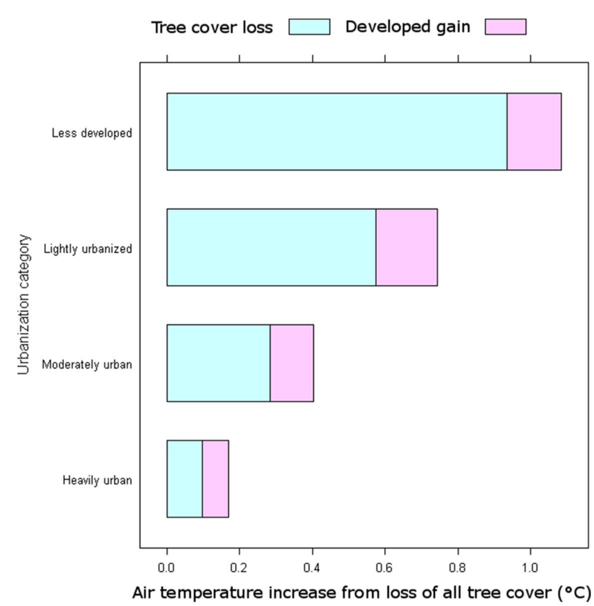

Fig. 2. The average daily mean air temperature increase (°C) in the 97 study cities i.e., modeled to occur if all urban tree cover is lost, by level of urbanization (see Table S1 for more details). In our model, we estimated how much the loss of tree cover would directly increase temperature (in blue). We also assumed in our tree cover loss scenario that tree cover would be replaced by the average mix of other land cover in the urbanization category, leading to some developed land-cover gain and a further increase in temperature (in pink).

air temperatures due to tree cover, while another 4.1 million people (14% of urban dwellers in this biome) receive a reduction of greater than 1°C. In cities in the grassland biome, 3.2 million people (22% of urban dwellers in this biome) receive a 0.5–1°C reduction in summer daily mean air temperatures due to tree cover, while another 3.2 million people (22% of urban dwellers in this biome) receive a reduction of greater than 1°C. Cities in mesic regions, in desert and mediterranean biomes, have comparatively few people living in neighborhoods receiving summer daily mean air temperatures reduction due to tree cover of greater than 1°C. In total, across the 97 cities studied, 15.0 million people (25.4% of urban dwellers) receive a 0.5–1°C reduction in summer daily mean air temperatures due to tree cover, while another 8.0 million people (13.5% of urban dwellers) receive a reduction of greater than 1°C.

Our analysis, however, permits a much more disaggregated look at where urban dwellers receive different levels of temperature reduction, relative to our counterfactual scenario. There is substantial variation among cities. Average city-level data are shown in Table S4 (Electronic supplementary material 7), as well as the uncertainty present in our estimation of the temperature reduction value of tree cover, relative to our counterfactual scenario. There is also substantial variation within cities (Table S5 in Electronic supplementary material 8). In many cities, population density is greater in more urbanized areas (e.g., urban centers), but these areas often have lower tree cover and hence lower estimated temperature reduction. Less urbanized areas (e.g., suburbs and exurbs) have lower population density, but in many cities have higher tree cover and hence greater estimated temperature reductions.

The reduction in exposure to high ambient air temperatures for urban dwellers due to urban tree cover, relative to our counterfactual scenario, is estimated to decrease heat-related mortality (Figure 3A). Compared to temperature and expected heat-related mortality in the counterfactual scenario, current annual avoided mortality due to tree cover in the 97 cities is estimated at 296 (95% CI 245–346). Our results are based on the Bobb and others' (2014) estimate of current mortality–temperature relationships. Bobb and others (2014) also estimated mortality–temperature relationships in the 1980s, when mortality was significantly more sensitive to temperature spikes, presumably due to lower prevalence of air-conditioning in homes. We estimate that if 1980s mortality–temperature relationships applied today, urban tree cover would help avoid 719 (95% CI 662–777) deaths annually, a 2.4-fold increase over the avoided mortality estimated using current temperature–mortality relationships.

