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Analysis

Tree Shade, Temperature, and Human Health: Evidence from Invasive Species-induced Deforestation

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A B S T R A C T

By providing shade and through evapotranspiration, trees and forests moderate temperatures, and thus, can indirectly affect human health, an economic variable of interest. In this paper, we measure the temperature and temperature-induced health effects of quasi-random tree cover loss caused by an invasive species, the emerald ash borer (EAB). We use monthly temperature data on the near-universe of US counties containing the invasive over 1995–2014 to estimate a temperature dose-response relationship. Then, dose-response results are integrated into a bioeconomic-health model to study the mortality and morbidity consequences of temperature fluctuations. We find that highest and mean monthly temperatures are increased by 0.28 °F and 0.09 °F, respectively, after EAB detection. There is also a 2.1% higher probability of experiencing at least one ≥90 °F day per month after EAB. Bioeconomic model results suggest that an invasive-caused 10% loss of forest canopy leads to increases in mean temperature that result in a maximum of 0.12 per 100,000 additional annual deaths and a maximum of 10.0 per 100,000 additional annual emergency department visits. At peak impact, invasive-induced tree loss creates $1 million in annual mortality and morbidity temperature-related costs. Cumulative health costs of a 10% loss of tree canopy are $17.9 million over 25 years.

1. Introduction

Climate change and temperature increases are among the greatest natural threats to human and economic welfare in the 21st century (World Economic Forum, 2016; Costello et al., 2009; Stern, 2008). An important influencer of the climate are the world's forests and trees, which, through physical, chemical, and biological processes and feedbacks, affect planetary energetics, the hydrologic cycle, and atmospheric composition (Bonan, 2008). Much attention over the years has been given to the carbon sequestration properties of trees as attenuators of global atmospheric greenhouse gas concentrations (e.g., Nowak et al., 2013; Pan et al., 2011; Nowak and Crane, 2002; Bateman and Lovett, 2000; Stavins, 1999). While forest carbon sequestration is important to study, it is not the only temperature-related impact of trees. Through evapotranspiration and the provision of shade, trees and forests can moderate temperatures. With a warming Earth, tree shade will become increasingly beneficial. Our understanding of the economic consequences of tree shade is largely limited to its impacts on energy consumption (e.g., Pandit and Laband, 2010; Simpson, 2002). However, by impacting temperatures, especially extreme temperatures, it is likely that tree shade also affects human health, itself an important economic variable of interest. Yet, rigorous empirical assessments of the relationship between tree shade, temperature, and health are lacking.

In this paper, we estimate the relationship between tree shade and temperature by exploiting a quasi-experiment caused by the loss of tens of millions of North American ash trees (*Fraxinus* spp.) due to the invasive emerald ash borer (*Agrilus planipennis*), or EAB, hereafter. That is, we estimate what, if any, impacts on temperature result from quasi-random losses of millions of shade trees in the US. Specifically, we exploit quasi-random month-to-month variation in county-level EAB detections, and hence variation in county tree shade within US states to document how several measures of monthly county temperature respond to increased tree mortality. Given that ash are one of the most common shade tree species in the US and die within a relatively short period of time after EAB introduction, we are investigating an arguably exogenous shock to local forest canopies and tree shade. Our research design can mitigate many common environmental confounders of concern since EAB spread is based in part on random insect flight and insect ride (hitching a ride on moving vehicles), and since ash tree loss is extensive (> 99% in many areas).

To measure and economically value the mortality and morbidity consequences of observed changes in temperature, we embed the originally estimated temperature dose-response function into a bioeconomic-health model of trees and temperature. Use of a bioeconomic-health model allows us to combine econometric estimates from several different sources as well as allowing for dynamic simulations under differing assumptions. This is advantageous in the present setting because it allows us to merge our empirical estimates with the extant literature on temperature and health,

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rather than having to re-estimate this relationship, in light of recent, credible empirical estimates that already exist (White, 2017; Deschênes and Greenstone, 2011, and see Dell et al., 2014).

Three conclusions arise. First, the highest monthly temperature in counties with EAB, and hence those experiencing widespread tree loss, is increased by 0.28 °F or 0.38% compared to contemporaneously non-infested counties within the same state. We also find that after EAB detection there is a 2.1% increase in the probability that a county experiences at least one day a month with ≥ 90 °F temperature. Second, the causal interpretation of our results are bolstered by the finding that temperature impacts are strictly increasing in time since initial EAB detection. Highest monthly temperature is 0.34 °F higher in the first year after EAB and 2.53 °F higher 12 years after initial EAB detection. With a longer lag, mean monthly temperature is 0.20 °F higher at year +8 after detection and is 2.78 °F higher at year +12 after detection. These findings are consistent with increasing ash mortality over time, which is commonly observed in EAB infested areas. Finally, our baseline bioeconomic model results suggest that an EAB-caused 10% loss of forest canopy leads to increases in mean temperature that result in a maximum of 0.12 per 100,000 additional annual deaths and a maximum of 10.0 per 100,000 additional annual emergency department visits. Cumulative temperature-related health costs of a 10% loss of tree canopy are $17.9 million over 25 years.

