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Defining the Pattern of the Sustainable Urban Region - Development of Regional Measurement Methods

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DEFINING THE PATTERN OF THE SUSTAINABLE URBAN REGION - DEVELOPMENT OF REGIONAL MEASUREMENT METHODS

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Abstract
To date, the debate on the sustainability of human settlements has focused on the urban portion of the land use pattern. Since urban areas rely on suburban, rural, and other less densely settled areas for their existence, these areas must be included in any sustainability assessment. This need for a regional view has resulted in a typology of regional form, which allows comparisons of relative sustainability between various regional land use patterns. Based on resource efficiency, this regional analysis includes measurements related to water, agricultural land, habitat, energy use, and transportation and identifies primary indicators for each category. Existing methods employed to assess urban sustainability are reviewed and compared with two new methods, introduced here, that take a more holistic regional view: population density zones and regional characteristic curves. Future work to fully evaluate the properties of these new methods by applying them to a variety of regional form types is described.

1. Introduction

Efforts to define, describe and implement sustainable cities and towns have been a part of the land use planning profession for more than a decade. Much of the focus, however, has been on the urban component of the settlement pattern. Particularly in the United States, with the theoretical and media focus on neo-traditional planned communities, the primary issue in the debate on the sustainability of cities - their ecological impact - has been urban form irrespective of the surrounding land matrix. A typology of urban form was presented by Kevin Lynch nearly five decades ago (Lynch 1954) that defined the urban core using shape terms such as compact, linear, star, and constellation. Typologies such as Lynch's continue to influence discussions about cities and towns today.

A focus solely on urban form unfortunately neglects the critical interaction of suburban, exurban, and rural land uses with the urban center and with each other. It follows, then, that a complete discussion of the effects of sprawl and sustainable development patterns must be based on a regional perspective, since sprawl by definition includes land area other than the traditional urban core. Without a typology that defines various land patterns as regional entities and accommodates their complexity, it is difficult to adequately differentiate between more or less sustainable land use patterns.

Both the terms 'sprawl' and 'sustainability' have become elusive catchwords in the popular media. For the purposes of this paper, sprawl is defined as low density development, a land use pattern in which land is consumed at a faster rate than can be explained by population growth alone (Fulton et al. 2001). Sustainability, on the other hand, is variously defined in physical, economic, political, social and cultural terms throughout the literature. Since the goal of this research effort is to assess the effects of land use patterns on natural resources or natural capital (Costanza & Daly 1992), sustainability is defined here only in terms of its physical impact on ecological and natural resources; the resource efficiency of the region.

In order to assess the relative resource efficiency of urban/regional land use patterns, this paper will explore the link between a regional land cover pattern's spatial form and its level of resource efficiency. The key to advancing this investigation is the development of a measurement system that can simultaneously address the issues of spatial organization, regional measurements, and the lack of a clear regional measurement boundary. The following discussion will expand a theoretical framework for the measurement of regional resource efficiency, presenting two methods for characterizing regional impacts that shed new light on sustainability assessment while comparing and contrasting them with existing measurement methods used to assess urban and regional sustainability. This comparison includes the existing measurement methods of ecological footprinting (Wackernagel & Rees 1996), its modifications (Luck et al. 2001), and calculations based on urban metabolism concepts (Wolman 1965; Baccini & Brunner 1991), as well as some proposed and operational indicator frameworks.

2. Measuring regional resource efficiency

Resource efficiency describes the relative impact a region has on its ecological basis - its hinterlands or 'environment' – through its use of materials and energy. Implicit in the term resource efficiency are several important ideas. First, that cities and regions are entities that require energy and materials to function and to maintain their internal structure and organization. In thermodynamic terms, they are complex, highly ordered (low entropy) systems that are maintained in that ordered state by flows of energy and materials from outside their boundaries, relying on what some researchers have called imported carrying capacity (Wackernagel & Rees 1996). This reliance on external flows to maintain internal order and complexity locally increases entropy (disorder) globally (Schneider & Kay 1994). Cities and regions thus act as 'dissipative structures', supporting their form and function by continuously dissipating energy drawn from the larger (eco)system of which they are an integral part. Finally, and most importantly, entities that use fewer resources in the process of functioning (i.e. are more resource efficient) will be more able to continue to function as these resources become scarcer and more costly. A central thesis of this work is that resource efficiency is directly related to regional form and that resource efficiency can be modified by changes in regional land use patterns.