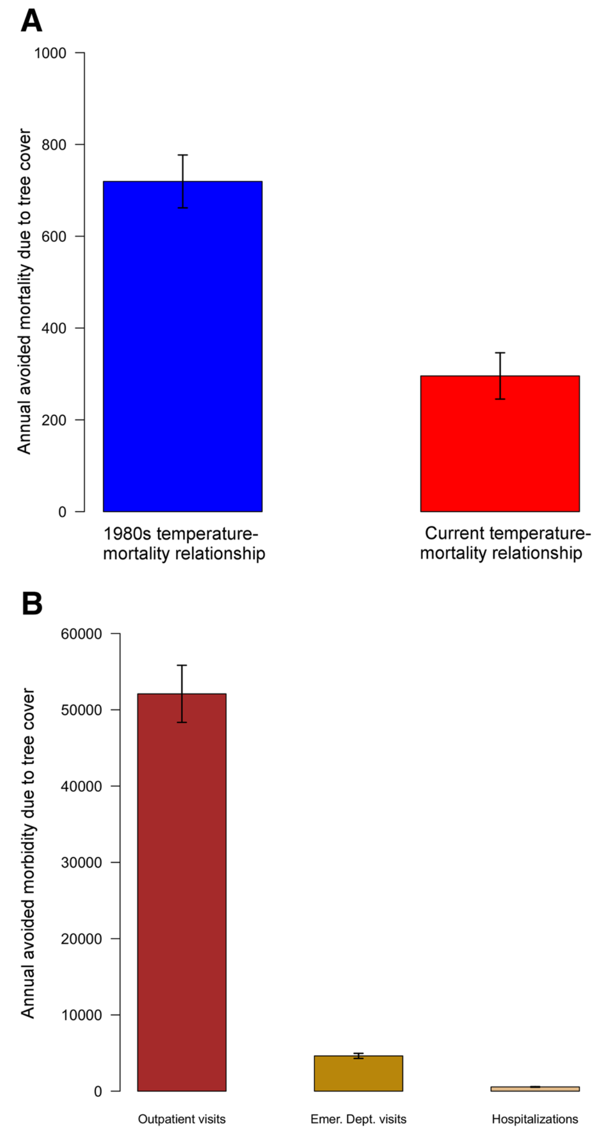

Fig. 3. Avoided health impacts in the 97 study cities due to tree cover. **A** Annual avoided mortality due to tree cover. **B** Annual avoided morbidity due to tree cover, expressed as the number of outpatient visits, emergency department visits, and hospitalizations.

Similarly, the reduction in ambient air temperature exposure for urban dwellers due to urban tree cover, relative to our counterfactual scenario, is estimated to decrease heat-related morbidity (Figure 3B). The number of current annual avoided heat-related hospitalizations in the 97 cities due to tree cover is estimated at 555 (95% CI 505–605). Based upon published ratios in the literature, we estimate that the number of current annual avoided emergency department visits due to tree cover is 4623 (95% CI 4291–4955), with the number of outpatient visits avoided due to tree cover even higher, 52,091 (95% CI 48,348–55,834).

The reduction in ambient air temperature due to tree cover, relative to our counterfactual scenario, also significantly reduces electricity use for space cooling (Figure 4). In our analysis, we contrasted two models of the sensitivity of electricity consumption to temperature, Santamouris and others (2015) and McFarland and others (2015). In the 97 cities studied, the range across both models of annual avoided electricity use due to tree cover (including the 95% CI of each estimate) is 2.0–3.2 TWh, which is 0.8–1.3% of average current annual US household electricity consumption (10,764 kWh) (EIA 2016).

We estimate the total annual avoided heat-related costs, relative to our counterfactual scenario, as $1.3–2.9 billion for our 97 study cities (Table 1). The majority (76–84%) of that total is due to avoided mortality. Avoided electricity consumption is the next-largest component of the total, with avoided morbidity accounting for a relatively minor portion. We estimate that for all US cities, the total annual avoided heat-related costs due to urban tree cover is $5.3–12.1 billion.

