Urban Studies **at 50**

Article

Urban Studies

50(16) 3262–3282, December 2013

The Spatio-temporal Clustering of Green Buildings in the United States

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[Paper first received, September 2012; in final form, February 2013]

Abstract

This paper explores the spatial and temporal patterns of green building in the commercial and institutional sectors in the US. While these buildings are becoming more commonplace, they have yet to reach a critical mass to affect the entire construction industry. Given the potential for green building practices to reduce energy consumption and carbon emissions, the paper seeks to understand the geography of green building. Using multiple metrics, it explains the patterning of geography of LEED and Energy Star certified buildings in the US. Strong evidence is found of clustering at the metropolitan and sub-metropolitan scales. This exploratory research serves as a foundation for future research aimed at specifying the nature of agglomerative processes in green buildings.

1. Introduction

Although the US is making significant progress in the development and deployment of renewable energy sources, the majority of energy production remains fossil-fuel based, and is likely to be exacerbating climate change. For this reason, policy-makers have continued to emphasise energy efficiency as an important mechanism for reducing aggregate energy consumption. The largest and most visible energy efficiency efforts have focused on the built environment, which accounts for nearly the majority of all energy consumed, with commercial buildings alone responsible for about 20 per cent of all energy consumption in the US (Energy Information Administration, 2011). Accordingly, since the late 2000s there has been a significant push to increase the energy efficiency of buildings through a variety of incentive programmes offered by utilities, government agencies and regulators.

One of the ways in which building-sector energy efficiency is realised is through

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0042-0980 Print/1360-063X Online

DOI: 10.1177/0042098013484540

promotion of green building construction. Some analysts estimate that the number of green buildings could rise from 15 per cent of the non-residential buildings in 2009 to 50 per cent in 2050 (Kats, 2009). Green buildings are those that are constructed from environmentally sustainable materials by following waste-reducing construction practices, are easier to operate and maintain, protect occupant health, and conserve energy and water, even when the definitions are malleable. Various certifications and labels exist, and some get revised periodically, to communicate the effectiveness of a building in achieving these goals.

While green buildings are becoming increasingly popular in the US, we know little about their geography. In a preliminary study, Cidell (2009), characterised the geography of Leadership in Energy and Environmental Design (LEED) certified buildings and of LEED-accredited professionals and found that between 2000 and 2007, LEED-certified construction spread from the coastal cities to the mainland of the US. Similarly, Kok *et al.* (2011, p. 82) found that diffusion of energy efficient buildings appeared "more rapid in metropolitan areas with higher incomes and in those with sound property market fundamentals." Nevertheless, these studies are done at the scale of metropolitan regions and have not examined the trends within and across metropolitan regions and have not examined the potential spillover effects over time. We posit that there is a strong path dependency and clustering in the adoption of green building technology that manifests itself in space and time, and the purpose of this paper is to explore these spillover effects. We find evidence for this through our analysis of LEED and Energy Star commercial and institutional buildings.

There are several reasons why these buildings can cluster in space. First, green buildings make financial sense in some markets either because energy savings, indoor air quality benefits or other positive effects outweigh the extra construction and maintenance costs. Secondly, niche green building markets within a region may develop—for example, as a result of demand preferences or environmental awareness, which itself may be geographically concentrated. These could be due to a regional economic structure that privileges certain types of industry (education, research & development, office, etc.). Thirdly, there may be institutional mandates and incentives from place-based organisations (such as local governments) or from the hierarchy within the firm (such as a company-wide initiative emanating from national or international headquarters). A fourth reason for the clustering of energy efficient buildings is that there may be thresholds beyond which skill levels within the labour market improve through knowledge spillovers and increasing experience. Fifthly, there may be copying and transfer of building construction, finance and maintenance practices. It is likely that agglomeration economies provided by spatial clustering are particularly important in a highly technical and emerging industry (see Storper and Walker, 1983; Vernon, 1960). This is consistent with the literature on economic development which focuses on the role of a particular form of spill-over resulting from the exchange of highly technical and/or tacit knowledge (Saxenian, 1994; Cooke and Morgan, 1998). Porter (2000) argues that knowledge spillovers, along with traditional agglomeration economies, lead certain regionally based industry clusters to out-innovate and ultimately outcompete their peers. Moreover, the process of spatial clustering of green buildings and its spread across various spatial scales over time is also informed by the classical literature on the spatial diffusion of innovation (see Hägerstrand, 1966; Rogers, 1995), which stresses the role of communication within and across networks, and notes why the diffusion of new practices may occur in a regular pattern over time. To date, however, the preponderance of research attempting to understand the pattern of green buildings has focused on the role of local and state policies (Simons *et al.*, 2009) or state-level politics (Choi and Miller, 2011).

In this paper, we take a first step in understanding the geography of commercial green buildings by examining spatial and temporal trends in the construction and retrofitting of non-residential buildings in the US. Specifically, we analyse the two main comprehensive efforts that promote energy efficiency for buildings in the US: Energy Star and LEED certification. While Energy Star (henceforth ES in this paper) certification started in 1999, LEED certification was first issued in 2000. While ES certification is binary, LEED certification relies on different tiers (such as Certified, Silver, Gold and Platinum that reflect increasing levels of stringency). If such geographically clustered patterns exist, then design, technology and process spillovers and institutional factors could be important mechanisms through which green buildings are operationalised.

The purpose of this research is exploratory. We do not explicitly verify the causal mechanisms that undergird the clustering process. Nevertheless, we consider this a first step in a research agenda that unpacks the agglomeration economies in green building construction. We return to the potential explanations of clustering—which we put forward as a future research agenda—in our conclusions. From our analysis, we find significant evidence of spatiotemporal clustering in the construction of green buildings. This finding supports a research agenda aimed at understanding the exact nature of agglomeration economies that are important for this emerging sector. Once understood, these factors could prove to be important policy levers for actors seeking to speed up the development of green buildings and the promotion of greater energy efficiency.

The remainder of this paper is organised as follows. Section 2 presents background information on green building policies in general and the LEED and ES programmes in particular. This section also reviews the motivation for why clustering holds so much potential for green buildings. Section 3 describes the data sources and methods used to describe the spatio-temporal patterns exhibited by green buildings in the past decade. Section 4 discusses the main findings and the final section concludes and outlines next steps in the research agenda.