This paper makes three primary contributions to the existing literature. First, ours is the first attempt to rigorously study the consequences of actual tree shade loss on temperature for a near national cross-section of counties. This is an important contribution because much of the extant literature relies on predictions from biophysical models of trees and temperature rather than actual empirical estimates such as those from a quasi-experiment setting. Second, we depart from the extant literature on tree shade by considering health effects of temperature fluctuations rather than changes in energy consumption. Finally, we integrate original econometric results with a bioeconomic-health model. This is atypical in the extant literature where it is more common to have either an econometric results paper *or* a bioeconomic model paper. Given that parameterization of bioeconomic models generally rely on results from other studies, there may be a certain degree of hypotheticality present in bringing together pieces of models and data from many, potentially disparate, sources. Using original estimates, like here, can add certainty, richness, and factual consequentiality to bioeconomic models results.

2. Trees, Temperature, and Human Health

There are two separate literatures that this work connects to: (i) the literature on trees and temperature, and; (ii) the literature on temperature and health. We will begin with separate discussions of each and then will discuss why it is important to link them together in the current context.

Trees and forests reduce air temperature in two ways: by blocking solar radiation from reaching the ground (creating shade) and through evapotranspiration (water evaporating from the leaf surface).[1] The conversion of water to air vapor through evapotranspiration removes heat energy from the air, thereby cooling nearby surroundings. The focus of this paper is on deciduous trees, such as North American ash, that only moderate temperatures in the non-winter months when leaves are present (i.e., spring, summer, and fall).[2] Previous studies that have looked at the effect of tree shade on temperature use either small-scale controlled experiments on individual structures or large-scale simulation modeling (see Mullaney et al., 2015 for a review and also Donovan and Butry, 2009 for related studies). Estimates from this literature suggest a wide range of temperature impacts. For example, Berry et al. (2013) found that tree shade on three buildings in Australia resulted in ambient temperature reductions of up to 1.8 °F (1 °C). By contrast, Mullaney et al. (2015) reported that street trees reduced daytime temperatures by 9 °F to 36 °F (5–20 °C) based on their review of two case-study papers. The wide range of findings from these studies may have to do with their small samples, absence of rigorous controls for confounding effects, or that controlled simulation exercises may not accurately reflect the complexity of the biophysical linkages between trees and temperature. Additionally, it is likely that past work, which tends to combine results from multiple tree species, is confounded by the fact that different species of trees have heterogeneous effects on temperature (Wang et al., 2009).

It is worth noting that trees may also have meso-scale effects on temperature, reducing the phenomena known as the "urban heat island effect." That is, in addition to individual trees affecting their immediate micro-climates, the collective contribution of many trees in an urban area may reduce the overall ambient temperature in a city, even, to a degree, in areas with little or no tree cover (Block et al., 2012). Previous simulation results suggest that meso-scale effects on ambient urban temperatures may range from 0.72 °F to 1.8 °F (0.4–1 °C) (Ng et al., 2012; Rosenzweig et al., 2006).

Separately from investigations of the tree-temperature relationship, there is a large extant economics literature on how temperature relates to human health (e.g., White, 2017; Barreca, 2012; Deschênes and Greenstone, 2011; Deschênes et al., 2009, and see Dell et al., 2014 and Deschênes, 2014 for reviews). Much of this work is based on a conceptual framework derived from Becker-Grossman models of health production (Grossman, 2000). The idea is that the full welfare effect of an exogenous change in temperature is reflected in changes in the survival rate and the consumption of goods/services that increase the probability of survival (e.g., an air conditioner). Using this conceptual framework, Deschênes and Greenstone (2011) estimate a dose-response relationship between daily mean temperature and mortality in the US.

While the focus of this literature is often on mortality, White (2017) recently estimated the relationship between temperature and morbidity. Specifically, he found a largely linear relationship between contemporaneous temperature and emergency department (ED) visits in California. At least one paper has also examined the relationship between temperature and infant health (Deschênes et al., 2009).

It is believed that observed mortality and morbidity increases are the result of excessive temperature-related stress experienced by the human body. While the body's heat regulatory function enables us to cope with exposure to high and low temperatures, this coping also increases the stress on many functions, primarily the cardiovascular system (Deschênes, 2014). As ambient temperatures rise due to climate change, there is thus a concern that significant public health impacts will follow (Costello et al., 2009). It is therefore necessary, we believe, to bring together the tree and temperature literature with the temperature and health literature.

2.1. Invasive EAB as a Deforestation Quasi-experiment

To identify the causal relationship between trees and temperature, we exploit quasi-random losses of ash trees due to the invasive emerald ash borer (EAB). First detected in Michigan in 2002, EAB is a small phloem-feeding beetle native to Asia that was accidently transported to the US through trade in ash and ash by-products. EAB lay eggs in the conductive tissue of ash trees and the larvae feed on the inner layers of the tree, disrupting the trees' regulatory functioning. At sufficient beetle density, the tree dies. Ash mortality among unhealthy or stressed trees can begin almost immediately after invasive introduction, whereas healthy adult trees typically die within 5–8 years, though sometimes closer to 10 years depending on EAB density (Herms et al., 2014; Poland and McCullough, 2006).[3]

EAB spread across the Midwestern and eastern US has been extensive,

[1] For simplicity, in the rest of the paper, we will use the term "tree shade" to refer to both the solar radiation and evapotranspiration temperature properties of trees.

[2] By contrast, evergreen trees (which are not considered in this work) will moderate temperatures all year long, which can be problematic during the winter months when solar radiation is blocked from warming cold surfaces.

[3] The lagged timing between detection and tree mortality will be exploited in our empirical models as a check that our temperature findings are indeed increasing over time as more trees die.