Annals of the American Association of Geographers
Routledge
Taylor & Francis Group

Cities as Coral Reefs: using rugosity to measure metabolism across the urban interface

Journal:	*Annals of the American Association of Geographers*
Manuscript ID	AN-2017-0689.R3
Manuscript Type:	Revised Manuscript
Manuscript Category:	Cross-cutting/Multiple
Key Words:	edge effects, urban growth, multifunctional agriculture, urban planning

Title: Cities as Coral Reefs: using rugosity to measure metabolism across the urban interface

Abstract:

Drawing from ecology, this research translates the metric of rugosity to urban and agricultural studies. Typically used to estimate the topography of complex ecosystems, rugosity is an important edge proxy and provides simple correlates for total ecosystem metabolism, growth and resilience. This research uses the perimeter of Urban Areas to estimate urban rugosity. The relationship between urban rugosity and vitality of both urban and peri-urban agricultural land-uses is empirically explored through spatial multivariate analysis. Findings show that longer urban interfaces are associated with greater population growth and higher agricultural sales. The resulting county-level model predicts that for every kilometer of urban interface, the annual agricultural sales increase by ~$230,000. Urban areas with interfaces less than 65km in length tended to lose population, and every kilometer of urban interface corresponded to a county population gain of roughly 250 people over the 2000-2010 time period. By showing a statistically significant positive relationship between the urban interface length and both population gain and agricultural productivity, this research lays the groundwork for future studies investigating how longer, less concentric urban interfaces may support the long-term vitality of both urban and agricultural areas alike.

Keywords: edge effects, urban morphology, urban planning, multifunctional agriculture, urban growth, urban ecology

Introduction: toward a shared agricultural and urban metabolism

Despite a deep and rich scholarship focused on the shared metabolism of agricultural and urban areas, scholars and practitioners rarely acknowledge the form of the Peri-Urban Interface (PUI) between the two land-uses as important to this metabolism (for review: Brinkley, 2017a). By applying methods used to measure metabolism in ecosystems, this research tests the explanatory potential using an urban edge proxy to measure the vitality of both urban and agricultural systems. The addition of a simple edge proxy is expected to further theoretical and empirical insights into planning for the sustainable development of urban and agricultural areas in tandem.

The co-evolution of farms and cities occurs at the urban interface as cities grow outward and farmland correspondingly transitions (Brinkley 2012 and 2017a). Because of the historic interdependence of cities on their peri-urban farms (Sorokin and Zimmerman, 1929), Jane Jacobs (1969) famously argued that cities invented agriculture. Market-oriented farming and animal husbandry fed growing cities and freed up human intellect for other industrial pursuits (Taylor, 2012). Others have stated that agriculture enabled cities (Smith et al., 2014; Cronon, 1991), which developed only in locations where fertile ground and a ready supply of water would support growing food for dependent urban populations (Bogue, 1956). Vitiello and Brinkley (2014) have shown that historic cities and their attending farmlands were often planned in conjunction with one another with explicit acknowledgement of the interdependencies and desired distances between urban consumers and food-producing lands.

The shared metabolism between urban and farmlands continues beyond historic underpinnings despite a now globalized food system. Brueckner and Fansler (1983) find that US cities are less expansive in regions where farmland has greater value. Similarly, Angel et al (2005) find that doubling the value produced per hectare results in a 26 percent decline in land conversion to urban uses when assessing the urban growth of 90 global cities. To offset land rent costs, peri-urban farms generate greater revenues per acre with specialty crops and dairy occurring closer to cities and grain production further away as first noticed by von Thünen in 1826, and later empirically verified (Hart, 1976 and 1991). More recently, scholars have added that farms near urban areas become multi-functional (Zasada, 2011) in order to supply a wider array of goods and services to nearby markets. In addition to food production, peri-urban farms have adapted ancillary programs for energy, waste management, recreation, and education to remain financially solvent near expanding metro areas (Brinkley, 2012, 2017a). Higher peri-urban land values restrict urban growth, promoting higher density development, which is, in turn, associated with a myriad of outcomes from health through greater walking (Oakes et al., 2007) to innovation through job clustering (Carlino et al., 2007).

Newly developed “Fringe Theory” (Brinkley 2017a) elaborates upon the ways that urban form shapes the fortunes of both urban and agricultural lands. This research tests Fringe Theory by exploring the relationship of the PUI to urban and agricultural vitality, furthering the application of ecological concepts to social phenomenon (Hiner, 2016) and providing insights into understanding and planning for sustainable development. An overview of current knowledge of urban and agricultural metabolisms in political ecology and complex systems science is reviewed below to inform variable selection for later modeling.

Vital parameters for metabolic flows

This research both informs and is informed by political ecology. Newell and Cousins (2015) employ bibliometric review of the three main theories and methods that social and physical scientists have employed in understanding and quantifying three types of urban metabolism. First, Marxist urban political ecology is typified by qualitative measures focused on the flow of capital, power structures and politics in shaping urban social form and function (Swyngedouw and Heynen, 2003; Swyngedouw, 2006). Second, drawing from Burgess (1925) and the Chicago School of Sociology, Industrial Ecology focuses on physical material flows (Baccini and Bruner, 1991; Baccini 1996 and 1997) and life cycle assessments to predict and explain social structure and physical form (Wolman, 1965; Ayres and Kneese, 1969). Third, Urban Ecology draws from Odum’s (1968) early work on complex systems. Urban Ecology seeks to model the shared non-urban and urban functions as the ecology of a system, an ecosystem, representing a complex assemblage of organisms interacting with the physical environment (Golubiewski, 2012). In all of the above theories, a city with a thriving metabolism should continue to grow in the population it can support whereas cities with failing metabolic flows will shrink in population.

Empiric models build on the above theories by denoting how scale changes urban metabolism (Bettencourt et al, 2008). Physicists argue that cities follow metabolic sublinear scaling laws similar to living organisms (West et al, 1997; Lobo et al, 2013). These physical scaling laws hold true over systems ranging from animal circulatory, respiratory, renal, and neural systems, to the systems that supply food, water, power and information to human societies (West and Brown, 2005). In much the same way that an animal's size can predict its heart rate and caloric needs, city size and growth correlates with resource metabolism rates and economic output. For example, cities with larger populations tend to need less energy and material infrastructure per person, from roads to sewer lines (Bettencourt, 2007). Where urban scale can predict metabolic pace, it cannot predict growth or death as it would in a living organism.

Analogous studies in agriculture use input-output-based economic modeling to identify farming metabolisms based on local material sourcing, job creation, and regional capture of capital resulting from sales (Pender et al., 2014; Christiansen and Hardesty, 2016; Schmidt et al., 2016). Unlike their urban counterparts, metabolic agricultural studies are more closely aligned with measurements used in complex adaptive systems ecology which emphasizes modularity, diversity, redundancy and nonlinear feedbacks as the key components to predicting total ecosystem growth, resilience, and death (Levin et al., 2013). For example, the diversification of farming practices and products coupled with interpenetration of urban land-uses spurs more diversified household income streams where households shift between agricultural and industrial jobs (Rigg, 1998). In this sense, the reported value of agricultural products may not always predict thriving agricultural economies, but high land rents coupled with longer farm tenure does.

The metabolic interface: the importance of form to function

An important deficiency in the above political ecology theories and empiric metabolic studies reveals a significant deviation from the earliest biomedical studies of metabolism. Urban and agricultural studies do not explicitly acknowledge the metabolic interface through which services and goods are absorbed. In traditional medical, and even ecological, metabolic studies, form alters the flow of materials. Early studies of metabolism explicitly identified the functional interface across which nutrient exchange occurs as crucial to understanding health, disease, growth and resilience. Even where researchers focus on the farm-city as an ecosystem, studies often lack an edge proxy at which the urban area is distinct from its surrounding environment. Perhaps as a result, urban metabolic analyses are time-consuming, lack easily comparable metrics, and are rarely conducted over multiple cities for contrast. Nonetheless, cross-sectional multi-city studies are necessary in forming a deeper understanding of how cities and agriculture develop within their regions (Meinel and Winkler, 2002; Angel et al., 2005; Angel et al., 2012). The theoretical and empirical deficiency in a practical measurement of the metabolic interface hinders progress toward the above goals.

By grounding the study of farm and city metabolism in ecosystem studies, this research derives and explores the importance of a spatial indicator for metabolism. The empirical focus is expected to help inform practice, particularly as urban planners and developers manipulate the urban interface. For example, planning greenways into urban areas is expected to help ecosystem services penetrate to areas of demand (Ahern, 1995; Linehan et al., 1995; Fabos, 2004; Turner, 2006). Similarly, housing values are higher on the urban periphery near farmland (Bergstrom and Ready, 2009). Indeed, scholars increasingly acknowledge that the physical flows of material involved in urban metabolism are socially governed (Heynen et al., 2006). Thus, a focus on identifying not only the metabolic boundary, but its governance (Brinkley, 2018), is important to understanding how policies guiding form might constrict or engender metabolic flows. The supply from such metabolic flows impact neighborhood socioeconomics and can contribute in aggregate to understanding total resource efficiencies and our planetary boundaries (Rockström et al., 2009). But first, how can researchers practically measure the PUI, and how does the PUI correlate with urban and agricultural vitality?

Coral reef interfaces and urban interfaces

This research adapts metrics used in empiric studies of coral reef ecosystem metabolism and growth. A coral reef offers an analogy for the city. Similar to cities, coral reefs are complex, relatively static, yet growing, living structures which provide a large variety of habitat niches for diverse and mobile populations (Goreau and Goreau, 1959). While reefs occupy only 0.2 percent of the ocean, they are home to a quarter of all marine species and play an important role in stocking the ocean with fish (Friedlander and Parrish, 1998). Correspondingly, over half the human population lives in cities, occupying less than 3 percent of the total land area (Liu et al., 2014). Surrounding metropolitan area farms account for significant food production on minimal land. In the United States, "urban influenced counties" contain only 20 percent of the total farmland, but produce over 90 percent of all fruits, nuts and berries; 80 percent of vegetables, 70 percent of dairy, and 50 percent of poultry and eggs (2012 Census of Agriculture, USDA Economic Research Service).

In both cases, the structural complexity of the interface, termed *rugosity*, is expected to engender more use-niches and greater metabolic exchange (Brinkley, 2017a). More complex topographies in coral reefs correspond to greater biodiversity and larger populations of reef creatures (Chapman and Kramer, 1999; Edinger and Risk, 2000; Alvarez-Filip et al., 2009). Figure 1 provides a simplified birdseye view of two urban areas; the urban area on the left has a higher rugosity. This research asks if a higher rugosity PUI similarly results in greater population growth and higher value of agricultural production.