2.1 A typology of regional form

In a previous discussion of this regional theoretical framework, Brabec and Lewis (Brabec & Lewis 2002), described a typology of regional form, and expanded concepts of regional sustainability measurement. This typology of regional form extended Lynch's (1954) and Bacon's (1976) urban typologies to a regional context and is shown in a simplified schematic form in Figure 1. The first type, the classic urban regional form and the focus of the neo-traditional movement, is the compact, nuclear city. Taken in regional context, the nuclear city has as its outer space a low density, rural matrix surrounding the higher density urban core. The boundary between urban and rural is clearly defined, and the type is exemplified by such medieval cities as Carcassonne, France.

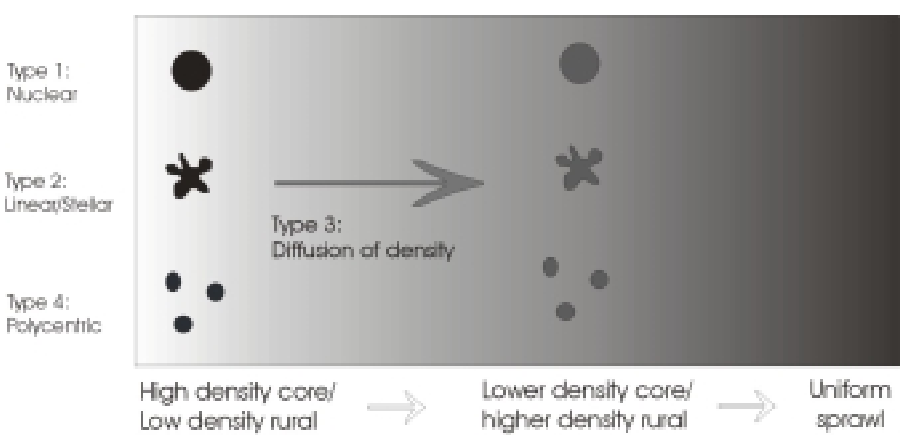

Figure 1. Schematic depiction of the extended typology of regional form illustrating the continuum from high density urban core in a rural matrix to uniform sprawl.

The second type, the outreach pattern, is the linear or stellar form wherein two or more fingers of development have extended out from the urban core to expand the urban area into the rural matrix. This expansion typically occurs along a railroad or highway corridor and is exemplified by early railroad towns across the U.S. In its most evolved form, the green city, the stellar form exhibits an equivalent push and pull of the urban and rural forces, the city and its surrounding mass of green space. Thus in the regional perspective, ribbons of urban development move out into the rural matrix while at the same time, ribbons of rural land and green space move into the urban core. Bath, England is a prototypical green city.

The third regional form is a result of the thrust of development diffusing density outward almost indefinitely. This is of course classic urban sprawl. The city expands in a relatively uniform mass with little differentiation in land cover to fill the former rural land matrix, leaving little or no boundary definition. At its farthest extent, sprawl can be described as a uniform, undifferentiated mass of development. Los Angeles, Phoenix and Houston exemplify the urban area that has developed into a sprawling regional form.

Lynch's constellation city form provides the basis for the fourth type of regional development form. This is the polycentric city, the focus of considerable current research (e.g. (Gordon & Richardson 1996)). The polycentric city can either take the form of a series of interrelated nuclear cities in a low density rural matrix, joined by transport and proximity to form a functional whole, or a series of core areas joined by a matrix of urban sprawl to form a new urban region. Therefore, polycentric regions can be either nuclear in form, or based in a matrix of sprawl such as the suburban region surrounding Washington, D.C. In the regional context, it is important to see this typology of five regional forms not as individual prototypes, but as a continuum along which any region may be categorized.