2. Background and Motivation

Cities and regions have supported energy efficiency goals by retrofitting their existing building stock (Berry and Schweitzer, 2003) and by promoting voluntary building standards in new construction (Nash and Ehrenfeld, 1996). This phenomenon is not unique to the US and is observed elsewhere as well (Lee and Yik, 2004). However, given the institutional unwillingness to impose and enforce mandatory and strict building standards on the entire building stock in their jurisdictions (Iwaro and Mwasha, 2010), most government agencies and regulators are adopting an incentive framework that relies on nudging private sector actors and developing markets for green buildings (see for example, Geller *et al.*, 2006). To this end

> Various LEED initiatives including legislation, executive orders, resolutions, ordinances, policies, and incentives are found in 442 localities (384 cities/towns and 58

> counties and across 45 states), in 34 state governments (including Commonwealth of Puerto Rico), in 14 federal agencies or departments, and numerous public school jurisdictions and institutions of higher education across the United States.[1]

In addition, many utility regulators have used their oversight powers to force investor-owned utilities to develop rebate programmes and other programmes to promote energy efficiency retrofits and green building practices that meet or exceed current building standards.[2]

While local building codes are usually less strict than some of the voluntary standards, many agencies are increasingly adopting these voluntary standards to guide their own practices. For example, many federal agencies including US Departments of Agriculture, Defense, Energy, General Services Administration and Veteran Affairs have green building policies that stipulate all new construction and major renovations be either certified by LEED or similar certifications. The Energy Independence and Security Act (EISA) of 2007 requires that leases of federal agencies after December 2010 should be in buildings that are ES certified. Executive Order 13514 requires that 15 per cent of each federal agency's facilities and building leases meet Environmental Protection Agency Portfolio Manager's guiding principles.[3] Cities such as Boston, Seattle and Boulder now require major city building construction and renovations be LEED Silver certified. The state-wide building code in California (CALGreen) that went into effect in early 2011, mirrors some components of LEED green building but with mandatory requirements. Policies that require organisations to manage their building assets in a sustainable fashion, as well as goals and incentives that send signals to other participants in the real estate markets (such as lessees, developers, etc.) have led to an increasing number of green buildings. Collectively, these policy innovations and regulations have helped to push the concept of green buildings in the market and have provided some financial support in the form of incentives and/or directed public purchasing.

2.1 LEED and ES: A Tale of Two Voluntary Standards

Many green building standards exist; many are popular in specific countries such as BREEAM in the UK, DGNB in Germany and CASBEE in Japan. All of these standards take into account energy, resource and location efficiency. The two major green building standards that are prevalent in the US are ES and LEED. While ES focuses primarily on energy efficiency, LEED has a more comprehensive approach to green buildings. In any case, both standards require careful attention (although with varying emphasis) to be paid during design, construction and operations phases of buildings.

ES began as a joint programme between the US Environmental Protection Agency (EPA) and the US Department of Energy (DOE) in 1992. Primarily designed to promote energy efficient appliances and equipment, this voluntary programme was embraced by the information technology industry whose boom was getting underway. In 1995, ES for homes was awarded to residential buildings that are 30 per cent more efficient than the 1993 model energy code (MEC) and in 1999 the label was extended to office buildings that perform in the top 25 per cent of the market. In 2000, Portfolio Manager was launched to track energy usage and maintenance of certification.

In contrast to the government-led initiative, the United States Green Building Council (USGBC) is a non-profit organisation that promotes green buildings through its widely known rating system, LEED. LEED was originally established in 1998 and various new standards have been added to its repertoire. The LEED-NC (new construction) standard has gained the largest traction in the US; however, LEED EB:O&M (Existing Buildings: Operations and Maintenance) is a growing category.

ES certification is reflective of the management and operational practices in a building, whereas LEED certification is more skewed towards design and construction practices. The certification process employed by ES requires it to be a continuing (annual) certification, whereas LEED is largely a one-time certification. By most accounts, the ES programme has been a qualified success. Within two decades, according to USEPA (2010), the programme was responsible for a saving of almost 5 per cent of the annual US energy consumption. The market penetration in new housing construction is also noteworthy—25 per cent of the new housing starts in 2011 in the US are ES certified.[4] Of the estimated 29 billion square feet in the US (Florance *et al.*, 2010), over 2 billion of commercial buildings are certified. The LEED programme is smaller than the ES programme. The average proportion of the LEED certified space is less 1 per cent of the commercial stock in many markets (Fuerst *et al.*, 2011).

3. Data Description and Methodology

3.1 Data Description

We use the locations of LEED and ES buildings to explore the spatial and spatio-temporal clustering of green building practices in commercial buildings in the continental US. We restrict attention to the continental US due to the difficulty in treating unconnected areas in a geostatistical framework. Furthermore, we restrict our attention to commercial structures, as there are no easily available datasets that are comparable for both certifications for residential and industrial buildings. The construction sector in the US is also specialised by the type of construction (residential and non-residential); therefore, it is worthwhile to study them as separate processes.

ES data are from the Energy Star website.[5] The first year in which a building achieved certification during the 1999–2010 period was recorded along with the address information. K-12 Schools and Offices were the largest percentage of the buildings that are ES certified. Supermarkets like FoodLion, Giant, SuperValu Inc., and department stores such as Target, JC Penney and Kohl's, large school districts such as Los Angeles, CA, Polk County, FL, Gwinnet County, GA, each have over 100 buildings that are ES certified. The number of new ES certifications rose dramatically after 2007 (Figure 1, right). It is important to note that this certification is an annual certification and hence this Figure does not represent the number of buildings that are certified any given year, but only buildings that received certification for the first time in the particular year.

The addresses of LEED buildings are from the USGBC.[6] All registered projects before November 2011 were used. Buildings with confidential information were discarded from the dataset. LEED gold certifications have outpaced all other certifications since 2008 (Figure 1, left). The downturn in the certifications in 2011 is due both to the fact that the data for 2011 are for only 11 months and to the downturn in the economy.

Multiple geocoding services were used to generate location information from the address strings. The ArcGIS On-line geocoding service was supplemented with the Google geocoding Application Programmeming

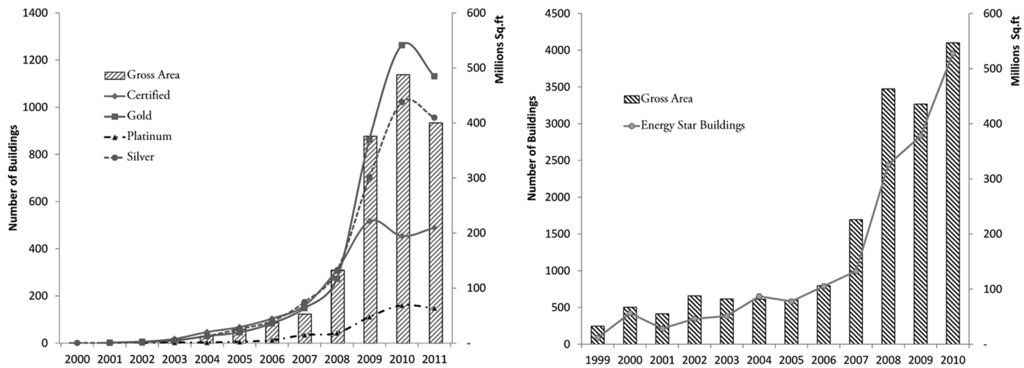

Figure 1. Trends in new green building certifications. *Left*: LEED certified buildings; *right*: ES buildings.

Interface (API) service to generate the latitude and longitude information. This is necessary to overcome data entry errors. All the entries were matched uniquely. Where there were multiple candidates for the standardised address, the information was cross-checked between the two services. In some cases, ties were broken, addresses were corrected through human intervention and visual checking. Of the 8055 non-confidential LEED buildings in the continental US, 99.2 per cent addresses were matched. All the 13 709 ES buildings were successfully geocoded through these methods.

Some buildings were both LEED and ES certified (954). No unified dataset exists and, therefore, to avoid double counting, we identified these buildings, first by matching the addresses. However, due to persistent typographical differences in the addresses, we then matched building locations from one dataset to another. If the building falls within a threshold distance of 50 metres, we assumed that the buildings are a match. Visual inspection and random spot checking confirmed that this threshold avoids double counting. To examine trends within and across regions we use the metropolitan statistical area (MSA) geographical definitions from the US Census Bureau.[7] Similarly, census tracts of the 2000 vintage distributed by ESRI are used at finer scales.