A reef's complex topographic structure is often estimated by transect. A flexible chain is laid atop the reef, and the degree of variation from a straight line is calculated. While there now exists light-scatter, sonographic and three-dimensional topographic reef mapping programs with increased scales of resolution, the analog rugosity measurement method is still widely used in monitoring because it is simple, inexpensive, and effective (McCormick, 1994; Shumway et al., 2007). This research applies the ecological concept of rugosity from coral reef interface and metabolism studies to the PUI to test its usefulness.

In this analogy, the city perimeter is analogous to a coral reef's rugosity. As with the reef analogy, there are numerous other intervening populations and environs that bound the structure of a city's edge and shape its growth and transition. In many instances, suburban developments, wildlands, forests, lakes and exurban rural residential developments provide a buffer between agriculture and urban areas. Just as reef topography offers an estimate of a thriving marine ecosystem, the rugosity of the urban interface may offer a proxy for the shared metabolism between regional farms and their cities. Similar to a coral reef, a greater degree of structural complexity at the urban interface is expected to create multiple niches. On the urban side, these niches could correspond with greenways and ecosystem services, generating amenities such as viewsheds. On the non-urban side, higher rugosity may correlate with more niches for multi-functional agriculture and increased flow of farm goods and services to urban markets. The resulting metabolism across a high rugosity interface is expected to grow both urban and agricultural areas alike while providing increased resilience to economic and environmental exchanges (Brinkley, 2017a).

[insert Figure 1]

Early research on the PUI by Sokolow (2003) used maps generated by the Farmland Mapping and Monitoring Program (FMMP) of the California Department of Conservation to compare California's urban area outlines in 1988 and 1998. Sokolow (2003) found that urban areas were bordered by 17,301 kilometers of agricultural uses, and "cropland edges" in California concentrated in counties with the highest farm market values and most of state's prime farmland. Sokolow (2003) concluded that too little was known about urban-agricultural edge effects. This research expands on Sokolow's (2003) efforts with a national dataset.

Methods

First, a measurement of the PUI is determined. Second, inclusion criteria limit study counties to those with significant agricultural and urban land-uses to focus on the shared metabolism between both land-uses. To inform later regression analyses, the first phase of the study includes descriptive and inferential statistics on study county data to compare conceptual variable covariance and spatial autocorrelation. Covariance is further investigated in paired t-tests on counties with similar populations and farm acres, but differing lengths of PUI, to understand correlates of agricultural vitality. Last, stepwise spatial regression identifies associations between the PUI and agricultural production.

Determining an Urban Interface Measurement

For practical ease of use in replicability, this study proposes a simplified rugosity metric based on the outline of census-defined Urban Areas (UA). Urban Areas (UA) in the United States are defined by the U.S. Census Bureau as contiguous, densely settled census block groups (BGs) and census blocks that meet minimum population density requirements (1000 people /sq mi or 390 ppl/km^2), along with adjacent densely settled census blocks with a density of at least 500 people/sq mi (190 ppl/km^2) that together encompass a population of at least 50,000 people. UAs are delineated without regard to political boundaries. The granularity of the urban interface measurement is based on the outline of U.S. census blocks. The dataset covers the 50 States plus the District of Columbia within United States.

To compare the rugosity measurement suitability with an established metric in current geography and landscape literature, this research includes Thinh's (2001) *jaggedness degree,* which measures the concentricity of urban form. Where *jaggedness degree* is most often used in understanding urban growth, land conversion and suburban sprawl, this study assesses both urban rugosity and *jaggedness degree* as a proxy for the complex morphology of an urban area in relation to the functionality of its surrounding farmland and population growth. An important distinction between *jaggedness degree* and rugosity is that a small, but highly non-concentric UA can have the same *jaggedness degree* as a large, but highly non-concentric UA. *Jaggedness degree* refers only to concentricity, whereas rugosity is measured by the total PUI length.

Geographical Information Systems and the ArcMap "sum" tool were used to summarize the UA perimeter length (P) and Urban Area (A) in each county using the U.S. Census UA shapefiles. *Jaggedness degree* (Thinh, 2001) was calculated with the following equation: $P/(2\sqrt{\pi A})$. A score of "1" indicates a perfectly concentric urban area. *Jaggedness degree* and UA perimeter length measurements are used in subsequent statistical correlations using the national census and agricultural data set to understand significant relationships and determine a meaningful urban rugosity measurement.

Study County Selection

Just as reef ecologists limit the scope of their studies to reef-associated organisms, this study focuses primarily on urban-influenced areas using census-defined Metropolitan Statistical Area (MSA). MSAs are defined by the U.S. Office of Management and Budget as geographical regions with a relatively high population density at their core and close economic ties throughout the area. MSAs are comprised of a core county of with a city of 50,000 or more people and adjacent counties with more than 20,000 people that have strong economic ties to the core county. Most farmland preservation literature further demarcates peri-urban agriculture by the value of production, including only counties with annual sales greater than $50 million in farm products (Sorensen et al., 1997).

In building from the political ecology understandings of urban metabolism presented in the introduction, this study employs the county-level unit of analysis. County-level data is replicable, easily accessed in national datasets, and rich in social and economic context. The county plays host to a variety of political conflicts important to Marxist Urban Political Ecology, Industrial Ecology and Urban Ecology understandings of urban metabolism. County government designates where undeveloped land and infrastructure is placed, and also arbitrates residential complaints over nearby farming and development practices (Walker and Hurley, 2011). The county is also often the governance framework for many agricultural economic development outreach organizations, such as the Farm Bureau, County planning agencies and offices of USDA's Farm Service Agency. Moreover, the US Census of Agriculture provides county-level agricultural data. Conducted every fifth year, this census allows comparison of several measures of agricultural activity per county from 1997 to 2002 and 2007 editions. After the National Agricultural Statistics Service took over responsibility for the Census of Agriculture from the Commerce Department in 1997, sampling procedures changed so that more farm operations were included than possible under previous procedures. For this reason, agricultural census data is only comparable from 1997 and onward, limiting more retrospective analysis. National regression data is based on 1997, 2002, and 2007 data to assure uniformity in collection method and a comparative timeframe for population census data.

Counties were selected based on the following criteria: a county must be in a 2000 Census defined Metropolitan Statistical Area (MSA), intersect a 2000 Census defined Urban Area (UA), and have total 1997 Agricultural Census commodity sales over $50 million. There are 1184 counties in MSAs, of which 1130 border an urban area, and 483 of these have agricultural sales over $50 million. The 483 remaining counties (Figure 2) represent a collection of counties engaged in peri-urban agriculture. Study counties exhibited similar population and agricultural production profiles to the national dataset, but differed in that they did not capture many of counties with less than 50,000 farm acres (nearly 25 percent of US counties, see Table 1) due to the $50 million imposed floor. The 483 selected counties were used in subsequent correlation, t-test and spatial multivariate regression analyses.

[Insert Figure 2 here]

[Insert Tables 1 and 2 here]

Descriptive and Applied Vital Statistics

This research employs the concept of vital parameters to explore the shared historic and current interdependence between urban and agricultural lands. Because farmland conversion is spurred by declining agricultural profitability (Angel et al., 2005), agricultural commodity sales and total acres in active farming offer indicators of agricultural vitality. For urban areas, population gain is an indicator of urban vitality, considering its association with migration patterns, housing development and related job market opportunities (Arrow et al., 1995; Ravenscroft, 2000).

To better understand how rugosity relates to urban and agricultural vitality, UA perimeter length and *jaggedness degree* calculations are spatially joined by county with USDA Agricultural Census data (1997, 2002, 2007), US Population Census data (2000, 2010), home state, region, Economic Research Service Natural Amenity Scores (2000), and County Typology (2004) codes. The above datasets offer explanatory variables and correlates for both agricultural and urban vitality. For example, amenity scores provide county-level data on the average winter temperatures, hours of sunlight, and water availability. Such variables may be important for both population dynamics and agricultural production. Similarly, the 2004 County Typology codes classify all U.S. counties according to six non-overlapping categories of economic dependence (eg. mining or recreation) and seven overlapping categories of policy-relevant themes (eg. persistent poverty) that may influence population dynamics and agricultural vitality. Please see Table 2 for a full list of conceptual variables employed in spatial autocorrelation and covariance analysis.

Inferential statistics were computed to explore the relationships between each of the explanatory variables and the rugosity measurements. Pearson correlation statistics are used to measure collinearity and help to later limit use of co-linear dependent variables in regression models. Only correlates over 0.5 are reported. Spatial-autocorrelation of variables was tested using Moran's I to reveal regional patterns ($p = < 0.001$) in GeoDA (GeoDa 0.9.5-I, Anselin, 2003b; Anselin et al., 2006). Data from select variables are used to explain later exclusion or inclusion in regression models.

To further understand the relationship between farmland production and PUI, a paired t-test assuming unequal variances was employed on 236 counties. Counties were paired based on statistically similar population and farm acres, but significantly statistically different measures of rugosity and *jaggedness degree*.

Multivariate spatial regression of urban perimeter length against commuting population, farm sales, and farm acreage at the county level provides a spatial look into the association between land in farms, the value of agricultural production, and urban morphology. State variables help control for fixed effects that could be due to specific policies or geographies.

To achieve the most normal distribution, a distance weights matrix was utilized based on the inverse distance between counties. The threshold distance obtained (using Euclidean Distance) was 405km, representing the minimum distance required so that each observation had at least one neighbor (Anselin, 2003a). The residuals from ordinary least squares (OLS) regression for spatial autocorrelation were tested using a Moran's I test with 999 permutations. In each regression reported in the findings, a test of the residuals using Moran's I indicated that no further spatial error dependence occurred.

In combination with OLS regression, spatial error and spatial lag models employed the same distance weights matrix. Lagrange multiplier (LM) diagnostics and their robust forms (Robust *LM*) are employed to differentiate between the form of spatial dependence (spatial error or spatial lag) and because Moran's *I* is inappropriate in the presence of heteroskedastic or non-normally distributed errors (Anselin and Rey, 1991; Anselin and Florax, 1995; Anselin et al., 1996; Anselin, 2005). The Jarque-Bera statistic was used to test the assumption of normality. The spatial multivariate regression is presented step-wise to verify coefficient signs and magnitudes in relation to control variables.

Limitations

Future iterations of this research may wish to test alternate measures of the PUI beyond the outline of UA. For example, future studies could use alternate definitions of UA to derive rugosity measurements based on the outline of impervious surface area, nighttime skylights, or three-dimensional population measurements similar to a topographic coral reef surface. In addition, the error term in the model indicates that there are likely omitted variables in the model. Future research may wish to uncover such omitted variables or test other explanatory variables for their fit.

