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Trees and vegetation for residential energy conservation: A critical review for evidence-based urban greening in North America

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ABSTRACT

The effects of trees on residential energy demand have been extensively studied over the past several decades; yet a comprehensive analysis of their magnitude, variation and emerging issues and evidence has not been updated in the literature. Given this gap, a systematic review was conducted by assessing major disciplines, geographic distributions, methods and reported energy-saving performances for cooling and heating residential homes. An overwhelming majority of literature focused on single family housing types in North America, with a strong geographic concentration in California. In North America, 40 peer-reviewed studies were published from 1979 to 2017 by 19 different journals across disciplines. Researchers used simulation modeling and empirical approaches in roughly equal proportions. The review confirms that the conceptual and empirical evidence to support trees' energy saving effects is solid, especially for cooling effects, but the magnitude of reported energy-savings widely varied depending on climate, method, data and assumptions for buildings and trees. A building with trees used 2.3% to 90% less cooling energy, mostly through shading effects, and 1% to 20% less heating energy through windbreak effects, in comparison to buildings without trees. Takeaways for evidence-based urban greening are that practitioners and researchers should: i) pay careful attention to different methods and assumptions used when interpreting and comparing research findings ii) pursue long-term monitoring and evidence-based management to enhance tree survival and growth; iii) incorporate emerging trade-offs and synergies such as rooftop solar energy, water conservation, and net carbon savings into design and policies; and iv) prioritize planting for underserved and vulnerable communities.

1. Introduction

In the past several decades, manystudies have shown ample evidence that trees and vegetation around buildings contribute to reducing buildings' energy demand for cooling and heating (Ko, 2013; McPherson and Rowntree, 1993; Meier, 1991). Starting mainly in the 1970s, arborists, landscape architects, architects, and planners began to develop climate-responsive site and community design guidelines including tree planting and landscaping practices (see Fig. 1) (Brown and Gillespie, 1995; Erley and Jaffe, 1979; Hammond et al., 1981; McClenon and Robinette, 1977; McPherson, 1984; Reed, 2010; Robinette, 1983; The AIA Research Corporation, 1978). Generally speaking, tree shade reduces building energy demand for air conditioning by reducing solar radiation on walls and roofs (Donovan and Butry, 2009; Hildebrandt and Sarkovich, 1998; Ko and Radke, 2014; Simpson and McPherson, 1996). Trees also indirectly save cooling energy by lowering ambient temperature through evapotranspiration, which mitigates many of the Urban Heat Island (UHI) effects of the residential lots and communities (Akbari and Taha, 1992; Akbari et al., 1992; Huang et al., 1987; Stone and Norman, 2006). Trees are also known for reducing heating energy demand by reducing wind speed or blocking cold wind (i.e. windbreaks), especially when they are planted in a setting perpendicular to the wind in cold climates (DeWalle and Heisler, 1983; Hammond et al., 1981; Jaffe and Erley, 1979). Conversely, it has also been shown that in cold climates the addition of trees can increase energy demand, specifically for heating, because of irradiation reduction by tree shade (DeWalle et al., 1983; McPherson et al., 1988). Accounting for both the penalties and the energy savings provided, it is commonly accepted that trees provide a positive net energy saving for homes when they are strategically planted (Akbari, 2002; Akbari and Taha, 1992; Hwang et al., 2016; Simpson, 1998; Simpson and McPherson, 1998, 1996). Trees' energy saving effects are considered one of the major ecosystem services of urban forests (Roy et al., 2012). These research findings provide both scientific evidence and rationale for tree planting initiatives such as shade tree programs supported by utilities and communities (Ko et al., 2015a; Young and McPherson, 2013).

Although many studies have been conducted on how much energy is

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Fig. 1. Typical tree planting guideline for energy-savings.
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saved by trees, a comprehensive understanding of the extent and variation of the impact of trees on reducing residential energy demand is still lacking. McPherson and Rowntree (1993) conducted a literature review and show a wide range of energy saving values across regions and climate zones in the U.S. Since then, there has been no systematic comparison of heating and cooling energy loads by climate regions. Considering trees and vegetation as part of urban forms, Ko (2013) provided an updated review on this topic by grouping studies by methods. Roy et al. (2012) and Wang et al. (2014) conducted literature reviews on the benefits of urban forests and green infrastructure including energy savings, microclimate effects and thermal comforts with many other ecosystem services; however, given the extensive scope of the review, a fair number of relevant studies were not included in these reviews. Recent empirical studies question the magnitude of the impact of trees on reducing space-conditioning energy demand, particularly for well-insulated homes (Abbott and Meentemeyer, 2005; Nelson et al., 2012). In order to support evidence-based urban greening for energy conservation, it is imperative to systematically assess what scholarly evidence exists regarding the energy-saving performance of trees in various disciplines and climate regions, what the emerging issues are and how they are interrelated, and how study findings can contribute to state-of-the-art urban green infrastructure planning and design (Brown and Corry, 2011).

The goal of this study is to provide a systematic review of trees' energy-saving performance reported from peer-reviewed literature. This review provides a comprehensive summary of research findings by discipline, geography associated with climate regions and methods that can be linked to implications for tree planting practice and future research on urban greening. Encompassing the largest number of peer-reviewed papers published on this topic up to 2017, it seeks to answer the following questions: i) How has the effect of trees on residential energy use been studied across different disciplines and regions? ii) How have the different methods been used and can their results be compared and interpreted? iii) What are the emerging issues that practitioners and researchers need to be aware in order to maximize the energy-saving benefits through evidence-based urban greening?

2. Methodology

This paper employs a systematic review approach (Roy et al., 2012) focusing on the literature that examines the impact of trees and surrounding vegetation on residential energy use based on the disciplines, geographic (climate) locations and the research methods. Among all building types, this review focuses on residential buildings, because there is considerable difference between residential and commercial buildings in terms of structural, ventilation, and heating and cooling requirements which affect energy usage (Skelhorn et al., 2016). Furthermore, most of the literature on trees' energy saving effects focus on residential buildings.

Scholarly online databases such as Web of Knowledge and Google Scholar were used to find the relevant studies on energy-saving impacts of urban trees. Keywords entered for the article search were "urban trees energy saving" "vegetation energy saving" "tree shade energy" "trees cooling energy" "trees heating energy" and "trees residential energy". Among the papers found in the search results, relevant papers for this research were selected based on the following criteria: i) peer-reviewed journal articles; ii) papers that quantitatively demonstrated how much trees and vegetation (shrubs and turfs) *near* residential buildings affect heating or cooling energy use. This review does not include papers such as i) non-peer reviewed papers such as conference papers, government reports, books, white papers, or magazine articles; ii) papers that addressed microclimate and thermal effect of trees such as changes in air or surface temperature in/outdoor environments (Wang et al., 2014) or shade pattern change affecting building facades (Hwang et al., 2015), but that did not include quantified energy saving performance; and iii) papers that investigated the effect of vegetation *on* building surfaces (vines on facades or green roofs) (Raji et al., 2015). Using "backward chaining" (Booth, 2008), additional papers that were cited in the reference of the papers reviewed were also included.

As a result of an extensive literature search, it was found that the overwhelming majority of the studies that fit into these criteria were conducted in the U.S. and Canada (89%, 40 out of 45 papers). This overwhelming concentration on the North American region has several explanations. First, most research literature regarding the benefits and