2.2 Existing measurement methods

This typology of urban form provides a basis for comparison of the resource efficiency of various urban regions. The primary question is "What should we measure?" A great deal of effort has gone into answering this question, at geographic scales ranging from local communities through national to global scales, effort that is frequently directed into the development of indicator frameworks. Indicators are measurable phenomena or physical entities that are directly related to, represent, or are predictive of larger phenomena. They are feedback signals that convey information on the state of some piece of a bigger system, such as using the amount of impervious surface in a watershed as a proxy for water quality, or on progress towards a goal (such as sustainability). An ecological indicator quantifying the concentration of nitrogen oxides (NO_x) in the air, for example, is a measure related especially to power plants and use of automobiles and other forms of transport, but also to furnaces and water heaters in residential buildings. It is one measure of the aggregate impact these activities have on the atmosphere and it tells us about the state of the air we breathe. Combined with an understanding of the health effects of various levels of NO_x in the atmosphere, NO_x becomes an indicator of regional health. Unemployment rate and gross national product (GNP) are two familiar economic indicators, literacy rate and crime rate are examples of common social indicators, all of which may be measured at a variety of geographic scales.

Indicator frameworks comprise sets of individual indicators and the data collection methods on which they are based. Frameworks often include ecological, economic, and social indicators and are often focused on urban areas due to the large effect these areas have in all of these dimensions (Alberti 1996). The development of indicator frameworks is often process-oriented and is concerned with the participation of interested and affected individuals and groups in that process (Maclaren 1996). The group Sustainable Seattle presents an illuminating example of the process behind the development of a community-level indicator framework (AtKisson 1996), while Sawicki and Flynn review the National Neighborhood Indicators Project, an effort to bring primarily social indicators at a very local neighborhood scale into the policy arena (Sawicki & Flynn 1996). At the other end of the spectrum, the United Nations Center for Human Settlements, the United Nations Commission on Sustainable Development, World Bank, World Health Organization, Organisation for Economic Co-operation and Development, and the European Environment Agency have all been involved in efforts to develop indicator frameworks at various scales (Alberti 1996).

Indicator frameworks bring a large amount of disparate information together, but in their presentation these frameworks tend to emphasize the separation and incommensurability of their constituent parts. For example, ecological, economic, and social indicators are collected in separate groups, and integration and interpretation of the information represented by the aggregation of the indicators are left to the reader. Interpretation is the biggest challenge as it requires, in many cases, a high level of expertise and is complicated further by a lack of knowledge or agreement within the scientific community about the significance of particular indicator values. Relative judgements on indicator values – whether one value is more or less sustainable than another – are usually not difficult to make, but absolute judgements – whether a value indicates a sustainable condition or not – are much more difficult to find agreement on. The selection of individual indicators to include in a framework is at times driven by the availability of data more than by its probative value. This nod to practicality unfortunately also means that indicators that might be significant or valuable are not considered if the data they are based on are not collected. Another dimension of data availability, one that is critical for determining the presence and direction of trends, is the frequency of collection. Data collection frequency for indicators is influenced by the rate of variation in the underlying process, the cost and difficulty of data collection, and also by the requirements of related policy. There is wide variability in data collection frequency: population census data in the US are collected once a decade, other data sets are updated on an annual, quarterly (most economic data), or even monthly basis (electric utility companies), and air quality measurements are taken daily in some areas.

While indicator frameworks are currently a popular form of sustainability measurement, there are other methods that have relevance for the assessment of regional form. One of the oldest concepts developed to address the issue of assessing the long-term viability of urban areas is that of the urban metabolism (Wolman 1965). Wolman presented the analogy of the urban area as a living organism with caloric requirements, an organism that respires and produces waste in the course of its daily existence, that relies on the availability of food, clean air and water, and an external source of energy for warmth. In other words, like living organisms, urban areas have a measurable metabolism. Like metabolisms in different living organisms, different urban areas have different metabolisms, except in urban areas these metabolisms are not dictated by hormonal secretions as in humans, they are the aggregate result of individuals' decisions. 'Developed' cultures tend to have a higher metabolism than 'developing' cultures, and tend to have a different level of existence (or ‘standard of living’) as well.