The analysis presented in this research is primarily focused on agriculture in relation to urban form for two main reasons. First, agricultural production is tightly correlated with urban growth, urban form and land-use control (Angel et al., 2005; Brinkley, 2017 a and b). Second, the input and output basis for agricultural vitality is clearly understood and measured with USDA census data on inputs (fuel, fertilizer, wages) and outputs (value of land and buildings, value of agricultural products). This juxtaposes understandings of urban vitality where underlying inputs (jobs, company diversity) and outputs (population growth, gross domestic product) are highly debated (Storper et al., 2015; Jacobs, 1985).

Last, the time period of this study is chosen to limit the effects of the 2007 and 2011 financial crises which would impact population growth and land value for urban and agricultural communities. Future research may wish to undercover how various urban morphologies and their attending metabolisms fared before, during and after under the stress of financial market collapse. Future studies, for example, could include the 2012 agricultural census to cover the financial crises years and determine correlations between rugosity and resilience to economic market stress. Indeed, reef resilience directly correlates with reef rugosity (Hughes et al., 2003). Urban rugosity may similarly correlate with urban (and agricultural) resilience to shocks.

Results and Discussion: Measuring the Urban Interface and its Influence on Agriculture

Cities provide reef-like biodiversity hotspots for agriculture. Metropolitan area farms produce more value with less land than the national average and are more likely to focus on vegetable and fruit production. For the selected study counties, the figures are more impressive with a greater number of farms (26 percent of all US farms) producing more sales (34 percent of all US farm sales) on less land (15 percent of all US farmland). Natural growing parameters (hours of sunlight, temperature and water availability) did not correlate with agricultural sales (Figure 3). While total value of land and buildings on farms correlated with sales (0.87), when averaged on a per acre basis, the value of land and buildings correlated (0.5) with rugosity and not other urban variables, such as population or *jaggedness* (Figure 3). That cities provide the scaffolding for farming economies is lent credence by spatial observation, but this only partly explains the spatial autocorrelation in variables and covariance across variables.

Covariance and spatial autocorrelation, particularly in agricultural variables, reveal the complexity in forming an understanding of agricultural vitality and shared farm-city metabolisms. Before deriving urban and agricultural vitality variables, it is helpful to orient to specialized peri-urban agriculture typologies that occupy different geographic niches. Product, price, and farmland area are highly heteroskedastic (not normally distributed) and spatially auto-correlated, indicating coarser, regional patterns in market niches and diversity of operations. Fruit and vegetable production showed statistically significant spatial-auto clustering (Moran's I $p = < 0.001$), concentrating largely in California and Florida. Similarly, while crop and vegetable sales did not correlate with any of the livestock sub-categories, fruit sales correlated with dairy (0.5) indicating co-location of these industries as supported by von Thünen's agricultural land-uses paradigm where produce production occurs closest to cities, and livestock and grain production occurs further away (Thomas and Howell, 2003; Figure 3).

Animal agriculture production occupied other geographically distinct areas of the county (Figure 4). Hog sales spatially autocorrelated largely in the Midwest and North Carolina; dairy in California, the Upper Midwest, and the Northeast; and poultry in the South and Southeast (Figure 4). Total hog and poultry sales did not correlate with other variables, likely due to such extreme spatial autocorrelation. Overall, commodity sales highly correlated across years, indicating that counties exhibit relative stability in production type and expected sales according to their geographic niche. This combination of temporal, spatial, and co-variant data help further inform later spatial multi-variate methods by justifying the use of a single time period of data, while limiting use of spatially auto-correlated and covariant variables when not needed as controls.

The extreme ranges and regional variations in farmland products, sales, auxiliary farm operations and farmland loss further highlight the difficulty in describing average attributes of farm vitality, typology and shared agricultural and urban metabolisms. Annual agricultural commodity sales per acre were as low as $30 in Meade County, South Dakota, and as high as $5,900 in Suffolk County, New York. The income from commodities compared to the expense of operations ranged from -$45,000 in Marion County, Florida to $800,000 in Kern County, California. Total sales ranged from the baseline of $50 million to $2.8 billion in Fresno County, California while total farm acres ranged from 19,000 in Pickens County, Georgia to over two million in Kern, California, showing the vast spread of revenue and size of farming operations.

Such regional variations may well be the result of intentional policies rather than naturally emergent practices. For example, organic agriculture and on-farm energy generation correlated with total sales (0.7), total farm acres (0.5), and the state of California, reifying California's role in the organic food movement (Guthman, 2014) and policies that encourage on-farm energy through California's Global Warming Solutions Act, AB32 (Hanemann, 2007). Energy generation represents another on-farm income stream important to both the metabolic demand in urban and farming areas. Similarly, direct farm sales through Community Support Agriculture (CSA) and agritourism data were expected to give an idea of where farms are more spatially engaged with urban areas can could have more vibrant shared metabolisms. As reported by the USDA's Economic Research Service reports (2018), agritourism revenues and CSA numbers show significant spatial auto-correlation in the northeast and California, closer to major urban populations (Moran's I, $p = < 0.002$). Indeed, state and regional control variables indicate that California farm data correlates with multiple variables and should be controlled in a regression so that California data will not skew findings from the national dataset.

[Insert Figures 3 and 4]

Agricultural Vitality Indicators

Agricultural vitality parameters proved difficult to identify based on census data. For example, according to the USDA agricultural census over 25 percent of the study counties gained farmland from 1997 to 2007, with Weld County, Colorado gaining the most at nearly 200,000 acres. On the other hand, Kern County and San Bernadino County, California saw a loss of nearly half a million acres. Expressed as a percentage of total farm acres, some places like Broward and

Collier Counties in Florida lost 60-70 percent of their farmland. Farmland loss showed significant spatial auto-correlation, centering on Florida and California, areas of the country that were home to booming real estate housing markets over the 2000-2010 period. Yet, spatial autocorrelation of farmland loss may also be due to how agricultural census data is collected and classified. For example, changes in sampling methods employed in the agricultural census or re-classification of idle farmland to conservation land in the 2007 Agricultural Census would both result in loss of active farmland. Due to the aberration, changes in USDA Census farmland acreage data are discounted as a proxy for measuring true farmland loss.

An indicator of farming vitality based on sales data is incomplete and heavily skewed toward conventional farming operations due the measurements provided by the agricultural census, which overlook many specialty crops, value-added products, and cash-only transactions. The top seven counties with the highest commodity sale returns for expenses are in the state of California. Fifteen of the twenty-eight counties that made less in commodity sales than their expenses were in Texas. This pattern can be partially explained by the value-added sales from high-grossing farm products like wine in California. Conversely, low farm commodity sales in Texas may not identify a lack of farm vitality. Farm vitality could be derived from auxiliary income not captured by the agricultural census, such as on-farm oil drilling or wind energy. Moreover, total farm sales per county strongly correlate with conventional farming expenses in chemicals, fertilizers, farm labor, and fuel (Figure 3).

In summary, exploration of descriptive and inferential statistics based on the Agricultural Census proved unsuccessful in deriving a reliable indicator of farm vitality beyond the imperfect agricultural sales data. Agricultural commodity sales data fail to capture numerous auxiliary on-farm non-agricultural activities, a significant component in agricultural vitality representing new opportunities for economic growth through agritourism, energy generation and cash-only sales. To improve the farm vitality indicator, future studies may use farmland stability from satellite imagery, only recently made available through the National Agriculture Statistics Service Cropscape (Han et al., 2012).

Urban Vitality Indicator

Urban vitality measures proved more straightforward though urban features also varied considerably, as further discussed in correlation data. It is important to note that larger states with more total counties had more counties represented: California (33 counties in the study), Texas (33), Indiana (32), Illinois (30), Michigan (23) Wisconsin (22) and Florida (20) were the top states represented (Figure 2). County populations in 2000 ranged from 6,500 people in Carson County, Texas to 9.5 million in Los Angeles County, California. Counties showed no significant spatial auto-clustering in amount of urban area, and ranged from having nearly no urban area to counties that are mostly urban, such as Tarrant County, Texas which houses Fort Worth and is considered to be 75 percent urban.

Population gain was determined to be the best urban vitality indicator. Population change from 2000-2010 significantly spatially clustered, with one-ninth of the counties losing population, largely located in northeast Middle America. Erie County, New York lost 30,000 people from 2000-2010, while Maricopa, Arizona gained 750,000 over the same time period. Access to jobs, wages, retiring older populations and politics all influence where counties grow or decline in population.

Importantly, farmland loss did not correlate with population gain spatially. Many counties that gained population also gained farmland according to the agricultural census, rendering a simple farmland-conversion-to-development variable for urban predation imprecise and over simplified. While counties may develop more housing, and even convert peri-urban farmland, the agricultural footprint can be shifted further out as new farmland is created from conversion of forestry and wildlands. For such a conversion measurement, satellite data is needed, opening opportunities for future research on this topic. Indeed, on average, 85 percent of land uses in a given county are not classified as 'farm' or 'urban area', opening room for explanatory variables related to other land-uses in future iterations of this research.

While population change is likely the best indicator of urban vitality, this variable correlates with larger populations (0.6) and rugosity (0.6; Figure 3). This finding presents the "Matthew Effect" as places that already start with larger populations tend to attract more growth. Population growth did not correlate with any of the Economic Research Service county economic typology scores (Table 2), total urban area, nor natural amenity scores. That the rugosity variable of interest correlated with urban vitality indicators (Figure 3) and the value of farm land and buildings when averaged over acres speaks to its unique role in assessing a shared urban and farm metabolism.

In addition, because total county population tightly correlated with a variety of urban metrics (Figure 3), county commuting zone populations were determined to be the best variable for later regression analysis to control for population. Commuting zones are defined by the Economic Research Service as a way to measure labor-sheds, the number of people who could commute into over 700 unique economic regions. Where a county with a small population may border a county with a large population, the commuting zone population variable provides the sum of the population within the vicinity of each county. For example, Ogelthorpe County, Georgia has the least rugose PUI and a 2010 population of 12,600 people (Figure 5). Oglethorpe County has a commuting zone population of 166,100 because it is adjacent to the city of Athens, the sixth-largest city in Georgia. The commuting zone population acts as a control for collective purchasing power within commuting regions where more consumers may change the price of agricultural goods.

Measuring Urban Rugosity

The average urban perimeter length in a county was 209 km (+/- 170km) (Figure 6). As with many population-based and agricultural variables, the UA perimeter also spatially auto-correlates in the northeast and California. In comparison, the *jaggedness index* exhibited a lack of co-variate correlation and no spatial auto-correlation. The county with the most concentric UA was Ogelthorpe, Georgia and the least Robertson, Tennessee (Figure 5). The city of Oglethorpe in Ogelthorpe County is almost a perfect circle, and also had the least amount of PUI. Incidentally, the city and county of Oglethorpe take their name from James Edward Oglethorpe who founded the Georgia colony and designed the City of Savannah on a grid to infuse the urban fabric with green space (Reinberger, 1997). The City of Ogelthorpe does not share these design features.