3.2 Methodology

Three complementary methods and metrics are used to identify the spatio-temporal patterns: local Moran's I (Anselin, 1995); trends in the nearest neighbour distances (NND) and nearest neighbour indices (NNI) (Clark and Evans, 1954); and Kulldorff's scan statistic (Kulldorff *et al.*, 2005). These methods have been widely used elsewhere to identify clustering patterns in diverse applications such as disease detection (for example, Rothman, 1987), poverty (for example, Voss *et al.*, 2006), agglomeration economies (for example, Helbich, 2012) and industry linkages (for example, Feser and Sweeney, 2000). The Moran's I is a lattice approach that identifies clusters of census tracts that have a relatively high number of green buildings that neighbour other such tracts. This approach provides a snapshot view of the clusters at the end of the study period. The trends in the nearest neighbour distances indicate the type of spread of green buildings in metropolitan areas by measuring if new distinct clusters are being formed or if existing ones are becoming more mature,

Table 1. Different types of spread of green buildings

	Interyear	
	High	*Low*
Intrayear		
High	Dispersion	Emergence of dispersed clusters
Low	New cluster formation	Consolidation of existing clusters

without identifying the location of these clusters. The Kulldorf's scan statistic is used to identify clusters of buildings that are close both in space and in time. Taken together, these methods identify how green buildings are spreading both within metropolitan regions and across them, and when and where the clusters are emerging.

We identify purely spatial clusters by calculating the local Moran's I for each census tract within each MSA. All the green buildings are counted within a census tract and the statistic I_i is calculated according to

$$I_i = \frac{(n_i - \overline{n})}{\sum_{k=1}^{p} (n_k - \overline{n})^2/(p-1)} \sum_{j=1}^{p} w_{ij}(n_j - \overline{n}) \tag{1}$$

where, n_i is the number of green buildings in census tract i; p is the number of tracts in the MSA; $\overline{n}$ is the average; and w_{ij} is a measure of interaction between tracts i and j, in this case a row-standardised queen contiguity spatial weight matrix. The expectation and variance are given by Anselin (1995) and thus their statistical significance can be determined. We use the 'spdep' package (Bivand *et al.*, 2011) to calculate the statistic and test its significance.

The average nearest neighbour distance (NND) for all green buildings in an MSA is the average of the nearest neighbour distance for each building i, defined as

$$\overline{d}_o = \sum_{i \in b} \frac{\min_j d_{ij}}{|b|}$$

where, d is a distance metric; and b is the set of green buildings in the MSA.

This average distance is tracked for each time-period t. Three different distances are measured: average distance of nearest neighbour within new buildings—i.e. $i, j \in b_t$ where b_t are the set of buildings certified in year t; average distance of nearest neighbour in accumulated green buildings—i.e. $i, j \in B_{t-1}$ where, $B_{t-1} = \bigcup_{k=1}^{t-1} b_k$; and, average distance of nearest neighbour in between building in current year to previous buildings—i.e. $i \in b_t; j \in B_{t-1}$.

The spread of green buildings can be characterised by thinking about the relationship between intrayear (i.e. when i and j belong to the same set) and interyear (i.e. when i and j belong to different sets) nearest neighbour distances (Table 1). Large distances between buildings certified in the current year to the buildings in the previous year, coupled with small distances within themselves suggest an emergence of a new cluster. Small distances between buildings within a single year as well as to the buildings that are already certified suggest consolidation of the cluster.

Many of these analyses use algorithms from the 'spatstat' library (Baddeley and Turner, 2005) in R. Spatio-temporal clusters are identified through scan statistics utilising SaTScan software (Kulldorff, 1999). Scan statistics are essentially counts of green buildings in a window of variable size and shape that moves across the spatio-temporal realm. The observed value of these counts is compared with the expected value of the counts.

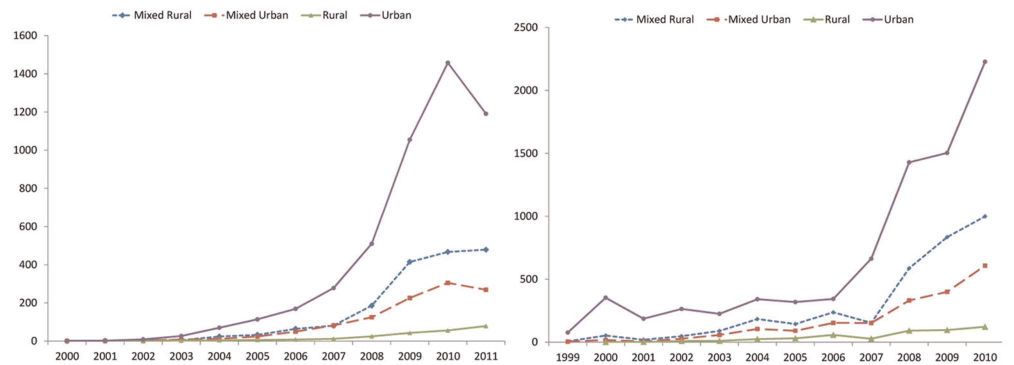

Figure 2. Trends by county type in new green buildings. *Left*: LEED certified buildings; *right*: ES buildings.

The likelihood is calculated based on both within and outside the window. In the current analyses, for computational reasons, we restrict our attention to windows of the elliptical shapes and centre them around each building address. The size of the ellipse is then increased from 0 until it encompasses 50 per cent of the buildings within the geographical region. The ellipse is then extruded in the temporal dimension at various heights from t_s (start) to t_e (end) incremented by the year. Thus, many cylinders are considered for each geographical region and the numbers of green buildings are counted that fall within and outside the cylinder. To avoid finding too many eccentric circles, we use the penalised likelihood ratio (PLR) to identify significant clusters (Kulldorff *et al.*, 2005).

The Kulldorff scan statistic is most suitable for identifying activity that is clustered in space and time. However, building construction, unlike epidemics, is durable. Thus, if two buildings are certified years apart even when they are located close to one another, the cluster is not identified as the buildings are not close to one another in the temporal dimension. This method is computationally intensive and therefore the analysis is restricted to MSAs that had 10 or more green buildings in 2010. We also computed the spatio-temporal clusters at the national scale by including all buildings irrespective of their location within an MSA. This is to identify supraregional clusters and spillovers that are likely to cross arbitrary regional boundaries. Computational considerations dictated that only circular windows are considered for analysis at the national scale.

These three methods provide different views of the same phenomena. The local Moran's I is an indicator of whether the clusters can be observed at the end of the study period, and where within a geography these are observed. While nearest neighbour distances reflect the clustering or dispersion within a region, the trends in the NND depict how the spatial clustering is changing over time and if spillover is indeed occurring. The scan statistic captures not only the adjacency in space, but also adjacency in time, pointing to economies of scale due to availability of qualified labour and building practices, among other factors.