The apt analogy of the urban metabolism has been used repeatedly and updated by other investigators since Wolman (for example, (Baccini & Brunner 1991), (Decker et al. 2000), and (Haberl 2001)). The metabolism approach to assessing an urban area involves quantifying all of the flows of material and energy into and out of the area. In some cases, subsets of the full metabolism will be calculated (just energy) or particular elements (carbon) or factors (water quality) will be characterized. Metabolism assessments are also sometimes called material flow analyses (MFA), for obvious reasons. These assessments typically involve the collection of a relatively large amount of detailed data and are similar to life cycle assessments (LCA) of commercial products (Lewis et al. 1999) that also track materials and energy from source through production and use to end-of-life disposition. Metabolism studies, like LCA, follow a generic assessment algorithm by drawing a boundary around the system/region of interest, identifying and quantifying all of the pertinent in- and outflows across the boundary, and then calculating a metabolism by accounting for all mass and energy involved.

Calculating the metabolism of an urban area in this way gives a very accurate picture of a dynamic situation at one point in time. Due to the effort involved, primarily in collecting all of the appropriate data, these calculations are not repeated frequently. The urban metabolism idea, at least as realized in material flow analysis, suffers from a technocentric view that sees human settlements as separate from and surrounded by 'the environment'. While this is only a mental construct meant to simplify calculations and develop knowledge of how urban areas function, it works against a more comprehensive understanding of the functioning of urban regions and does not provide the ability to assess regional sustainability.

Another existing measurement method that has been inspiring debate in the literature is the ecological footprint (EF) developed by Rees and Wackernagel (Rees 1992; Wackernagel & Rees 1996). The EF method is concerned with determining the land surface area necessary to support a given population, without regard to where on the planet that land is located. The EF is the inverse of the ecological concept of carrying capacity, a concept that states what population can be supported on a given piece of land. To calculate an EF, all demands of a target population are converted into equivalent land area: land to grow food; land to supply forest products; land to live upon; land to take up the atmospheric carbon resulting from fossil fuel use. The sum of all this land area is the EF of the population, and is a function both of the number of individuals in the population and their resource use practices (their 'standard of living'). This idea fits the form of IPAT equation presented by Meadows, et al. (Meadows et al. 1992), where the footprint is a measure of impact (I), P is population, and resource use practices are represented by the combination of A (affluence) and T (technology). Like metabolism methods, EF calculations require a relatively large amount of data related to the target population.

Ecological footprint analysis results in a clear, conservative, and easily communicated estimate of human impact that does not require expertise or special training to understand. The two main drawbacks associated with using this method to assess urban regions are that it is highly aggregated and that it does not sufficiently consider the ecology within the target population's region. A high level of aggregation is what makes the EF clear and easy to communicate, but it also results in the obscuring of details and assumptions that are important to proper interpretation and use of the EF. A more serious fault is disconnection from local ecosystems, since it is vital for individuals to understand their connections to the ecological support on which they depend in order to make rational decisions about how they use and care for it. Luck, et al. (Luck et al. 2001) and other investigators, including at least one of the EF's developers (Borgström Hansson & Wackernagel 1999), are working to address these difficulties without compromising the positive traits of the EF.

2.3 Appropriate measures of regional resource efficiency

Defining a framework of key measures of resource efficiency is a central aspect of regional sustainability assessment. The framework employed here includes several categories similar to those used in other studies to identify sustainable land use patterns: transportation, energy, and water. However, at least two additional categories must be added to the framework to fully assess a regional system: agriculture and habitat. Although the question of how to reconcile the differing regional boundaries of these measures has not been addressed previously, the basis for inclusion of these categories and for collecting relevant data have been developed in other studies.

Meeting the caloric requirements of a population is of such primary importance that some measure of the ease and cost of making food available is a central measure of regional resource efficiency. Local agricultural land is a significant component in food security. Farms associated with an urban region tend to produce organic products and be more often family-run resulting in local economic benefits and a reduction in toxic/hazardous inputs compared to large-scale corporate agriculture (Heimlich 1989; Bryant & Johnston 1992). In addition, local farm production results in a reduction in transportation costs and impacts. As indicators of the presence of agricultural land, both the percentage of total land in agriculture and the percentage of land in agriculture per capita are representative measures of regional resource efficiency related to food production.