California's Riverside County was the most rugose with the longest PUI. Both Robertson County, TN and Riverside County, CA have long histories of rich farmland surrounding leap frog developments (Brinkley, 2018).

Rugosity (UA perimeter length) correlated with three variables: larger populations, county population increases from 2000-2010, and the value of agricultural land and buildings on a per acre basis (Figure 3 and 6). The correlations demonstrate that urban areas with interfaces less than 65km in length tended to lose population, and every kilometer of urban interface corresponded to a county population gain of roughly 250 people over the 2000-2010 time period (Figure 6).

Correlations also show that the urban interface may be a better predictor of agricultural land markets than population. Longer UA perimeters correlated with higher values of agricultural land and buildings per acre (0.6, Figure 3), lending credence to farmland amenity studies that demonstrate how urban proximity raises farmland values (Bergstrom and Ready, 2009), not necessarily population. In support, there was no strong correlation between county population and the value of agricultural land and buildings on a per acre basis. This result helps monetarily quantify the urban edge effects on farmland described in previous studies (Hart, 1991; Sokolow, 2003), while drawing a distinction between population- and spatial urban land-use drivers of farming practices and economics. As previously mentioned, farmland value is seen theoretically as an indicator of urban proximity, not as an indicator of farm vitality (von Thünen, 1826). Further regression analysis helps to quantify how rugosity may alter farm productivity.

[Insert Figure 5 and 6]

Agricultural Vitality with Greater Urban Rugosity

The t-test paired counties with similar populations and acres of farmland by differing rugosity and *jaggedness* measurement. Results show that counties with more non-concentric and longer UA perimeters did not experience more farmland loss than counties with more concentric and shorter PUIs (Table 3). The t-test also revealed no significant differences in the expense-to-income ratio of farming operations; but did, however, show a significant difference in total agricultural sales across all three agricultural census data years (1997, 2002, 2007) with more non-concentric, higher rugosity counties outperforming counties with more concentric and low rugosity PUIs by 40 percent (Table 3). This finding could be due to greater access to markets for farm goods and services as hypothesized. Similarly, high rugosity counties with more non-concentric urban areas had on average 25 percent greater value of agricultural land and buildings and 30 percent greater expenses, indicating that greater urban interface exposure may grant higher profits, but is also associated with higher production costs (Table 3).

[Insert Table 3]

Multivariate Regression

A model was found to explain total agricultural sales in terms of the UA perimeter length. A step-wise ordinary least squares regression revealed significant Moran's I and LaGrange Multiplier effects, indicating the appropriateness of a spatial error model. There was no significant spatial auto-correlation for the residuals of this model, and the Jarque-Bera test for multicollinearity was 4.177342, but statistically significant. A score under 10 is considered passable in the literature (Anselin, 2003a). The Breusch-Pagan test for heteroskedasticity was significant, and the Likelihood Ratio Test for spatial error dependence was similarly statistically significant, which in combination with an insignificant Moran's I test on the residuals, indicates that the model has omitted other underlying explanatory variables which are not spatially correlated. Due to the appropriateness of the spatial error model, one can assume that high agricultural sales is not a social condition arising from imitation of one's neighbors, a ''feedback'' process yielding spatially auto-correlated residuals. Rather, high agricultural sales result from a complex mix of social, economic, and cultural factors, only a small number of which can be brought into a statistical model of the process. Much of it remains unaccounted for and summarized in the model's spatial error term ($148M). Spatial statistic models could not be fit to explain farm acres lost, *jaggedness*, or agritourism.

Several variables were insignificant and did not improve model fit. Natural amenity scores, climate region and weather-related variables were expected to play into agricultural output in terms of the types of production possible in many counties and warmer weather or longer growing season which would allow different types of crops to grow. That these factors do not influence total agricultural sales may speak to the variety of agriculture possible with technology, and perhaps particularly to animal agriculture as a high value product that does not necessarily hinge on weather or soil quality.

The resulting stepwise spatial error regression model predicts up to 69 percent of total agricultural sales in study counties, with similar results across all agricultural years surveyed (1997, 2002, and 2007). Controlling for total farm acres, state effects of California and the commuting zone population, the model shows the following significant variables: farmland loss, low employment, and UA perimeter length. The commuting zone population as used instead of county population to limit covariance with rugosity (Figure 3) and still control for areas with more purchasing power and larger populations. Table 4 presents a 4-step hierarchical regression, which involves the interaction between four continuous scores and two non-continuous control variables (California and low employment). In this example, control variables for farmland area, commuting zone population, and California state-fixed effects are entered at Step 1 (Model 1), change in farm acreage from 1997-2007 is added at Step 2 (Model 2), employment is added at Step 3 (Model 3), and the UA perimeter in meters is added at Step 4 (Model 4; Table 4).

[Insert Table 4]

The constant shows a negative baseline. Counties must overcome this threshold for agricultural sales with positive contributions to: farm acres, urban interface access, or being located in California. For example, if a county is in California, the model automatically adds $316 million to its baseline annual agricultural sales. Because California is such a high agricultural-producing state, the effects needed to be controlled for in the model. As expected, the presence of farmland contributes to agricultural sales. Every acre of farmland correlates with an average of $500 more in agricultural product per year. This figure nearly matches the significant variable of farmland loss over the ten-year span, showing that for every acre of farmland lost, the model predicts $680 more in annual agricultural sales, presumably to offset land competition. This finding can be potentially explained as remaining farms turn to more diversified marketing strategies to overcome the pressures to operate on high value lands sought for development. If a county has low employment, the model adds $324M in agricultural sales. Low employment was intended as an indicator of purchasing power. The bi-nomial low-employment indicator from the federal

Economic research Service surveys counties, with the national finding that 460 counties (396 of which are nonmetro) had less than 65 percent of residents 21-64 years old employed in 2000. This variable, however, may act more as an indicator of rural character than labor-force or earning power.

Last, every kilometer of UA perimeter, corresponds to $212,000 in agricultural sales. Stepwise regression was used to verify the coefficient sign, amount and significance as other variables were dropped from the equation, revealing similar outcomes. For every kilometer added to the urban interface, the annual agricultural sales per county increase by ~$230,000 when the below coefficients are averaged (Table 5). The average urban interface length is about 200km, which corresponds to roughly $42M in agricultural production per county according to the model.

[Insert Table 5]

Conclusion and Future Directions

This work is an initial attempt to consider the interplay of various forms of capital and material flows across a metabolic boundary between urban and farm lands. Findings show that increased urban rugosity is associated with both urban and agricultural vitality. The research reveals that counties with longer urban interfaces did not statistically lose more farmland and had greater farm commodity sales. The length of the PUI, not population, is correlated with agricultural land values on a per acre basis. Additionally, longer urban interfaces are associated with growing populations, proving the popularity and economic health of high rugosity urban places for both urban and agricultural communities alike.

Future studies can help corroborate or challenge findings and hone methods through alternate measurements of rugosity and its correlates in urban and agricultural vitality. First, measuring the urban perimeter offers the coastline paradox. The length of the interface depends on the unit used to measure it. The urban perimeter could be measured in kilometers or could theoretically be as fine as a hair's width resulting in a nearly infinite distance. Practically, using the Block Group to define the urban perimeter, and meters to measure its outline, attaches a fine-grained, yet feasibly measured unit with social construction. A more fine-grained (or broad) approach in defining the perimeter and measuring it could be compared. Newly available satellite land-use mapping will enable ever more detailed and reliable land-use profiles for agricultural and urban densities alike, and could assist fine-grained approaches that could be useful for the neighborhood-scale planning. Such studies could be helpful in assessing the success of land-use planning initiatives, such as the London County Plan, where micro-wedges of greenspace transition from "parkway to green wedge and green wedge to Green Belt" (Forshaw, 1943, p. 38). How might such gradations of rugosity influence urban and non-urban areas?

Second, alternate definitions of what constitutes the urban perimeter can be assessed. Future studies may wish to test urban land-use density measurements in conceptualizing the rugosity of the urban periphery. Urban land-use density could be based off of residential population densities, visibility of nighttime lights (Kyba et al., 2015), impermeable surface, or land-use typologies such as those employed by Wheeler (2008, 2015). There are numerous methods to identify and measure the complexity of the urban edge, but none thus far, with the exception of this study, have offered an easily replicable proxy for estimating both urban and agricultural vitality.

Ultimately, the findings from this study and others like it can help guide development. The ecological concept of rugosity can be transferred into urban planning theory and practice, and in many ways is already implicitly implemented with the ongoing research and practice of incorporating 'green networks' into urban areas (Ahern, 1995; Linehan et al., 1995; Fabos, 2004; Turner, 2006; Amati, 2008). Concentric growth (Blumfield, 1949; Southworth and Owens, 1993) minimizes the rugosity of the urban edge. This theory often plays out practically in urban planning, with recommendations for concentric urban growth boundaries and low-density fringe developments (see, for example, the transect model by Duany and Talen, 2002) that have been criticized for limiting the desirable fringe to a wealthy few (Anas and Rhee, 2007). In actuality, many urban greenbelts, such as Portland, Oregon's, exhibit high rugosity planning in form; and they may be more successful for it. Ironically, high density fringe developments may be able to harness NIMBY (Not In My BackYard) attitudes that sway politics in favor of further conservation of valuable, ecological peri-urban farmland in their viewshed.

In expanding this research, to study urban rugosity without acknowledging the many political systems that govern land-uses and their collective morphologies overlooks the action that regulators can take to optimize form and function. Urban form and function is heavily structured by a myriad of city, county, state and federal regulations governing land economics, housing markets, urban design conventions, and market preference (shaped in turn by the industry and culture). Follow-up studies may answer whether high rugosity is an explicitly desired land-use planning goal, or a construct of a specific set of regulations and geographies (see, for example, Brinkley, 2018). Indeed, policies needed to protect farmland with and without high urban rugosity may differ in important ways.

Similarly, the degree to which urban metabolism is a function of interface access and not merely a correlate deserves more study. This is particularly of interest for groups who do not benefit from nutrient-rich metabolic flows. As urban metabolism is a socially governed process (Heynen et al., 2006), certain constituents are precluded access. Indeed, the right to the city is now being framed as a right for the poorest residents to partake in "urban metabolism" (Schillington, 2013; Mattei and Quarta, 2015) where access to food, water (Cousins and Newell, 2015), energy and economies are uneven. If longer PUIs are design features of growing urban areas and thriving agricultural communities alike, attention to enabling these design features may engender more equitable distribution of resources, co-joining previously isolated rural and urban communities. If urban metabolism can be better understood through a simple metric like rugosity, perhaps cities and neighborhoods can be planned with attention to equity in access to the metabolic interface and its associated flows.