4. Results

While urban counties[8] have the largest number and increasing share of the green buildings, it is mixed rural counties that have higher number of both LEED and ES buildings compared with mixed and urban rural counties (Figure 2). In 2010, LEED

Table 2. Clustering of green buildings within various MSAs at the end of the study period

MSA	*Number of tracts*	*Number of buildings*		*Clustered tracts*		*Average Number buildings/year*	
		ES	*LEED*	*ES*	*LEED*	*ES*	*LEED*
Los Angeles-Long Beach-Santa Ana, CA	2629	1020	348	18	66	10.8	2.6
Washington-Arlington-Alexandria, DC-VA-MD-WV	1016	561	398	10	36	14.4	5.6
San Francisco-Oakland-Fremont, CA	870	489	312	8	20	17	7.7
Chicago-Naperville-Joliet, IL-IN-WI	2052	439	346	11	30	10	4.8
Atlanta-Sandy Springs-Marietta, GA	690	419	206	14	34	7.3	3.1
New York-Northern New Jersey-Long Island, NY-NJ-PA	4483	414	328	22	94	4.1	1.9
Dallas-Fort Worth-Arlington, TX	1046	368	175	10	33	7.4	2.2
San Diego-Carlsbad-San Marcos, CA	603	353	145	16	21	7.3	3.3
Boston-Cambridge-Quincy, MA-NH	915	313	230	8	27	7	4.6
Minneapolis-St. Paul-Bloomington, MN-WI	746	310	114	7	30	8.1	1.8

and ES buildings were concentrated in less than 12 per cent of the 64 900 census tracts in the continental United States (approximately 5000 and 8000 respectively). Of these, only 195 and 362 tracts have at least 5 LEED and ES buildings respectively. Commercial green building is also a decidedly urban phenomenon as only 10 rural tracts outside MSAs have a single green building.[9] These preliminary descriptors suggest a strong concentration of green commercial buildings and lend credence to the hypothesis that these buildings tend to cluster both within metropolitan regions and across metropolitan regions.[10]

LEED buildings are more clustered than ES buildings. Using the statistical significance of Moran's I (at 10 per cent), approximately 1200 tracts are identified as clusters for LEED buildings, whereas only about 300 such tracts are identified for Energy Star buildings within an MSA. In large metropolitan areas, almost 20 per cent of the ES buildings are within clustered tracts, while around 50 per cent of LEED buildings within MSAs are in clustered tracts (Table 2). Given that there are more ES buildings than LEED buildings, this suggests that ES buildings are more spread out in an MSA and LEED buildings tend to be more clustered.

In many MSAs, the tract clusters of ES buildings are markedly smaller in number than clusters of LEED buildings at the tract level (Table 2). However, on average, there are more ES buildings within these clustered tracts than LEED buildings in their clustered tracts. For example, in the New York metropolitan area, on average, about two LEED buildings are in tracts that are clustered, whereas there are four ES buildings. In the Minneapolis region, even though there are only 2.7 as many ES buildings as LEED buildings, they are 4.5 times as concentrated within tracts; while only 7 tracts form ES clusters, 30 tracts form LEED clusters (Table 2). These 30 tracts form 7 different distinct clusters within the metropolitan region, while the 7 ES tracts form 2 different clusters. About 150 tracts form significant clusters for both ES and LEED. These tracts are located all across the country, with relatively higher concentrations on both coasts, with California having the highest number.

Possible explanations for these phenomena are real estate dynamics and the emphases of the certification requirements. Most ES buildings are of older building stock that have been retrofitted and their maintenance optimised, as opposed to LEED buildings which are usually of new construction. Because newer real estate activity tends to occur in clusters, it is very likely that LEED buildings are more heavily clustered in the exurbs, but less dense than ES buildings.

Given these differences, it is worthwhile not only to explore the differences in total numbers of clusters of different types of green buildings, but also their spatial arrangements (Figure 3). For example, in Seattle, the LEED clusters are located in the downtown, in tracts that cover the University of Washington and its vicinity (north of downtown) and in the Bellevue region (west of downtown) (Figure 3(a)). On the other hand, the ES clusters are predominantly in downtown and are a subset of the LEED cluster. Similarly in Atlanta, GA, four distinct LEED clusters are observed: to the north and west of the city centre, one centred on the Hartsfield-Jackson International Airport and the other in Alpharetta. The ES clusters are primarily in the north east and east of the city (Figure 3(c)). Similarly, in Washington, DC, the ES buildings are concentrated in the core of the city, which houses most of the federal buildings. The LEED clusters are more extensive, with distinct clusters observed in the central city as well as the more office and commercial districts of Northern Virginia, areas around Dulles International Airport and in Gaithersburg, MD (Figure 3(e)). These specific cases provide some evidence to support the earlier explanation of how real estate activity dictates where different kinds of green buildings are located.

While, it is useful to envision the current spatial pattern of the green buildings, we are also interested in the evolutionary path of green building clusters. To visualise this, we first characterise the relative distances of the nearest green buildings of the current year to the previous years (Figure 4). In general, in most of the MSAs, the latter part of the decade saw a dramatic spurt in the number of certified buildings. This is likely to be due to increasing familiarity with the certification process, increasing adoption of these labels as well as change in the required standards for LEED. Furthermore, the increase in real estate activity in the earlier part of the decade before the Great Recession also could have contributed to increasing certifications.

In Washington, DC, San Francisco, CA, and Atlanta, GA, around 2005 and 2006, new LEED buildings were being built farther from one another as well as from the existing certified buildings, suggesting that new clusters were being formed then. In the later part of the decade, by contrast, both interyear and intrayear distances decreased suggesting maturation and consolidation of clusters. In the New York, Boston, Chicago and Los Angeles regions, however, by-and-large the dominant trend is locating close to