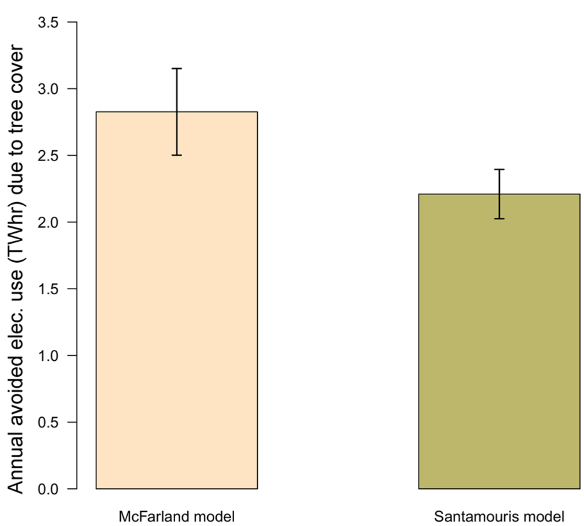

Fig. 4. Avoided residential consumption of electricity for space cooling due to current urban tree cover in the 97 cities studied. In our analysis, we used two papers that modeled the relationship between heat and electricity use: McFarland and others (2015) used electricity sector models to estimate regional sensitivity of electricity use to cooling degree days, whereas Santamouris and others (2015) collected empirical measurements of increase in electricity use during periods of high air temperature.

Discussion

Current urban tree cover, relative to our counterfactual scenario, reduces mortality in the 97 cities studied by an estimated 245 to 346 deaths annually (Figure 3A), and this avoided mortality is worth $1.0–2.4 billion per year (Table 1). If this rate holds true for all US urban residents, the nationwide annual avoided mortality might be 1030–1454 deaths, which would be valued annually at $5.3–12.1 billion. In a country where 2.6 million die annually (Kochanek and others 2016), and the GDP is $19.4 trillion (IMF 2017), the effect of tree cover on heat-related mortality can seem modest. However, given that there are currently an estimated 1300 deaths per year due to heat in the US (Kalkstein and others 2011), our results suggest that without urban tree cover this figure would be doubled (95% CI 1.79–2.12).

Interestingly, the value of tree cover for reducing heat-related mortality seems to have declined significantly in recent decades. If the temperature–mortality relationship observed by Bobb and others (2014) in the 1980s still applied today, current tree cover in the 97 cities studied would have avoided 662–777 deaths annually (Figure 3A). If this rate applied to all US urban dwellers, urban tree cover would have avoided an estimated 2780–3264 deaths and $9.7–24.8 billion in associated costs annually. This reduction over time in US population-level mortality due to excess heat appears to be due to the increasing fraction of households with air-conditioning (Hondula and others 2015; Nordio and others 2015; Barreca and others 2016). In effect, Americans are replacing an ecosystem service (shading and temperature regulation) with an engineered one (space cooling indoors). To the extent that outside temperatures are decoupled from indoor temperatures due to space cooling, the amount of urban tree cover matters now less for US public health than it did in the 1980s. The prevalence of air-conditioning in the US is higher than for many other countries. For instance, many lower-income countries have much lower prevalence of air-conditioning, although air-conditioning use is projected to increase rapidly (OECD/IEA 2018). Indoor temperatures in countries with lower AC prevalence thus currently remain more tightly coupled with outdoor temperatures than in the US.

Conversely, increased use of air-conditioning over time has increased sensitivity of electricity demand to air temperature. US air-conditioning prevalence has increased from 57% of households in 1980 to 87% of households in 2015 (EIA 2015). Although, due to data limitations, we did not

Table 1. Annual Avoided Costs Due to the Presence of Urban Tree Cover.