Land available as habitat for species besides humans is a significant factor in the healthy ecological functioning of a region. In fact, the amount of forested land in a region has been linked to overall watershed health (Steedman 1988; Hicks & Larson 1997). Undeveloped land (again as percent land area and percent land area/capita) is a simple measure of available habitat in a region. There is also an opportunity to use path-based metrics to assess the quality of undeveloped land as habitat (McGarigal & Marks 1995). These metrics include such measures as patch size, density, variability, diversity, contagion, and interspersion and are one way to understand and measure the quality and connectivity of undeveloped land as habitat.

Water is another resource of primary importance to a population and therefore a key aspect of the regional assessment framework. A primary measure of both surface and subsurface water quality is the amount of impervious area within a given region (Morisawa & LaFlure 1979; Arnold et al. 1982; Bannerman et al. 1993; Brabec et al. 2002). Impervious surfaces are a physical result of the spatial development pattern, therefore both the density and location of the impervious surface areas will change between the various regional types. Area of impervious surface is relatively easy to measure from aerial photos (both as a percentage of land area and a percentage of land area per capita) (Martens 1968; Hammer 1972; Graham et al. 1974; Gluck & McCuen 1975; Ragan & Jackson 1975). There are also methods linking impervious area to population (Morisawa & LaFlure 1979).

A fourth significant component of the regional resource efficiency framework is transportation. Regional form influences the impacts resulting from transportation primarily via the use of fossil-based energy in vehicles but also through the expansion of the area of impervious surfaces noted above. A significant amount of research has been done linking urban form to transportation impacts and efficiency, a parallel which we would expect to continue in a regional context (Pucher 1988; Newman & Kenworthy 1989; Banister et al. 1997). Two measures of regional transportation efficiency are the number of miles of road per capita and the number of vehicle or passenger miles traveled by the different transportation modes available in a region.

The representative measures discussed above are based on data that are relatively easy to collect. An important measure of regional resource efficiency for which data are more difficult to obtain is energy use in buildings. Energy used in buildings integrates climate, building construction type and quality, and occupant behavior (Pettersen 1994; Energy Information Administration 1999), and it is modified by the density and arrangement of buildings and the presence, location, and type of vegetation surrounding them (Heisler 1986; Huang et al. 1990; McPherson & Rowntree 1993; Laverne & Lewis 1996). Identifying the separate effects of these different factors is difficult, and not necessarily required to assess resource efficiency. If these data are available, either on a per capita basis or aggregated over some area (census tract, for example), they should be incorporated into the assessment.

3. A new approach to measuring regional resource efficiency

Each of the previously reviewed methods for assessing resource efficiency calls for defining an urban boundary. However, since the boundary of a region is difficult to define and varies between measures, the question remains: Is it necessary to draw boundaries or determine where flows originate to assess resource efficiency? It is certainly necessary to decide upon a region of interest, and regions do, by definition, have boundaries. So in many cases the selection of a region selects a boundary as well, but determining the geographic extent at which assessment ends is not always necessary or even possible. A meticulously thorough and accurate assessment of regional resource efficiency does indeed call for evaluation of the largest system affected. This 'largest system' may be local, regional, or global in extent, though this determination depends both on the source of the particular flow being considered and on whether all possible flows are to be included in the accounting. Our interest here is on regional linkages and effects, and the methods presented below are focused on regional measures. The key to assessing the relative resource efficiency of various regional development patterns is a measurement system that can tolerate the uncertainty of an indistinct boundary and boundaries that change with the quantity being measured.

3.1 Population Density Zones

One approach to measuring regional resource efficiency takes population density data as its starting point. These data are collected for areal subunits within the region of interest and are used to construct a choropleth population density map of the region. This map is then divided into zones of given population densities, zones that are agglomerations of similar-valued subunits. The zones comprising this new tessellation of the region stratify the region by population density as shown in Figure 2, and serve as the basis for evaluating the resource efficiency measurements discussed above. Measurements are made separately for each density zone and the results are collected in tabular form. Table 1 illustrates an example of a portion of a results table for a hypothetical nuclear - form region, showing how a numeric profile of the region is built up as multiple measurements are made.