References

Ahern, J., 1995. Greenways as a planning strategy. *Landscape and urban planning*, *33*(1), pp.131-155.

Alberti, M., 2005. The effects of urban patterns on ecosystem function. *International regional science review*, *28*(2), pp.168-192.

Alvarez-Filip, L., Dulvy, N. K., Gill, J. A., Côté, I. M., & Watkinson, A. R. (2009). Flattening of Caribbean coral reefs: region-wide declines in architectural complexity. *Proceedings of the Royal Society of London B: Biological Sciences*, *276*(1669), 3019-3025.

Amati, M. (Ed.) (2008) Urban Green Belts in the Twenty-first Century (London: Ashgate).

Anas, A., and Rhee, HJ. 2007. When are urban growth boundaries not second-best policies to congestion tolls? *Journal of Urban Economics* 61 (2): 263-286.

Angel, S., Parent, J., Civco, D. L., & Blei, A. M. (2012). *Atlas of urban expansion*. Lincoln Institute of Land Policy.

Angel, S., Sheppard, S., Civco, D.L., Buckley, R., Chabaeva, A., Gitlin, L., Kraley, A., Parent, J. and Perlin, M., 2005. *The dynamics of global urban expansion* (p. 205). Washington, DC: World Bank, Transport and Urban Development Department.

Angelo, H., & Wachsmuth, D. (2015). Urbanizing urban political ecology: A critique of methodological cityism. *International Journal of Urban and Regional Research*, *39*(1), 16-27.

Anselin, L. and Florax, R.J., 1995. Small sample properties of tests for spatial dependence in regression models: Some further results. In *New directions in spatial econometrics* (pp. 21-74). Springer; Berlin: Heidelberg.

Anselin, L. and Rey, S., 1991. Properties of tests for spatial dependence in linear regression models. *Geographical analysis*, *23*(2): 112-131.

Anselin, L., 1988. Lagrange multiplier test diagnostics for spatial dependence and spatial heterogeneity. *Geographical analysis*, *20*(1): 1-17.

Anselin, L., 2003a. Spatial externalities, spatial multipliers, and spatial econometrics. *International Regional Science Review*, *26*(2): 53-166.

Anselin, L., 2003b. GeoDa™ 0.9 user's guide. *Urbana*, *51*, p.61801.

Anselin, L., 2005. Spatial Regression Analysis in R–A Workbook. *Urbana*,*51*, p.61801.

Anselin, L., Bera, A.K., Florax, R. and Yoon, M.J., 1996. Simple diagnostic tests for spatial dependence. *Regional science and urban economics*, *26*(1): 77-104.

Anselin, L., Syabri, I. and Kho, Y., 2006. GeoDa: an introduction to spatial data analysis. *Geographical analysis*, *38*(1): 5-22.

Arrow, K., Bolin, B., Costanza, R. and Dasgupta, P., 1995. Economic growth, carrying capacity, and the environment. *Science*, *268*(5210), p.520.

Ayres RU, Kneese AV (1969) Production, consumption, and externalities. *The American Economic Review* 59(3): 282–297.

Baccini P (1997) A city's metabolism: Towards the sustainable development of urban systems. *Journal of Urban Technology* 4(2): 27–39.

Baccini P, Brunner PH (1991) *Metabolism of the Anthroposphere*. Berlin: Springer.

Baccini P. (1996) Understanding regional metabolism for a sustainable development of urban systems. *Journal of Urban Technology* 4(2): 27–39.

Bergstrom, J. C., & Ready, R. C. (2009). What have we learned from over 20 years of farmland amenity valuation research in North America?. *Applied Economic Perspectives and Policy*, *31*(1), 21-49.

Bettencourt LMA, Lobo J, Helbing D, Kuhnert C, West G (2007) Growth, innovation, scaling and the pace of life in cities. *Proc Natl Acad Sci* 104: 7301–7306.

Bettencourt, L. M., Lobo, J., & West, G. B. (2008). Why are large cities faster? Universal scaling and self-similarity in urban organization and dynamics. *The European Physical Journal B*, *63*(3), 285-293

Billen, G., Garnier, J., & Barles, S. (2012). History of the urban environmental imprint: introduction to a multidisciplinary approach to the long-term relationships between Western cities and their hinterland. *Regional Environmental Change*, *12*(2), 249-253.

Blumenfeld, H. (1949). On the concentric-circle theory of urban growth. *Land economics*, *25*(2), 209-212.

Bogue, D.J., 1956. *Metropolitan growth and the conversion of land to nonagricultural uses* (No. 11). Published jointly by Scripps Foundation for Research in Population Problems, Miami University, and Population Research and Training Center, University of Chicago.

Brinkley, C. (2012). Evaluating the benefits of peri-urban agriculture. *Journal of planning literature*, 27(3): 259-269.

Brinkley, C. (2013). Avenues into food planning: a review of scholarly food system research. *International planning studies*, *18*(2), 243-266.

Brinkley, C. (2017a) Adding rugosity to the rural-urban interface in practice and theory. *Journal of Planning Literature.*

Brinkley, C. (2017b). Visualizing the social and geographical embeddedness of local food systems. *Journal of Rural Studies*, *54*, 314-325.

Brinkley, C. (2018). High rugosity cities: The geographic, economic and regulatory pathology of America's most non-concentric urban areas. *Land Use Policy*, *73*, 215-224.

Brueckner, J. K., & Fansler, D. A. (1983). The economics of urban sprawl: Theory and evidence on the spatial sizes of cities. *The Review of Economics and Statistics*, 479-482.

Burgess EW. (1925) The growth of the city: An introduction to a research project. Publications of the American Sociological Society XVIII: 85–97.

Carlino, G. A., Chatterjee, S., & Hunt, R. M. (2007). Urban density and the rate of invention. *Journal of Urban Economics*, *61*(3), 389-419.

Chapman, M. R., & Kramer, D. L. (1999). Gradients in coral reef fish density and size across the Barbados Marine Reserve boundary: effects of reserve protection and habitat characteristics. *Marine Ecology Progress Series*, *181*, 81-96.

Cowell, S. and Parkinson, S. (2006). Localisation of UK food production: an analysis using land area and energy as indicators. Agriculture, Ecosystems and Environment, 94, 221–236.

Cousins, J.J., Newell, J.P., (2015). A political-industrial ecology of water supply infrastructure for Los Angeles. *Geoforum* 58, 38–50.

Cronon, William. *Nature's metropolis: Chicago and the Great West*. WW Norton & Company, 1991.

Desjardins, E., MacRae, R., & Schumilas, T. (2010). Linking future population food requirements for health with local production in Waterloo Region, Canada. *Agriculture and Human Values*, *27*(2), 129-140.

Duany, A., & Talen, E. 2002. Transect planning. *Journal of the American Planning Association*, *68*(3): 245-266.

Edinger, E. N., & Risk, M. J. (2000). Reef classification by coral morphology predicts coral reef conservation value. *Biological Conservation*, *92*(1), 1-13.

Fabos, J.G., 2004. Greenway planning in the United States: its origins and recent case studies. *Landscape and urban planning*, *68*(2), pp.321-342.

Farji-Brener, A. G., Barrantes, G., & Ruggiero, A. (2004). Environmental rugosity, body size and access to food: a test of the size-grain hypothesis in tropical litter ants. *Oikos*, *104*(1), 165-171.

Fasano, A., & Catassi, C. (2012). Celiac disease. *New England Journal of Medicine*, *367*(25), 2419-2426.

Forman, R.T.T., Godron, M., 1986. *Landscape Ecology*, Wiley, New York.

Forshaw, JH and Abercrombie P. 1943. County of London Plan. Macmillan, London.

Francis, C., Lieblein, G., Gliessman, S., Breland, T. A., Creamer, N., Harwood, R., & Wiedenhoeft, M. (2003). Agroecology: the ecology of food systems. *Journal of sustainable agriculture*, *22*(3), 99-118.

Friedlander, A. M., & Parrish, J. D. (1998). Habitat characteristics affecting fish assemblages on a Hawaiian coral reef. *Journal of Experimental Marine Biology and Ecology*, *224*(1), 1-30.

Furuseth, O. J., & Lapping, M. B. 1999. *Contested countryside: the rural urban fringe in North America*. Ashgate Publishing Ltd.

Gerbens-Leenes, P. W., & Nonhebel, S. (2002). Consumption patterns and their effects on land required for food. *Ecological Economics*, *42*(1), 185-199.

Ghose, R (2004) Big sky or big sprawl? Rural gentrification and the changing cultural landscape of Missoula, Montana. *Urban Geography* 25(6): 528–549.

Giombolini, K. J., Chambers, K.J., Schlegel, S.A, & Dunne, J.B. (2010). Testing the local reality: does the Willamette Valley growing region produce enough to meet the needs of the local population? A comparison of agriculture production and recommended dietary requirements. *Agriculture and Human Values* 28(2): 247-262

Gliessman, S. R. (2006). *Agroecology: the ecology of sustainable food systems*. CRC Press.

Golubiewski N (2012) Is there a metabolism of an urban ecosystem? An ecological critique. *Ambio* 41(7): 751–764.

Goreau, T. F., & Goreau, N. I. (1959). The physiology of skeleton formation in corals. II. Calcium deposition by hermatypic corals under various conditions in the reef. *Biological Bulletin*, *117*(2), 239-250.

Green, GP; Deller, SC and Marcouiller, DW. (2005). Amenities and rural development: theory, methods and public policy. *Rural Sociology* 68(3): 366–386.

Guthman, J. (2014). *Agrarian dreams: The paradox of organic farming in California*. Univ of California Press.

Han, W., Yang, Z., Di, L. and Mueller, R., 2012. CropScape: A Web service based application for exploring and disseminating US conterminous geospatial cropland data products for decision support. *Computers and Electronics in Agriculture*, *84*: 111-123.

Hanemann, W. M. (2007). How California Came to Pass AB 32, the Global Warming Solutions Act of 2006. *Department of Agricultural & Resource Economics, UCB*.

Hardesty, S., & Christensen, L. O. (2016). Economic Impact of Local Food Marketing by Yolo County Producers in the Sacramento Region.

Hart, J. F. 1976. Urban encroachment on rural areas. *Geographical Review*, 1-17.

Hart, J. F. 1991. The perimetropolitan bow wave. *Geographical Review*, 35-51.

Heimlich, R. E., & Barnard, C. H. (1997). Agricultural adaptation to urbanization: Farm types and agricultural sustainability in US Metropolitan Areas. *Rural Sustainable Development in America. Wiley and Sons, New York*, 283-303.