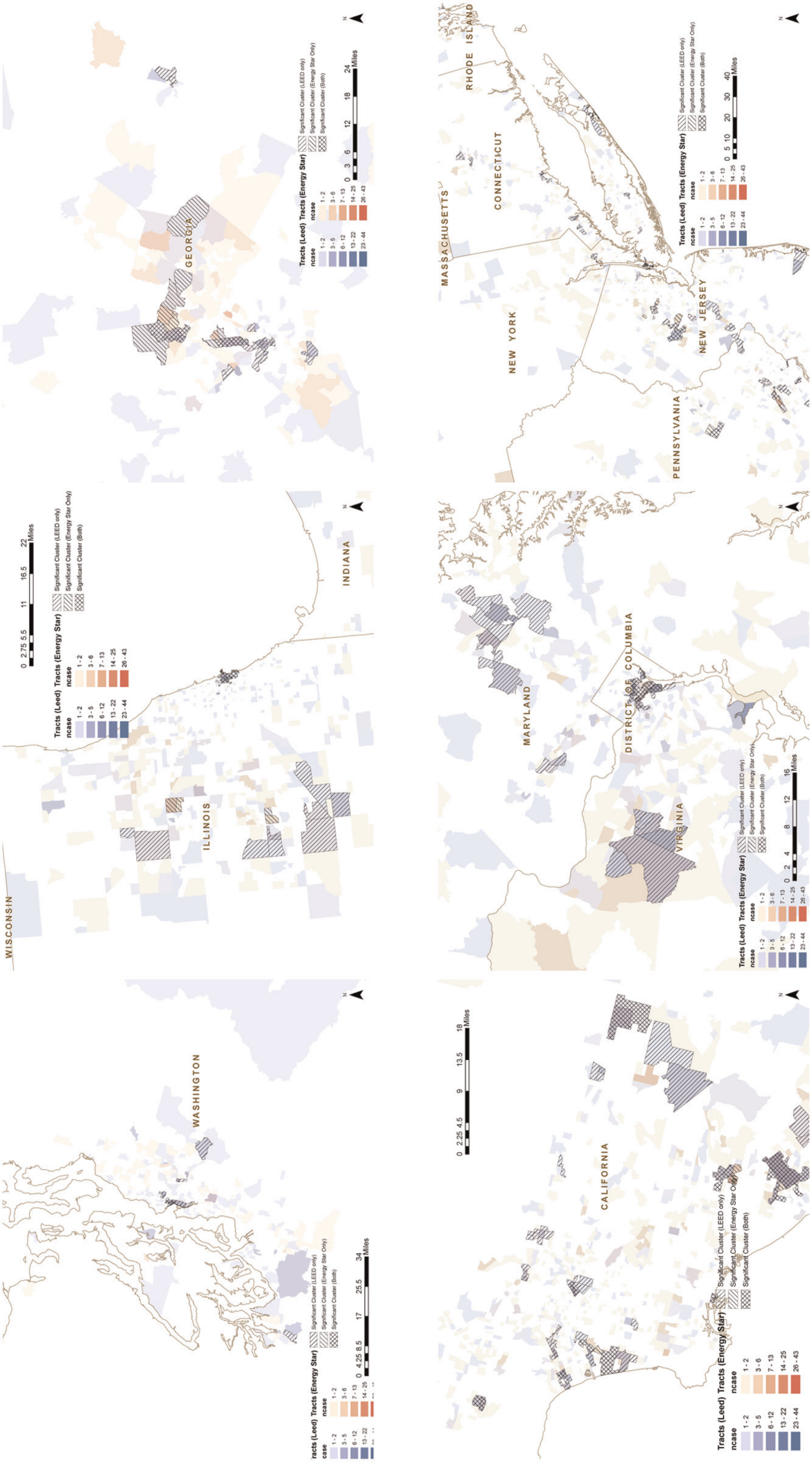

Figure 3. Spatial clusters of green buildings in selected regions.