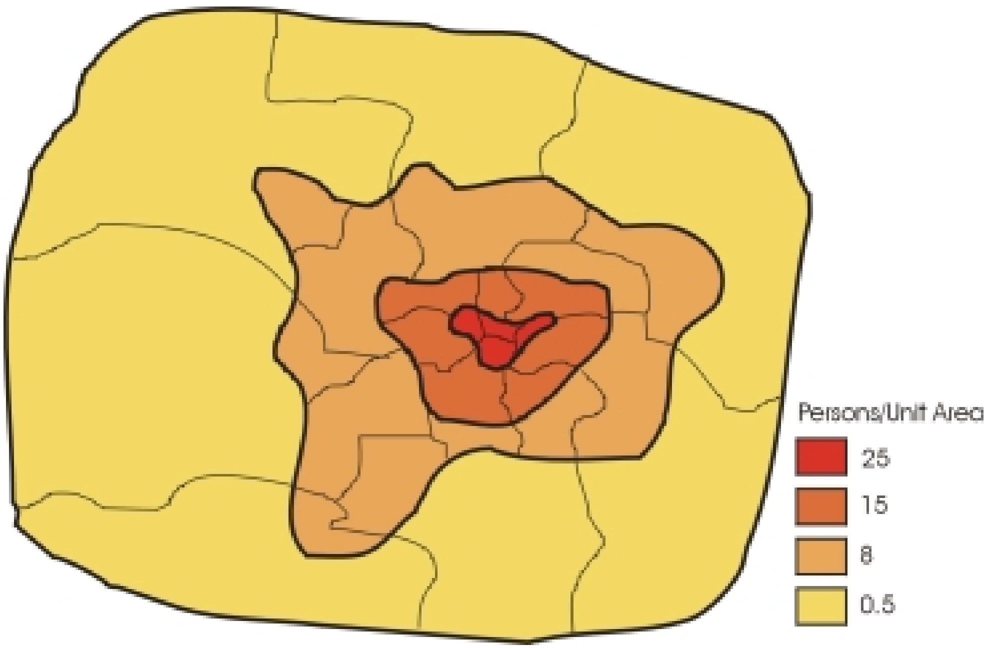

Figure 2. Illustration of population density zones for a hypothetical nuclear - form region

Table 1. Portion of a results table for a hypothetical nuclear - form region using population density to define assessment zones.

	Population density zones (persons per unit area)			
	25	15	8	0.5
Area	500	2,000	7,500	15,000
Total population	12,500	30,000	60,000	7,500
% impervious surface	96%	75%	25%	10%
% agricultural land	0%	0%	3%	10%
vehicle miles / capita - year	12,500	18,000	21,000	25,000

This method for evaluating resource efficiency is easy to model and interpretation of the results is relatively straightforward. Implementing this method in a geographic information system (GIS) would be a straightforward task, an attribute in its favor, however it contains some inherent difficulties. The outer limits of the region must be defined prior to data collection, resulting in the requirement to define at least a working boundary. This complicates the analysis of different measures, since the spatial boundaries may vary between measures (e.g. watershed boundaries and transportation routes). Secondly, the spatial relationships within the region are mostly lost in the conversion to a tabular format. Conversion of the data to a tabular format also complicates the comparison of different regions, especially if there are many density zones. However, by analyzing the tabular data in concert with a graphical representation of the region (i.e. a map), spatial variation and regional type can both be understood.

3.2 Regional Characteristic Curves

Categorizing the form of an urban region requires that a judgement be made based on the spatial organization of its constituent parts. None of the existing measurement methods reviewed briefly above are particularly sensitive to spatial relationships. The measurement of regional characteristic curves arose out of the desire to categorize actual regions into form types so that a comparative analysis of the resource efficiency of those forms could be conducted. This method is designed to generate a separate characteristic curve for each area-based aspect of interest without having to define a regional boundary *a* *priori*. These aspects include population density, energy consumption per capita, area of agricultural land, percent impervious surface, and percent canopy cover, for example, and can be aggregated into geographic units, such as census blocks or ZIP codes. Taken together, these characteristic curves present a signature of the region that includes a categorization of the form of that region. Population density is used here as an example to explain the method, but should not cause confusion with Ewing's urban density functions, which are illustrative plots of density versus distance from downtown (Ewing 1997).