Heimlich, R. E., and Anderson, W. D. 2001. *Development at the urban fringe and beyond: impacts on agriculture and rural land* (No. 33943). United States Department of Agriculture, Economic Research Service.

Heynen, N., Kaika, M., Swyngedouw, E., 2006. Urban political ecology: politicizing the production of urban natures, in: Heynen, N., Kaika, M., Swyngedouw, E. (Eds.), In the Nature of Cities Urban Political Ecology and the Politics of Urban Metabolism. Routledge, New York, pp. 1–20.

Hiner, C. C. (2016). Beyond the edge and in between:(Re) conceptualizing the rural–urban interface as meaning–model–metaphor. *The Professional Geographer*, *68*(4), 520-532.

Hinrichs, C. C. (2000). Embeddedness and local food systems: notes on two types of direct agricultural market. *Journal of rural studies*, *16*(3), 295-303.

Hoegh-Guldberg, O. (2011). Coral reef ecosystems and anthropogenic climate change. *Regional Environmental Change*, *11*(1), 215-227.

Hughes, T. P., Baird, A. H., Bellwood, D. R., Card, M., Connolly, S. R., Folke, C., ... & Lough, J. M. (2003). Climate change, human impacts, and the resilience of coral reefs. *science*, *301*(5635), 929-933.

Jacobs J, (1969) The economy of cities. Vintage, New York.

Jacobs, J. (1985). *Cities and the wealth of nations: Principles of economic life*. Vintage, New York.

Kyba, C.C., Tong, K.P., Bennie, J., Birriel, I., Birriel, J.J., Cool, A., Danielsen, A., Davies, T.W., Peter, N., Edwards, W. and Ehlert, R., 2015. Worldwide variations in artificial skyglow. *Scientific reports*, *5*.

Lapping, M.B., Penfold, G.E. and Macpherson, S., 1983. Right-to-farm laws: Do they resolve land use conflicts?. *Journal of Soil and Water Conservation*,*38*(6): 465-467.

Linehan, J., Gross, M. and Finn, J., 1995. Greenway planning: developing a landscape ecological network approach. *Landscape and urban planning*, *33*(1), pp.179-193.

Levin, S., Xepapadeas, T., Crépin, A. S., Norberg, J., De Zeeuw, A., Folke, C., ... & Ehrlich, P. (2013). Social-ecological systems as complex adaptive systems: modeling and policy implications. *Environment and Development Economics*, *18*(2), 111-132.

Liu, Z., He, C., Zhou, Y., & Wu, J. (2014). How much of the world's land has been urbanized, really? A hierarchical framework for avoiding confusion. *Landscape ecology*, *29*(5), 763-771.

Lobo, J., Bettencourt, L. M., Strumsky, D., & West, G. B. (2013). Urban scaling and the production function for cities. *PLoS One*, *8*(3), e58407.

Luckhurst, B. E., & Luckhurst, K. (1978). Analysis of the influence of substrate variables on coral reef fish communities. *Marine Biology*, *49*(4), 317-323.

MacArthur, R. H., & MacArthur, J. W. (1961). On bird species diversity. *Ecology*, *42*(3), 594-598.

Mattei, U., & Quarta, A. (2015). Right to the City or Urban Commoning: Thoughts on the Generative Transformation of Property Law. *Italian LJ*, *1*, 303.

McCormick, M. I. (1994). Comparison of field methods for measuring surface topography and their associations with a tropical reef fish assemblage. *Marine ecology progress series. Oldendorf*, *112*(1), 87-96.

McGranahan, D. (1999). “Natural Amenities Drive Rural Population Change” (AER-81). United States Department of Agriculture Economic Research Service, Washington, DC.

Meinel, G., & Winkler, M. (2002). Spatial analysis of settlement and open land trends in urban areas on basis of RS data–studies of five European cities over a 50-year period. In *Geoinformation for European-wide Integration, Proceedings of the 22nd Symposium of EARSeL (Ed. Tomas Benes), Prague* (Vol. 4, No. 06.05, p. 2002).

Meinel, G., Winkler, M., & Lavalle, C. (2001). Indicators for the spatial analysis of settlement and open land trends in urban areas-studies on base of five European cities over a 50-year period. In *Sustainability in the Information Society”, 15th Symposium Environmental Informatics, Zurich*.

Nelson, L and Nelson, PB (2010). The global rural: gentrification and linked migration in the rural USA. *Progress in Human Geography*.

Nelson, PB. (1997). Migration, sources of income, and community change in the Nonmetropolitan Northwest. *The Professional Geographer* 49 (4): 418-430.

Nelson, PB., Lee, AW, Nelson, L, (2009). Linking baby boomer and Hispanic migration streams into rural America: a multi-scaled approach. *Population, Space and Place* 15: 277-293.

Nelson, PB; Oberg, A, and Nelson, L. (2010). Rural gentrification and linked migration in the United States. *Journal of Rural Studies* 26

Newell, J. P., & Cousins, J. J. (2015). The boundaries of urban metabolism Towards a political–industrial ecology. *Progress in Human Geography*, 36(6): 702-728.

Oakes, J. M., Forsyth, A., & Schmitz, K. H. (2007). The effects of neighborhood density and street connectivity on walking behavior: the Twin Cities walking study. *Epidemiologic Perspectives & Innovations*, *4*(1), 16.

Odum EP (1968) Energy flow in ecosystems: A historical review. American Zoologist 8(1): 11–18.

Pender, J. L., Weber, B. A., Johnson, T. G., & Fannin, J. M. (2014). *Rural wealth creation*. Routledge.

Peters, C. J., Bills, N. L., Lembo, A. J., Wilkins, J. L., & Fick, G. W. (2009). Mapping potential foodsheds in New York State: A spatial model for evaluating the capacity to localize food production. *Renewable Agriculture and Food Systems*, *24*(01), 72-84.

Peters, C. J., Bills, N. L., Lembo, A. J., Wilkins, J. L., & Fick, G. W. (2012). Mapping potential foodsheds in New York State by food group: An approach for prioritizing which foods to grow locally. *Renewable Agriculture and Food Systems*, *27*(02), 125-137.

Phillips, M. (1993) Rural gentrification and the processes of class colonisation. *Journal of Rural Studies* 9(2): 123–140.

Pretty, J.N., Ball, A.S. and Morison, J.I.L. (2005). Farm costs and food miles: An assessment of the full cost of the UK weekly food basket. Food Policy, 30, 1-19.

Purkis, S. J., Graham, N. A. J., & Riegl, B. M. (2008). Predictability of reef fish diversity and abundance using remote sensing data in Diego Garcia (Chagos Archipelago). *Coral reefs*, *27*(1), 167-178.

Ravenscroft, N., 2000. The vitality and viability of town centres. *Urban Studies*, *37*(13): 2533-2549.

Rees, W., & Wackernagel, M. (1996). Urban ecological footprints: why cities cannot be sustainable—and why they are a key to sustainability. *Environmental impact assessment review*, *16*(4), 223-248.

Reinberger, M. (1997). Oglethorpe's Plan of Savannah: Urban Design, Speculative Freemasonry, and Enlightenment Charity. *The Georgia Historical Quarterly*, *81*(4), 839-862.

Rigg, J. (1998). Rural–urban interactions, agriculture and wealth: a southeast Asian perspective. *Progress in Human Geography*, *22*(4), 497-522.

Risk, M. J. (1972). *Fish diversity on a coral reef in the Virgin Islands*. Smithsonian Institution.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin III, F. S., Lambin, E., ... & Nykvist, B. (2009). Planetary boundaries: exploring the safe operating space for humanity. *Ecology and society*, *14*(2).

Rogers, C. S. (1993). Hurricanes and coral reefs: the intermediate disturbance hypothesis revisited. *Coral Reefs*, *12*(3-4), 127-137.

Sale, P. F. (1991). Habitat structure and recPUItment in coral reef fishes. In *Habitat structure* (pp. 197-210). Springer Netherlands.

Samsel, A., and Seneff, S. (2013). Glyphosate, pathways to modern diseases II: Celiac sprue and gluten intolerance. *Interdisciplinary toxicology*, *6*(4), 159-184.

Sassen, S. (2001). *The global city: New york, london, tokyo*. Princeton University Press.

Shillington, L.J., 2013. Right to food, right to the city: Household urban agriculture, and socionatural metabolism in Managua, Nicaragua. Geoforum 44, 103–111.

Schmit, T. M., Jablonski, B. B., & Mansury, Y. (2016). Assessing the Economic Impacts of Local Food System Producers by Scale A Case Study From New York. *Economic Development Quarterly*, 0891242416657156.

Sebens, K. P., & Johnson, A. S. (1991). Effects of water movement on prey capture and distribution of reef corals. *Hydrobiologia*, *226*(2), 91-101.

Shumway, C. A., Hofmann, H. A., & Dobberfuhl, A. P. (2007). Quantifying habitat complexity in aquatic ecosystems. *Freshwater Biology*, *52*(6), 1065-1076.

Smith, M. E., Ur, J., & Feinman, G. M. (2014). Jane Jacobs' 'Cities First' Model and Archaeological Reality. *International Journal of Urban and Regional Research*, *38*(4), 1525-1535.

Sokolow, A. D. (2003). California's edge problem: Urban impacts on agriculture. *California [22]*.

Sorokin, P. A., & Zimmerman, C. C. (1929). Principles of rural-urban sociology.

Southworth, M. and Owens, P.M., 1993. The evolving metropolis: studies of community, neighborhood, and street form at the urban edge. *Journal of the American Planning Association*, *59*(3), pp.271-287.

Storper, M., Kemeny, T., Makarem, N., & Osman, T. (2015). *The rise and fall of urban economies: Lessons from San Francisco and Los Angeles*. Stanford University Press.

Swaney, D. P., Santoro, R. L., Howarth, R. W., Hong, B., & Donaghy, K. P. (2012). Historical changes in the food and water supply systems of the New York City Metropolitan Area. *Regional Environmental Change*, *12*(2), 363-380.

Swyngedouw E (2006) Circulations and metabolisms: (Hybrid) natures and (cyborg) cities. *Science as Culture* 15(2): 105–121.

Swyngedouw E, Heynen NC. (2003) Urban political ecology, justice and the politics of scale. *Antipode* 35(5): 898–918.

Taylor, P. J. (2012). Extraordinary Cities: Early 'City-ness' and the Origins of Agriculture and States. *International Journal of Urban and Regional Research*, *36*(3), 415-447.

Theobald, D. M. 2001. Land-use dynamics beyond the American urban fringe. *Geographical Review*, *91*(3): 544-564.

Thinh, N. X. (2003). Contemporary spatial analysis and simulation of the settlement development of the Dresden city region. *The information society and enlargement of the European Union. Part*, *1*, 253-261.