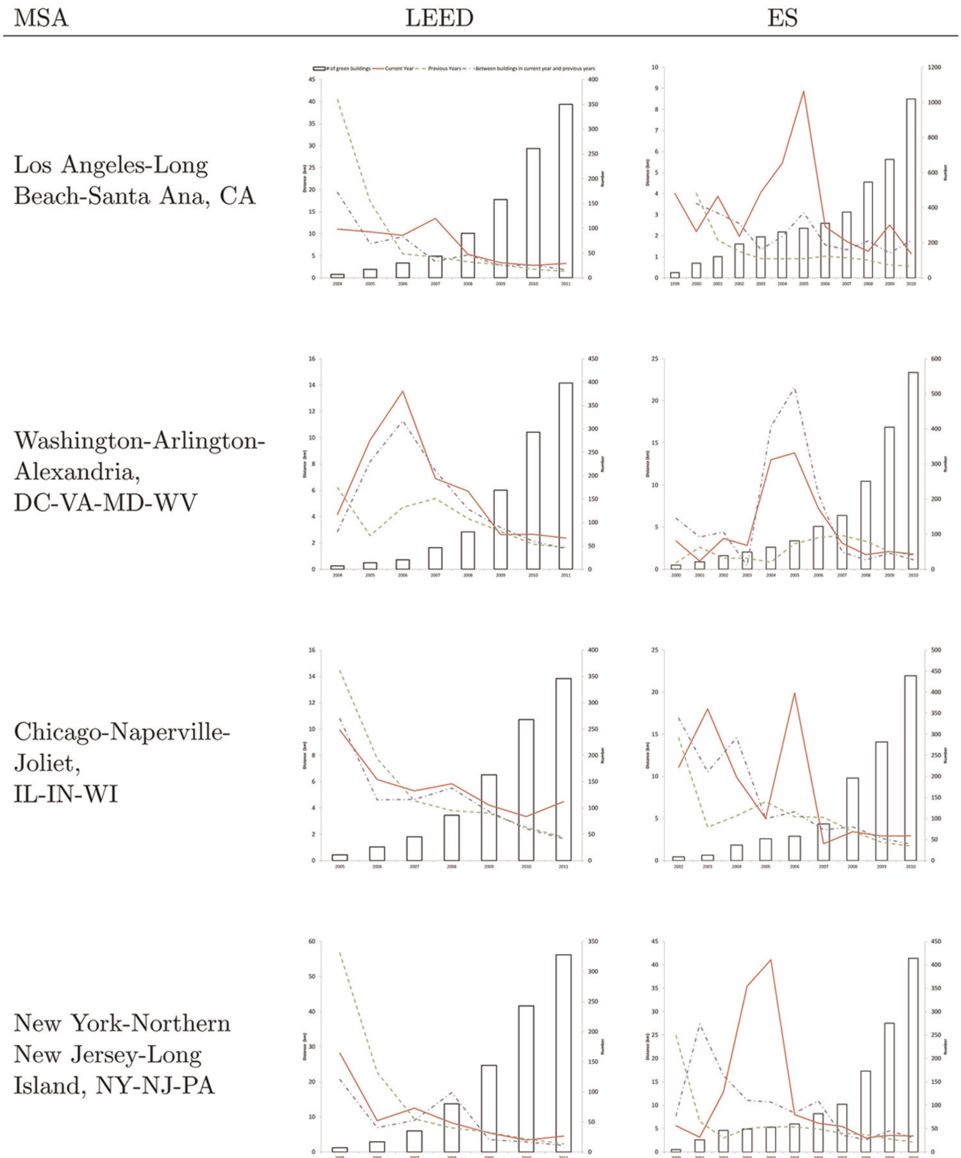

Figure 4. Continued

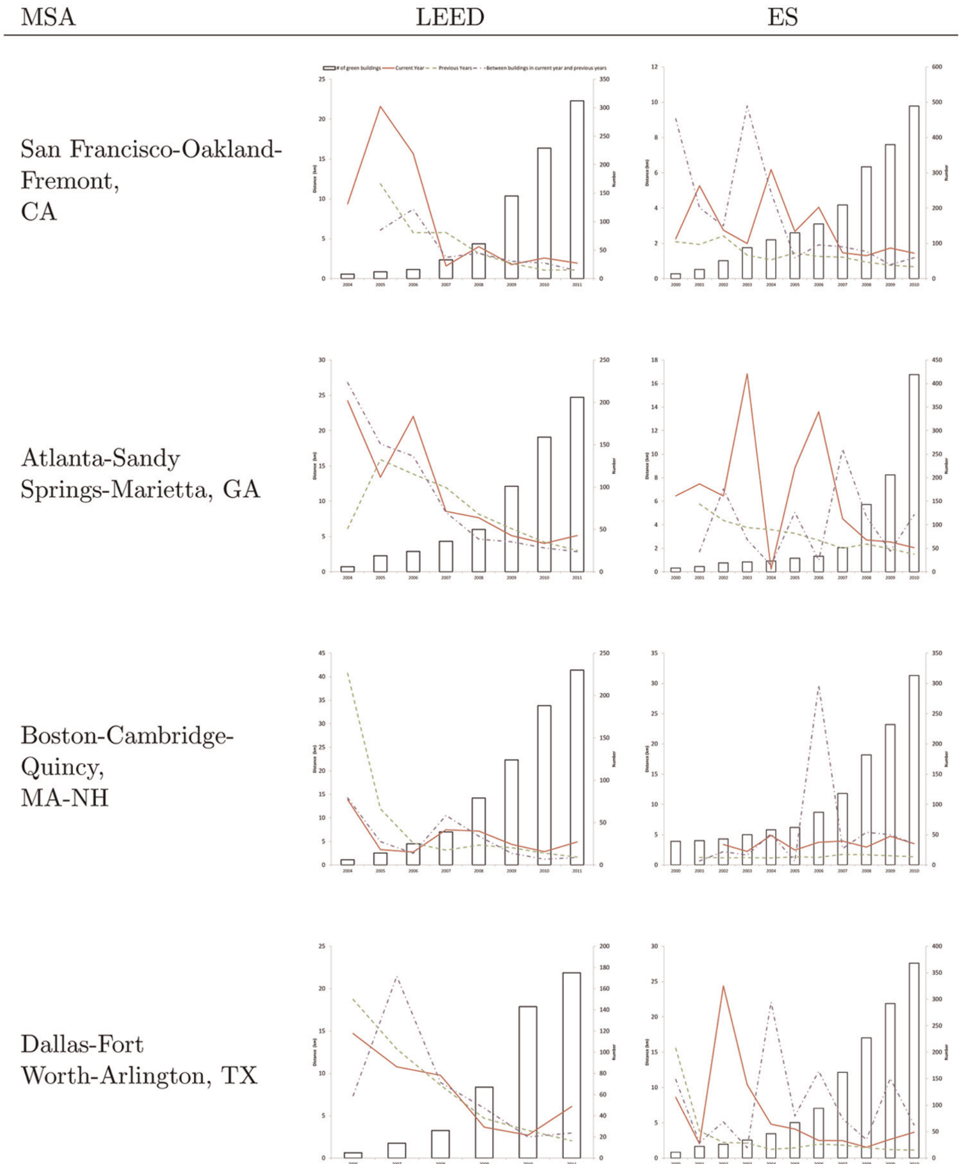

Figure 4. Trends in the nearest neighbour distances (solid line = current year, dashed line = cumulative, dot-dashed line = between current and previous) and cumulative number of green buildings (bars) in various MSAs.

one another as well as locating close to existing buildings. This suggests a spillover form of growth of LEED buildings.

The nearest neighbour distances for ES buildings exhibit a different pattern (Figure 4). The pattern of the distances appears cyclical. This suggests a pattern of leapfrog seeding of new clusters followed by their natural growth. An interesting case is Dallas-Fort Worth, TX. Since 2003, the new buildings that are being certified are located closer to one another. However, the interyear distance between the new buildings and previous buildings exhibits a cyclical pattern. This suggests the dispersed formation of new clusters.

While the patterns of distances are consistent across various regions, regional real estate characteristics are apparent in the scale on the y-axis. The Los Angeles and New York regions have a large distance range, whereas Chicago and San Francisco have much smaller distance ranges. In Los Angeles, the ES buildings are much closer to one another than LEED buildings, while the situation is reversed in the Chicago region.

The trends in the NNI suggest that, in general, MSAs with a large number of LEED and ES buildings have significant clustering throughout the study period. By 2011, the NNIs in the metropolitan areas that have the largest number of green buildings are well under 1. NNIs for LEED buildings have been in decline in most major metropolitan areas.[11] In New York, Boston and Chicago, the spike in NNIs between 2005 and 2008 is a reflection of the dramatic reduction in nearest neighbour distances in the previous time-periods rather than spatial dispersion (see Figure 4).

The NNI trends in ES buildings tell a different story. In general, there is significant clustering of the buildings within the MSA with indices well under 1. However, New York, Chicago and Washington experienced some increases in the index between 2001 and 2005. The dramatic trend is in Boston, between 2003 and 2007. In this time-period, while the intrayear distance among the new buildings remained low, the interyear distance dramatically increased (Figure 4) suggesting new cluster formation in this time-period rather than overall dispersion. A similar spike can be observed in New York, between 2001 and 2003. This is due to high intrayear distances in the new buildings. However, the interyear distance continued to decline suggesting the maturation of existing clusters.

The Kulldorf's scan statistic was used to identify the likely clusters at both national and within MSA scales. The significant clusters of LEED buildings at the national scale are in the Pacific Northwest between 2001 and 2006 (92 buildings), while the east coast clusters in the New York and Boston areas are relatively later, during 2008 (118 buildings). Another relatively important cluster was in the Pittsburg, PA, area between 2000 and 2005 (Figure 5).

Of the 347 likely clusters at the MSA level, 18 are statistically significant (10 per cent level). Interestingly, none of them is on the west coast (Figure 5). However, all of these significant clusters except one have fewer than 10 certified buildings and all are in the later part of the study period. Between 2004 and 2007, a LEED cluster containing 82 buildings formed in the area that spanned Newark, NJ, and Philadelphia, PA. Other substantively significant clusters include areas around Colorado Springs, CO, and Las Vegas, NV.

All the 13 likely clusters identified for the ES buildings at the national level are statistically significant. However, more often than not, these clusters spanned only one or two years. The largest cluster of ES buildings is around Washington, DC, spanning large parts of North Carolina as well (649 cases) from 2003 to 2006. Another significant cluster is in Texas with 171 cases in 2004. However, the more concentrated of the clusters are in Atlanta with 142 buildings in 2010, the San Diego, CA, region with 122 buildings in 2000, and in Tampa, FL, with 115 buildings in 2008.

Of the 496 likely ES clusters in MSAs, 134 are statistically significant (Figure 5). Unlike LEED, ES clusters are more evenly spread throughout the various metropolitan areas, although a heavy concentration can be seen in the north-east corridor. Over 30 of these significant clusters have more than 20 Energy Star certified buildings. These 30 substantively significant clusters are located

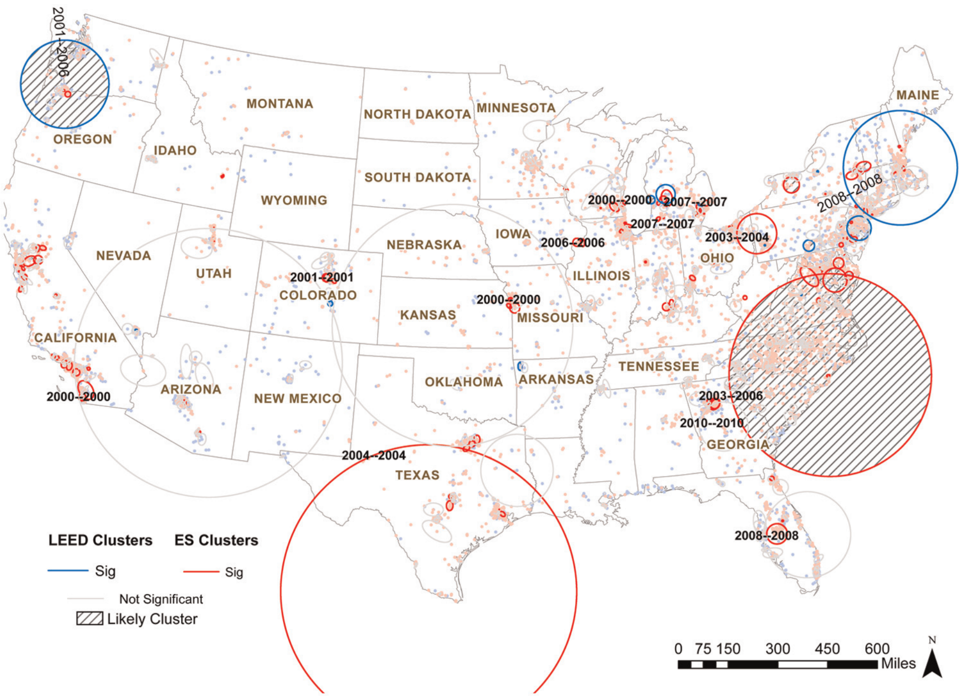

Figure 5. Spatio-temporal clusters of green buildings in the US.

mainly in California, Denver, CO, Dallas-Fort Worth, TX. However, smaller cities such as Louisville, KY, Milwaukee, WI and Grand Rapids, MI, have clusters with significant numbers. The largest cluster of 123 buildings in the Atlanta region was observed within a single year in 2010. However, only a minor drop in the NNI suggests that ES buildings are already heavily clustered in the region.