The method begins with the determination (or selection) of the center of the target region. This center point can be the main street intersection, a regional population centroid, a city hall, or some other obvious social or natural regional center. The characteristic curve is then assembled as a series of points in an X – Y plot, each point the result of evaluating the quantity of interest (population density, for example) for a circular area centered at the center of the target region, as depicted in Figure 3. The first point in the regional characteristic curve results from evaluation over the smallest radius circle, the second point corresponds to the next larger radius circle, and so on. The quantity of interest is evaluated over the whole circle at each step, not just over the annulus between the previous and current circles, so that each point in the characteristic curve represents the entire circular region for that step and not just the incremental region added since the previous step. The X – axis of the characteristic curve plot contains the values of either the area included in the evaluation circles or the radii of the circles, the Y – axis contains the matching values of the quantity of interest. Open water or other areas determined to be "out of bounds" are excluded from the calculations. Allowing for excluded area is the reason for plotting area on the X – axis instead of radius, which does not account for excluded area. Alternatively, evaluation circle radius could be plotted on the X – axis and any excluded area would become part of the measured quantity of interest. The expectation is that these characteristic curves contain features that are useful for categorization: inflection points, minima, maxima, plateau values, and significant slopes. The presence of these features and the evaluation circle area at which they occur are all condensed data that are characteristic of the region and provide a basis for discriminating between form types. The process of constructing a regional characteristic curve for a hypothetical region is depicted in Figure 3.

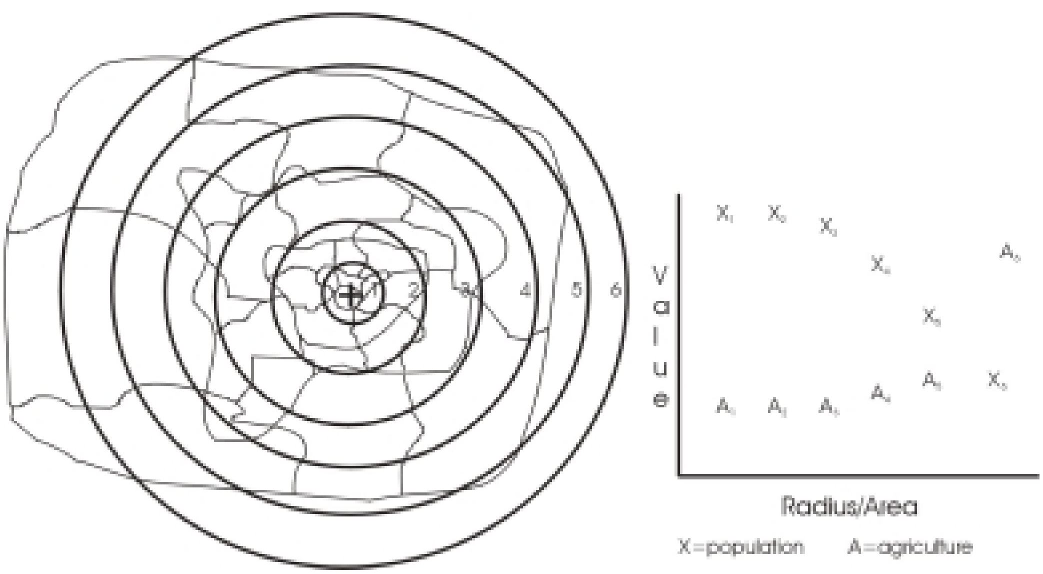

Figure 3. Construction of regional characteristic curves for a hypothetical nuclear - form region measuring population density and agricultural land area. The subscripts in the plot on the right correspond to the evaluation circles in the regional map on the left.

Several practical questions arise at this point. First, how big or small should the first evaluation circle be? Second, how large or small should the steps in evaluation circle radius be? Third, when should evaluation cease? The first evaluation circle radius can be as small as data allow but should be no bigger than the smallest scale of data variability. In addition, the steps in evaluation circle radius should not be so large that significant features are missed. The cost of a small starting radius and small radius increment are both the same: increased computation. The question of determining when evaluation should cease – the boundary of the region – is more elusive. In some cases, it may be obvious that there is not much to be gained from continuing if the curve is changing slowly or not at all. In regions where there is variability over large areas, or the land pattern merging with other adjacent regions, the decision to cease evaluation will be less clear cut.