Thinh, N. X., Arlt, G., Heber, B., Hennersdorf, J., & Lehmann, I. (2001). Pin-pointing sustainable urban land-use structures with the aid of GIS and cluster analysis. In *Institute for Ecological and Regional Development, Dresden. In: LM Hilty & PW Gilgen (Eds.), Sustainability in the Information Society, 15-th International Symposium Informatics for Environmental Protection (Zurich), metropolis Verlag Marburg* (pp. 559-567).

Thomas, J.K. and Howell, F.M., 2003. Metropolitan Proximity and US Agricultural Productivity, 1978–1997*. *Rural Sociology*, *68*(3): 366-386.

Thompson, J., & Scoones, I. (2009). Addressing the dynamics of agri-food systems: an emerging agenda for social science research. *Environmental science & policy*, *12*(4), 386-397.

Turner, T., 2006. Greenway planning in Britain: recent work and future plans. *Landscape and urban planning*, *76*(1), pp.240-251.

USDA's Economic Research Service reports (2018). https://www.ers.usda.gov/data-products/charts-of-note/charts-of-note/?topicId=14887 Accessed Feb 13, 2018.

Vitiello, D. and Brinkley, C. (2014). The hidden history of food system planning. *Journal of Planning History*, *13*(2), 91-112.

Von Thunen, JH (1826). "The Isolated State" *Der Isolierte Staat in Beziehung auf Landwirtschaft und Nationalökonomie.* Hamburg: Perthes.

Walker, B. K., Jordan, L. K., & Spieler, R. E. (2009). Relationship of reef fish assemblages and topographic complexity on southeastern Florida coral reef habitats. *Journal of Coastal Research*, 39-48.

Walker, P. A. and P. T. Hurley (2011). Planning paradise: Politics and visioning of land use in Oregon. Tucson, AZ, University of Arizona Press.

West, G. B., Brown, J. H., & Enquist, B. J. (1997). A general model for the origin of allometric scaling laws in biology. *Science*, *276*(5309), 122-126.

West, G. B., & Brown, J. H. (2005). The origin of allometric scaling laws in biology from genomes to ecosystems: towards a quantitative unifying theory of biological structure and organization. *Journal of experimental biology*, *208*(9), 1575-1592.

Wheeler, S.M., 2008. The evolution of built landscapes in metropolitan regions. *Journal of Planning Education and Research*, *27*(4): 400-416.

Wheeler, S.M., 2015. Built Landscapes of Metropolitan Regions: An International Typology. *Journal of the American Planning Association*, *81*(3): 167-190.

Wolman A. (1965) The metabolism of cities. *Scientific American* 213(3): 179–190.

Zasada, I. 2011. Multifunctional peri-urban agriculture—A review of societal demands and the provision of goods and services by farming. *Land Use Policy* 28(4): 639-648.

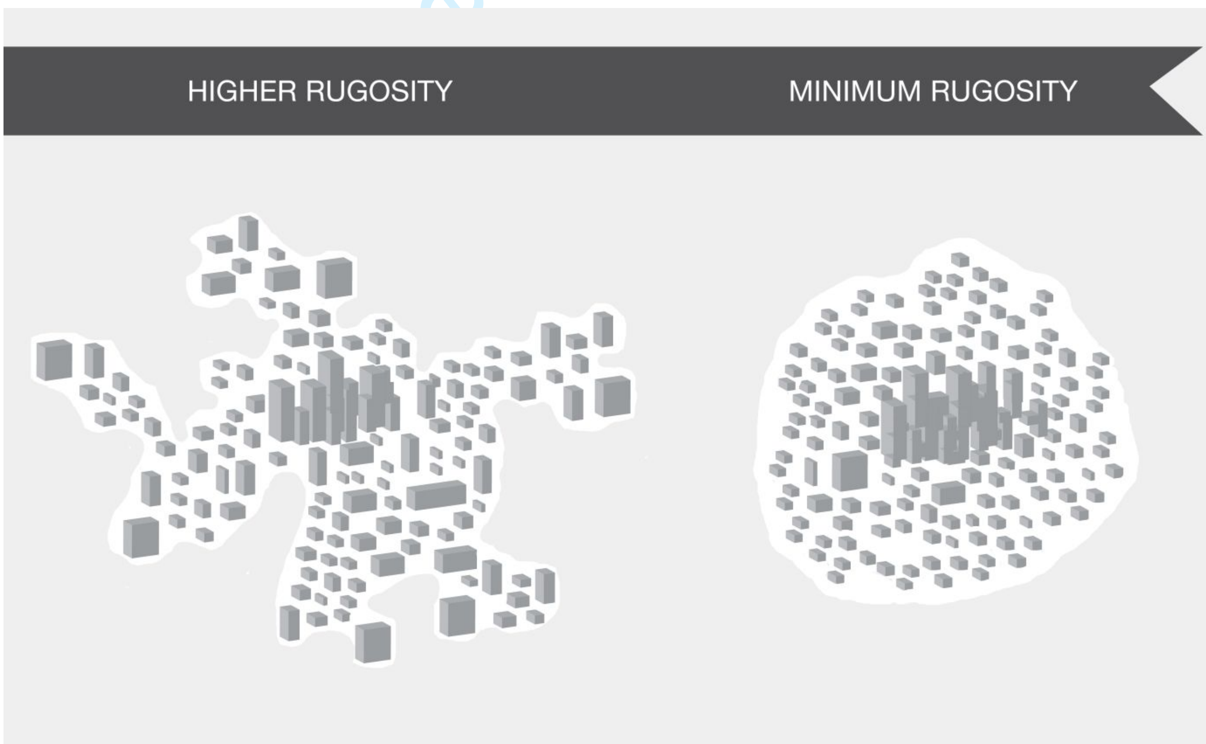

Figure 1. Rugosity Visualization from Brinkley 2017a. Higher rugosity (left) and minimum rugosity (right) for the same urban area (shown in white with simulated buildings) as compared to the non-urban area (shown in gray). Higher urban rugosity can be achieved by maximizing the urban interface through implementation of greenbelts, green wedges, and wildlife habitat corridors. Higher densities on the urban interface will also theoretically increase the functional urban interface. Image created by Elizabeth Brinkley.

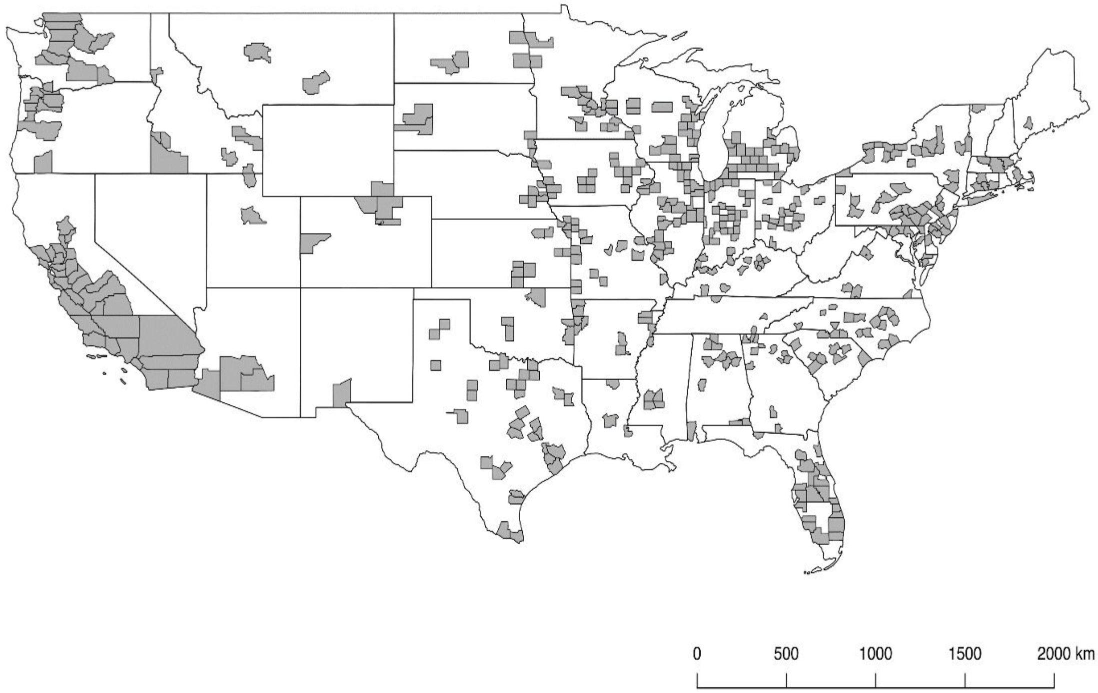

Figure 2. Study counties are shaded with the outline of US states to identify where study counties are located.

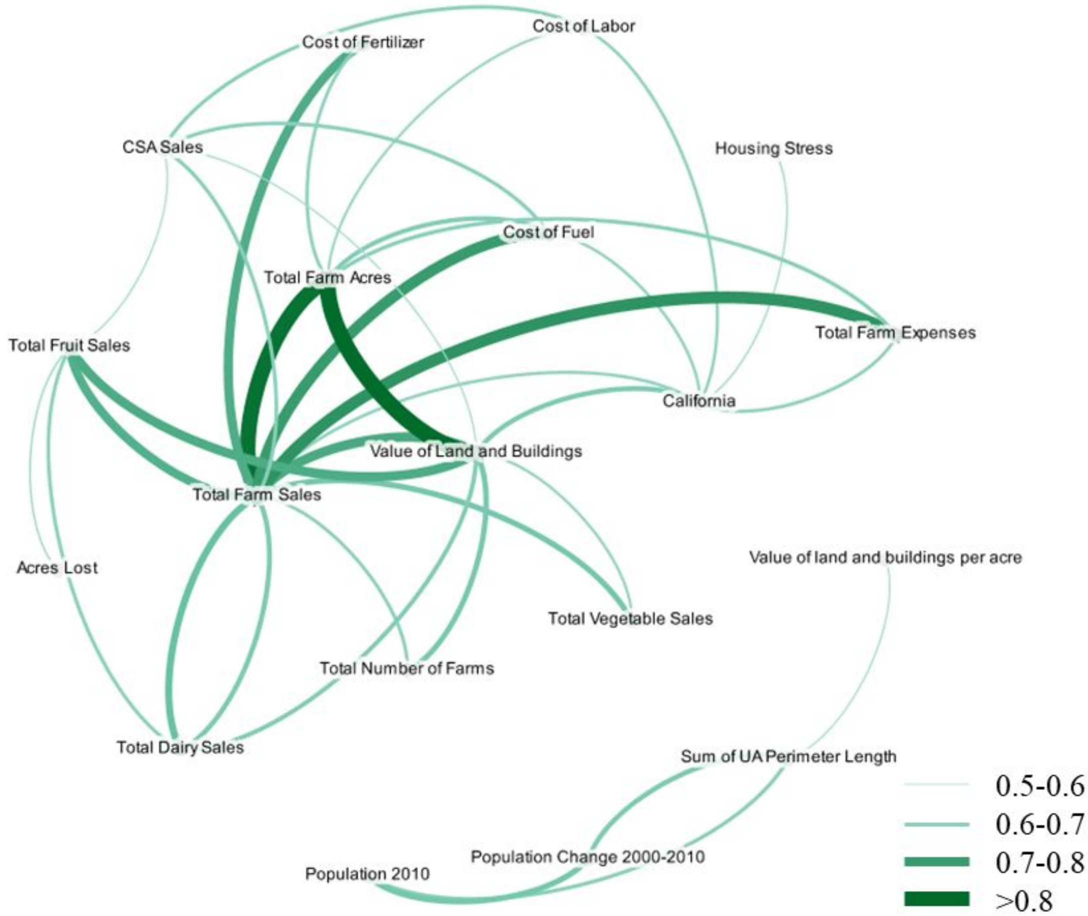

Figure 3. Correlation web of variables. The strength of the Pearson product correlation is provided in the key on the bottom right. Many variables, such as total hog production and total urban area, did not correlate with other variables and are were not represented in the figure.