Category	Total cost (million USD), 97 cities		Total cost (million USD), US urban population	
	Min	Max	Min	Max
Avoided mortality	959	2431	4027	10,210
Avoided morbidity	58	65	244	275
Hospitalizations	3	4	15	17
Emergency department visits	4	5	19	22
Outpatient visits	50	57	208	239
Avoided electricity	248	389	1042	1634
Total	1265	2885	5313	12,118

The range shown is the 95% CI, across all models considered. Note that for avoided morbidity, we show subtotals for the costs of hospitalizations, emergency department visits, and outpatient visits. As these are 95% CIs, subtotals within the avoided morbidity category will not sum to the CI for total avoided morbidity.

model in this paper the changed economic value of tree cover for mitigating electricity use due to increased prevalence of air-conditioning, it seems likely that this economic value has increased over time. We estimate that currently, tree cover helps avoid $248–389 million per year in total household electricity costs in our 97 cities. On a per-household basis, this would represent a relatively modest 0.8–1.3% of annual household electricity consumption. If this rate applied to all US households, total annual avoided electricity costs due to urban tree cover would be $1.0–1.6 billion. This value is less than that of Nowak and others (2017), who estimated annual reductions in electricity use due to trees at $4.7 billion for urban and community residents, a larger population than for our study, which just looked at urban residents.

Note that urban trees provide multiple ecosystem services beyond the heat-mitigation services considered in this paper (Roy and others 2012). For instance, trees sequester carbon, reducing greenhouse gas concentrations; they can help manage urban stormwater by increasing infiltration; they provide aesthetic beauty and increase residential property values; and they remove ambient air pollutants, reducing associated human health impacts (McDonald 2015; Keeler and others 2019). Trees, however, also cost money to plant and maintain and sometimes impose additional costs (e.g., the hazard of wind throw damage). One study in California looked at a large set of ecosystem services and found that the benefits of trees outweighed the costs of planting and maintenance by a factor of 5.8 (McPherson and others 2015). Our goal in this study was to provide a detailed estimate of only heat-related ecosystem services. However, urban forestry managers and other decision makers should make decisions considering the whole spectrum of ecosystem services provided.

Our results suggest that heat-related services from trees have an economic value i.e., large relative to the cost of planting and maintaining urban tree cover. For the 97 cities we studied, the total economic value of heat-related services from trees is an estimated $1.3–2.9 billion per year, and we estimate the value for all US urban residents at $5.3–12.1 billion per year. On a per capita basis, trees provide $17–42 per person per year in heat-related benefits. For contrast, the average town in the US in 2007 spent $5.83 per person per year on urban forestry activities (American Public Works Association 2007), although it should be noted that this number includes activities by only municipal agencies—any money spent on forestry activities by other levels of government, or private actors, is not counted. Nevertheless, the value of heat-related services alone from trees likely exceeds tree planting and management costs.

These heat mitigation benefits of urban tree cover accrue to individuals, health agencies, and electric utilities, but not to the municipal agencies in charge of planting and maintaining trees. This is a classic example of the ''wrong pocket'' problem, where the person or agency that receives a benefit is not the entity that must pay for it (McDonald and others 2017). Perhaps in part because of this wrong pocket problem, urban tree cover is in decline in the US. There has been a 24% reduction in per capita investment in urban forestry between 1974 and 2007 (American Public Works Association 2007; Vogt and others 2015), leading to a decline in urban tree populations. Urban tree cover in US cities declined by 1% over the period 2009–2014 (Nowak and Greenfield 2018), an annual net loss of 36 million trees. Moreover, tree cover is inequitably distributed among neighborhoods, sometimes disproportionately impacting populations with high vulnerability (Declet-Barreto and others 2016).

This trajectory of urban tree cover decline might be reversed through public policies or incentives that reflect the value of heat reduction services by trees. For instance, many cities are crafting heat action plans to minimize negative health impacts of high air temperatures. Urban forestry can be one part of these plans, along with public cooling centers and heat-advisory warning systems. Similarly, some utilities such as Sacramento Municipal Utility District have provided rebates or other incentives to homeowners for tree planting, to minimize peak electric load (McDonald and others 2017). Although the appropriate mix of policies and incentives varies by city, it seems likely that policies like these will give financial value to the heat-related services trees provide, increasing tree cover and service provision. Our findings suggest that such policies or incentives are justified on economic grounds.

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