There is also a question of how to handle evaluating the quantity of interest when the underlying data have been aggregated over some geographic unit. This situation will cause difficulties when a geographic unit is divided by an evaluation circle so that it lies only partway in the circle. A simple, though ultimately incorrect way to deal with this is to assume that the entire area is homogeneous and divide the aggregate value in proportion to the area included in the circle. This is a quick solution that will not generate excessive errors so long as the underlying geographic units are small enough or shaped so that they lie mostly in (or out) of the evaluation circles. The closer a geographic unit is to being fully included, the more accurate the aggregate value reflects the true value over the area included in the circle. A more accurate approach, especially when dealing with larger geographic units, is dasymetric mapping (Fisher & Langford 1996). This technique uses auxiliary information from other data (such as land cover) to guide the process of apportioning data from the original geographic unit to subunits, including those resulting from division by the evaluation circle. For the example of population, forest, open water, and agriculture land cover types (among others) can be excluded from the process of apportioning population to geographic subunits since these cover types are assumed to have relatively little population. This allows population to be apportioned to the developed areas in which it is actually located.

The primary constraint of the method as described is that it has limited ability to discriminate asymmetric forms, at least when the characteristic curves are examined individually (i.e. one quantity of interest at a time). Characteristic curves tell us something about the spatial structure of the region, but may not capture all of the form information needed for categorization since they are blind to spatial variations at any given radius. For example, high values of population density in the north can be counteracted and masked by low values to the east. A modification that addresses this difficulty with individual curves is the construction of characteristic curves separately for sections of evaluation circles (quadrants, octants, etc.). Generating four or eight curves for each quantity of interest adds discriminatory power at the cost of some loss of interpretability. On the other hand, examining the several curves for different quantities of interest that make up the regional signature may also address this difficulty in a slightly different manner.

In summary, regional characteristic curves have properties that lend themselves to assessing regional resource efficiency. First, they remove the need to determine regional assessment boundaries *a priori*, though this need may possibly be replaced with the need to determine when to cease evaluation. Secondly, a degree of the original spatial relationship within the region is preserved with these curves, though a higher degree is preserved in the directional versions (quadrant, octant, etc.). Thirdly, some spatial information is preserved even though the curves condense the large amount of information contained in the original data set into the two dimensions of evaluation circle area/radius and attribute value. Finally, regional characteristic curves are directly connected to the landscape from which they are derived and provide a basis for categorizing regional form and performing comparative resource efficiency analysis by, in part, assembling a multi-attribute signature of a region.

4. Conclusions

The sustainability debate has been focused too closely on the urban and suburban segments of human settlements and has not sufficiently considered the surrounding land matrix. A holistic and more integrated regional perspective is proposed in efforts to assess sustainability, which is defined here as resource efficiency, a measure of the impact of human settlements on natural resources or natural capital. Since sustainability is, by definition, about connections and relationships across both space and time, a perspective that incorporates more of these connections will result in more useful and informative assessments. New methods presented here embrace this regional perspective and provide insight into regional properties that has not been demonstrated by any of the existing methods reviewed, as well as providing a basis for regional comparisons that highlight more or less sustainable land use patterns and practices.

Further work will require the application of the proposed techniques of population density zones and characteristic curves to a number of regions with different forms, including conducting analysis related to population, water quality, energy use, transportation, habitat, and agriculture. These results, in addition to refining the calculation methods, will enable an evaluation of the methods' ability to adequately characterize regional form. These methods enable the categorizing of regions according to Brabec and Lewis' typology of regional form, allowing the comparison of resource efficiency between types. In the case of the regional characteristic curves, the method results in elegant graphical representations of regional properties that do not require extensive and detailed data to construct and are directly tied to the landscape on which they are measured. Although the properties of the regional characteristic curves are not yet fully documented, application of this method to a series of regions that exhibit traits of the different regional types will allow these properties to be determined. These investigations into the properties of regional characteristic curves and population density zone analysis will indicate the value these methods have in conveying information about the relative sustainability of different land use patterns created on the landscape.

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