By combining the LEED and ES buildings, we can identify six clusters with over 100 buildings at the national level (Figure 6). They are primarily in the DC-MD-VA-NC region, the region in the Midwest encompassing Chicago, IL, Nashville, TN, and Columbus, OH, the outskirts of Tampa, FL. These clusters are essentially ES clusters (with mild shifts in radii and centre) suggesting the dominating force of the Energy Star certification at the national level. Of the 716 potential green building clusters at the MSA level, 157 are statistically significant. Of these, 59 clusters are newly identified as significant when both types of green buildings are considered. Clusters of more than 20 buildings are identified in San Antonio, Dallas, San Diego, Los Angeles and Portland.

5. Discussion and Future Work

The results point to a heterogeneous pattern of green building activity in various metropolitan regions. Overall, we find evidence that both LEED and ES buildings exhibit a clustered pattern. This analysis also shows that the process of clustering is more complex when viewed at various scales and over time. By-and-large, the metropolitan regions in the coastal US have dominated the green building market. Prior to the real estate market collapse, the LEED building activity had increased dramatically.

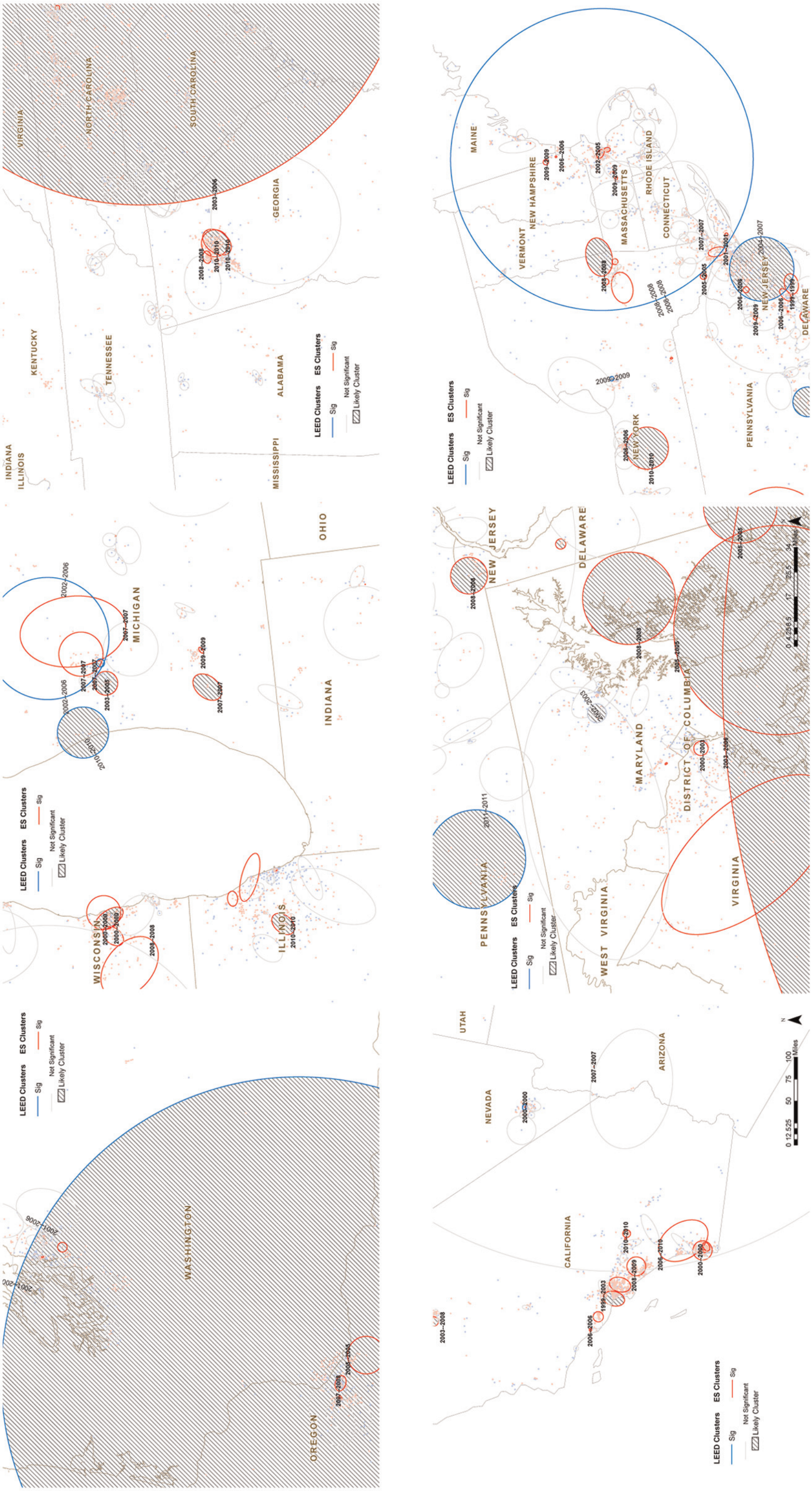

Figure 6. Regional spatio-temporal clusters of green buildings.

However, the Energy Star building certifications continue to rise with the possible increase in skills in building maintenance and certification practices. This points to different causal mechanisms at work that are enabling the adoption of different green building technologies.

While urban areas continue to dominate the green building markets, both LEED and ES buildings are becoming more common in mixed rural counties rather than mixed urban counties. Part of this could perhaps be explained by an increase in building activity at the fringes of urban areas. However, this does not explain why ES buildings are not becoming more prominent in mixed urban counties where there is a high concentration of existing buildings. Predominantly urban counties are driving the green building activity both for newer construction and for building maintenance.

In general, LEED buildings tend to be located much further away from one another, compared with the pattern within the ES buildings. The main reason for this is lower numbers of LEED buildings. Even when there are high numbers of census tracts that appear clustered for LEED compared with the ES, the concentration of LEED census tracts is significantly lower compared with ES buildings. Thus, ES buildings are much more concentrated within tracts and LEED buildings are concentrated across tracts in metropolitan areas. Overall, however, the trend in the past decade has been that both LEED and ES buildings are locating more closely to one another as time goes on. This suggests a contagion or spillover effect.