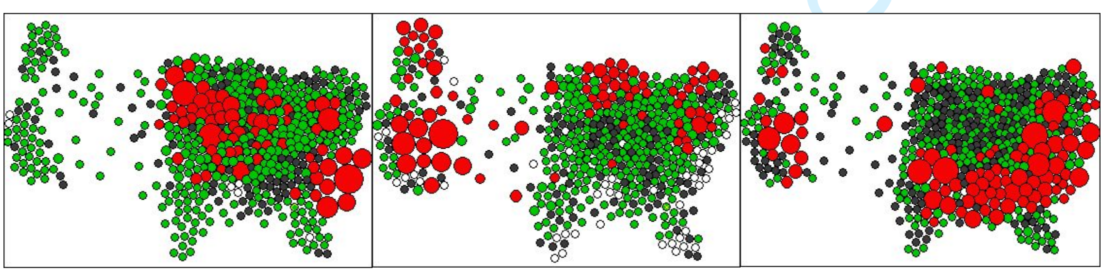

Figure 4. High sales volume animal agriculture clustering (red). Counties showed statistically significant spatial auto-correlation for 2007 hog production (left, Midwest and North Carolina), dairy (center, California, Upper Midwest, and the Northeast), and poultry (far right, South and Southeast) sales revealing the degree of spatial clustering of these industries. Red (high outliers in sales), Green (normal), Black (negative spatial correlation).

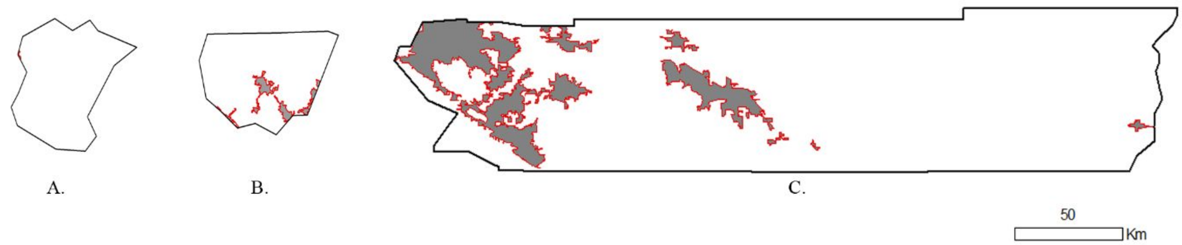

Figure 5. Least and most rugose counties in order of images left to right: A.) Ogelthorpe, GA has both the least PUI and lowest *jaggedness* score with a small urban area in the northeast/upper-left of the county; B.) Robertson, TN has the most non-concentric, highest *jaggedness* score C.) Riverside, CA has the longest PUI and highest rugosity. Dark gray: urban area, Red: urban area perimeter.

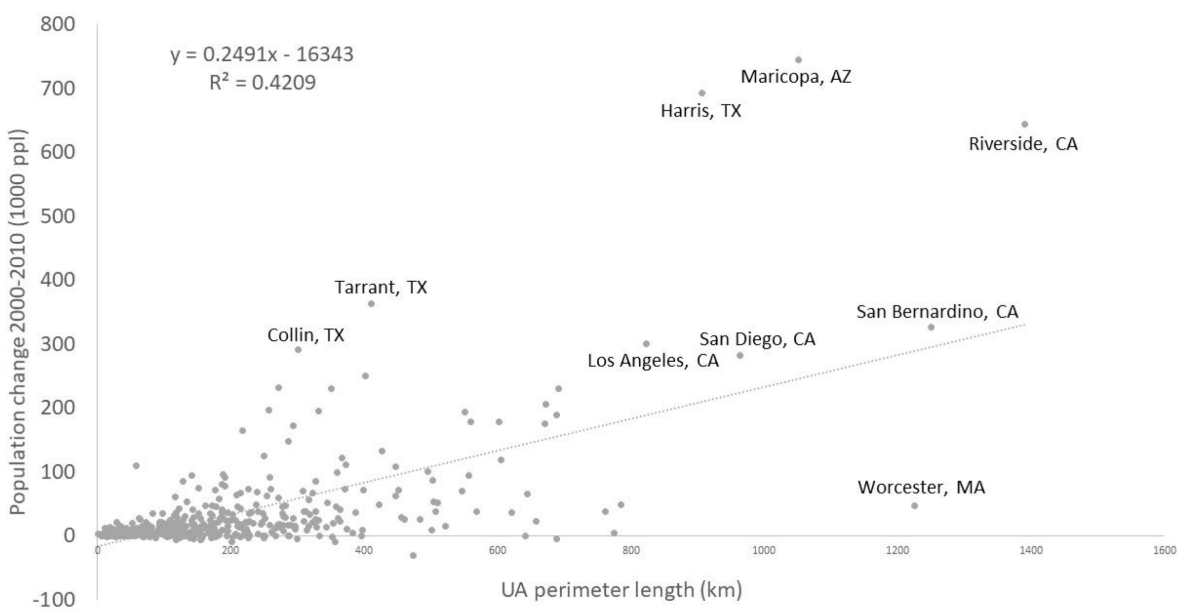

Figure 6. Population growth from 2000-2010 in relation to UA perimeter length. 2002 Urban Area perimeter length on the x-axis is plotted against county population growth from 2000-2010 on the y-axis, excluding those counties that lost population. Almost two-thirds of the nation's 3,143 counties gained population between 2000 and 2010. Study counties showed a similar breakdown. Some of the outliers in population growth are among the fastest growing US counties, including Los Angeles County, CA; Harris County, TX; and Maricopa County, AZ which gained over 300,000 people this decade. Outliers for urban perimeter length include San Bernadino and Riverside Counties in California, Worcester County, MA and Maricopa County, AZ with over 1000 km of Urban Area perimeter. Outlier counties are labeled.

Table 1. Comparison of study counties and national data to demonstrate representation.

	Percentage of Total (percent)	
Total Farm Acres per County	Study Counties	National Data
0-50,000	4	22
50,000-200,000	43	46
200,000-500,000	40	24
>500,000	13	8

Table 2. List of variables and sources considered in bi-variate analysis

Source	Variable
US Census	Population 2000, 2010
USDA Agricultural Census 1997, 2002, 2007 at county level	Total sales, farm acres, total crop sales value, total livestock sales value, total fruits sales value, total vegetable sales value, total hog sales value, total dairy sales value, total poultry sales value, total number of farms, change in number of acres farmed, value of land and buildings, total expenses, total rent expense, total chemical expense, total contract expense, total fertilizer expenses, total fuel expenses, total hired labor expenses, total tax expenses, agricultural tourism income (2002 and 2007 only), number of operations with community supported agriculture (CSA) sales (2007 only); organic food sales (2007 only); operations with energy production (2007 only)
Spatial data: Urban Area 2010, 2000	Percent urban area per county, sum of UA perimeter length, percent water
Economic Research Service County Typology Score 2010	rural urban continuum code, farm-influenced, mining-influenced, government- influenced, service sector-influenced, nonspecialized sector-influenced, housing stress, low-education, low employment, percent poverty, population loss, recreational, retirement community, percent child poverty, commuting zone population
Economic Research Service Natural Amenity Scores , 2010	January temperatures, Hours of sunlight, July temperature, July humidity, natural amenity score
State controls	All counties identified by state (eg., California) and region (eg. New England, Pacific, …)

Table 3. Agricultural vitality in high and low rugosity counties. Two-tailed t-test assuming unequal variances comparing 118 high rugosity counties with 118 low rugosity counties. Counties were paired based on statistically similar population and farm acres, but significantly statistically different measures of the UA perimeter and *jaggedness degree.*

	High Rugosity (average)	Low Rugosity (average)	Difference (*p two-tailed*)
Farmland Loss (1997-2007)	17,251 acres	17,341 acres	No difference (0.98)
Agricultural Sales	$111,000	$66,600	40 percent, (0.04)

Value of Land and Buildings	$1,200,000	$900,000	25 percent (0.03)
Agricultural Expenses	$174,000	$121,800	30 percent (0.04)

Table 4. Summary of Hierarchical Regression Analysis for Variables Total Agricultural Sales Per County (N = 458) *p < .05. **p < .01. Moran's I = 0. The mean for county agricultural sales across the 458 counties was $160M; Standard deviation of total agricultural sales in 2002 (Model 4): +/-$281M, with a standard error of $148M, constant of $ -37.875M. B= $1.00 units.

Variable	Model 1 (B, SE B)	Model 2 (B, SE B)	Model 3 (B, SE B)	Model 4 (B, SE B)
California (binomial)	**316,358,700, 42,579,890	**332,695,900 87,842,420	**286,898,000 89,135,990	**263,473,500 83,848,820
Commuting zone population	-.007, 5.59	-2.30, 5.57	-0. 602, 5.29	-5.54, 5.30
Farm acres	**581, 33	**521, 34	**467, 34	**473, 33
Farm acre change 1997-2007		**680, 168	**650, 160	**510, 160
Low employment (binomial)			**324,180,000 46,275,720	**338,883,100 45,473,060
UA perimeter length (km)				**212,000 48,000
Pseudo R^2	0.632168	0.639516	0.675221	0.687939

Table 5. Verification of UA perimeter constant by systematically removing variables.

Variables Removed	UA perimeter (km) coefficient and significance * (<0.01 pval)
Total equation (none removed)	$212,000 *
Farm Acres Lost 199-2007	$294,000 *
Low Employment (Bi-nomial)	$215,000 *
Commuting Zone Population	$210,000 *