Another interesting finding is that different metropolitan regions experience different types of cluster formations. While some regions exhibit an organically growing cluster that is initially seeded, some regions have experienced dispersion and a coalescent pattern of cluster formation. The latter is much more apparent in the ES buildings than in the LEED buildings. This raises some important new questions about the scale at which agglomeration economies, and particularly those based on knowledge spillovers and skilled labour pooling operate (for example, neighbourhood/sub-market, metropolitan level, etc.),

The spatio-temporal pattern of cluster formation is also heterogeneous. While the LEED clusters formed relatively early in the decade in the Pacific North-West, clusters on the East Coast formed later. In the latter part of the decade, the LEED buildings on the West Coast were more spread out in time, even if they were located spatially closer to one another, whereas the East Coast clusters are formed by buildings that were both spatially and temporally proximate. On the other hand, ES spatio-temporal clusters are primarily spatial clusters as their duration is at most two years.

The absence of some green buildings from the dataset poses concern for the validity of the results. Some LEED buildings are certified but are not available in the public directory. Some buildings are built to the green building standards but do not go through the certification process. Some buildings perhaps operate at a much higher efficiency than Energy Star certification without getting the certification as the requirements are cumbersome. Therefore, the results presented in the paper should be considered a lower bound, even when this uncertainty cannot be quantified.

Part of the clustering of green buildings can also be explained simply by normal construction activity and the locations of non-residential buildings. To examine this, we performed a sub-analysis with data from North Carolina (NC). We used the unique firm locations from National Establishment Time-Series data for NC at the census-tract level as a proxy for the underlying population of buildings. In NC, of the 62/25 tracts identified as ES/LEED clusters using raw counts, 48 (77 per cent) of the ES clusters and 15 (60 per cent) of the LEED clusters were still identified as clusters once we accounted for the underlying distribution of buildings using an Empirical Bayes estimate. This suggests that the current analysis is relatively robust, while pointing to directions for future research that tease out the causes of green building activity.

5.1 The Determinants of Clustering: A Research Agenda

The patterns that have emerged are various combinations of dispersion, clustering and seeding. We argue that is important to understand the geography of the green buildings irrespective of the underlying geography of the non-residential sector. While it is clear that clustering is occurring, to support fully the implementation of green building practices, and ultimately to exploit their potential for energy savings, we need to understand more about the specific agglomerative forces at work at various scales. We close with a discussion of several hypotheses that seek to explain the causal mechanisms that drive the clustering and, ultimately, the broader implementation of energy efficient buildings. This study suggests a number of hypotheses for the causal mechanisms that are enabling or hindering green building activity.

Levels and spatio-temporal patterns of green building activity in a region are likely to be dependent on both demand-side and supply-side considerations. Regional economic structures that are skewed towards certain types of sectors such as services and research & development are likely to drive the demand and therefore the pattern of green buildings. Furthermore, in the US, these sectors are likely to attract highly skilled workers that prefer these types of buildings. Therefore, as Kok *et al.* (2011) suggest, the level of green building activity may be tied closely to the type and growth of the regional economy.

Specifically, the literature on industry clustering suggests that the pooling of labour with highly specialised skills is critical to sustaining growth (see Florida, 2002; Porter, 2000; Doeringer and Terkla, 1995). If the emergence of significant green building clusters coincides with the location of skilled workers in building engineering and specialised construction trades, then training programmes and other workforce development policies may have an influence on the expansion of certain clusters. Thus, the first hypothesis to test is whether the geography of green buildings follows concentrations of green building professionals (for example, LEED certified architects, contractors who have experience with new technology). A related question is whether there are important threshold effects such that, once the concentration of skilled workers reaches some critical mass, the number of green buildings increases non-linearly.

Secondly, clustering may also influence the ultimate cost of green building through the agglomerative effects of learning and tacit knowledge exchange among contractors and architects. Thus it is crucial to explore further the issue of thresholds in green building clusters (i.e. does the number of projects ‘take off’ after an initial set of projects are completed). Lastly, the finding (in some metro areas) that clusters evolve from an initial core to multiclusters (for example, in suburban markets) indicates that competitive rivalry effects may help to advance green building construction. This ‘intracluster’ competition among actors within an industry cluster is one factor stressed by Porter (2000) in defining competitive clusters. For example, once some portion of a suburban office sub-market ‘goes green’, are there competitive dynamics among developers and landlords that may speed up green building in nearby properties? Thirdly, as the literature on industry clusters and new industry formation suggests (see Cooke, 2001; Saxenian, 1994; Storper and Walker, 1989), knowledge spillovers are likely to play a key role in explaining the diffusion of green building practices throughout a metropolitan area and across regions. However, we do not have a good sense of the mechanism through which such knowledge flows from some actors to others. For example, do contractors or developers develop knowledge of how to put green building practices into place through direct experience, by working on a project outside their home region, or through formal training programmes? The itinerant nature of construction projects—whereby different sets of skilled professionals and workers coalesce around a given project only to dissolve after completion—suggests that studying networks of green building professionals and firms is a good place to observe the process of knowledge spillovers.

Lastly, the green building sector has, since its inception, been closely associated with government policy to promote energy efficiency. Therefore, the final hypothesis is that public incentives and mandated building practices (for example, codes and regulations) should be a strong driver of green building clustering. For example, if a given city within a metropolitan area offers strong incentives to build LEED certified buildings, we would expect to observe a cluster of green buildings there. However, while public policy may lead to clustering in this direct way, it is also possible that public policy may play a subtler, yet powerful, role in market transformation. In other words, can incentivised green development reach a critical threshold in certain markets such that, after a point, contractors and customers in the market have shifted their production methods and preferences towards more energy efficient buildings? To answer this question, we would need to understand how public incentives and mandates impact the patterns of green building at a variety of geographical scales.

Ultimately, in finding significant evidence of the clustering of green buildings and divergent patterns in the diffusion of green building clusters over time and across scales, this paper provides researchers with a rich empirical description, which is ripe for future research. Given the potential for green buildings to reduce energy use, efforts to promote them will form a crucial part of the strategies that cities and regions develop to promote a more energy efficient future. A better understanding of the mechanisms behind the clustering of green buildings can only improve such policies.

Funding

This research received no specific grant from any funding agency in the public, commercial or not-for-profit sectors.

Notes

1. See: www.usgbc.org/DisplayPage.aspx?CMSPageID=1852 (accessed 29 December 2011).
2. See: www.cpuc.ca.gov/PUC/energy/Energy+Efficiency/eesp/ (accessed 31 January 2012).
3. See: www.energystar.gov/ia/business/government/State_Local_Govts_Leveraging_ES.pdf (accessed 29 December 2011).
4. See: www.energystar.gov/index.cfm?fuseaction=qhmi.showHomesMarketIndex (accessed 31 January 2012).
5. See: www.energystar.gov/index.cfm?fuseaction=labelled_buildings.locator (accessed 4 December 2011).
6. See: www.gbci.org/main-nav/building-certification/registered-project-list.aspx (accessed 12 December 2011).
7. See: www2.census.gov/cgi-bin/shapefiles/national-files (accessed 25 November 2011).
8. For the county typology, see Isserman (2005).

9. Nevada County, CA, and Payne County, OK, have the tracts with largest number of LEED and ES buildings that are outside MSAs and are within the Micropolitan areas.
10. In this paper, we only discuss some salient results, although we provide the complete set of results in an on-line appendix (see: http://maps.dcrp.unc.edu/nkaza/?page_id=631).
11. We only demonstrate the first-order nearest neighbour indices in this paper. Multidistance cluster statistics such as Ripley's K function and Getis G function were also calculated but not discussed because visualisation of the evolution of these metrics for a large number of regions is not practical here. However, both these functions confirm the results of the first-order nearest neighbour distance metrics.

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