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Regional land pattern assessment: development of a resource efficiency measurement method

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Abstract

Debate on the sustainability of human settlements has recently been focused primarily on the urban portion of the land use pattern. However, urban areas rely on suburban, rural, and other less densely settled lands for their existence. In order to quantify the impacts of various land patterns on their supporting resources, these exurban lands must be included in any sustainability assessment. This need for a regional view has resulted in a measurement method that enables comparisons of relative sustainability between various regional land use patterns. Existing methods employed to assess urban sustainability are reviewed and compared with the regional characteristic curves method, introduced here, that takes a more holistic regional view. Results from the application of the method are presented, displaying the spatial dimension it brings to the analysis of illustrative primary metrics as well as demonstrating its ability to spatially quantify change in these metrics over time.
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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. During that time, both the terms ‘sprawl’ and ‘sustainability’ have become catchwords in the popular media. Although most commentators agree that sprawl is ‘unsustainable’ as a land pattern that affects the ecological, social, and cultural fabric of communities (Diamond and Noonan, 1996), there has been debate over the severity of its effects. Some have even argued that polycentricity and sprawl, a low-density development pattern in which land is consumed at a faster rate than can be

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explained by population growth alone (Fulton et al., 2001), are inevitable and desirable consequences of the post-industrial city (Gordon and Richardson, 1996, 1997).

This debate over the pattern of land use and land cover lies at the center of land planning and growth management across the United States and throughout the world. A comparative analysis of the sustainability of alternate land patterns is necessary to support informed and valid responses in this debate. Perhaps more importantly, if political decisions to limit sprawl are to be actualized at the national, regional, and local levels, the analysis must be presented in a form that is easily accessible to a broad spectrum of society. Given the current state of research, analysis, and analytical methods, three primary issues emerge that constrain our ability to complete this type of comparative analysis. First, there is a tendency towards a focus solely on the (politically) bounded urban portion of the landscape, following the rationale that the majority of human impacts occur where the majority of humans are (Baccini and Brunner, 1991). This focus on the urban portion of the land pattern neglects the critical regional-scale interaction of suburban and rural land areas with each other and with the urban center. Lacking a holistic perspective of regional land patterns in all their complexity, it is difficult to adequately differentiate between more or less efficient land use patterns. A comprehensive discussion of the differential sustainability of land pattern and the effects of sprawl must be based on a regional perspective, since sprawl by definition includes land area other than the traditional urban core.

The second issue in analyzing the affect of land pattern on sustainability is the question of what to measure. Many sustainability analyses review the broad spectrum of topics that make up sustainability: politics, economics, ecology, and social issues (Alberti, 1996; Maclaren, 1996). However, the key factor in analyzing the effect of land pattern on sustainability is the quantification of an urban area's impact on its constituent ecological systems. Resource efficiency, a component of the larger concept of sustainability, describes the impact a region has on its ecological basis through the use and alteration of fundamental water, land, and energy resources. Regions that use fewer resources for a given function (i.e. are more resource efficient) will theoretically be better able to continue to function as these resources become scarcer and more costly.

Given the necessity for a regional perspective and the desire to analyze various land patterns by measuring resource efficiency, the third issue in conducting an analysis of land pattern and sustainability is the lack of an appropriate measurement method. A regional measurement method must be easily adaptable to various regions and a variety of metrics, providing a basis for equitable comparative assessment of the relative efficiency of alternative land patterns. Measurement approaches have been developed to assess sustainability across a variety of geographic scales ranging from local communities to the entire planet. These methods can be collected into three general categories: indicator frameworks, (urban) metabolism (Wolman, 1965), and the ecological footprint (EF) (Rees, 1992; Wackernagel and Rees, 1996).

Indicator frameworks collect sets of individual indicators (Arnold and Gibbons, 1996; Haberl, 1997), sometimes aggregating them to develop an overall index (Alberti, 1996; AtKisson, 1996; Maclaren, 1996; Sawicki and Flynn, 1996; Whitford et al., 2001). While indicator frameworks bring a large amount of disparate information together, in their presentation these frameworks necessarily tend to emphasize the separation and incommensurability of their constituent parts. Interpretation requires, in many cases, a high level of expertise and is complicated by multiple interpretations of the significance of particular indicator values.

The urban metabolism concept has been used repeatedly and expanded upon by other researchers since Wolman (Baccini and Brunner, 1991; Decker et al., 2000; Haberl, 2001). The metabolism approach to assessing an urban area involves quantifying all of the flows of material and energy into and out of a bounded area. Metabolism assessments are also sometimes called material flow analyses (MFA), for obvious reasons. There are several shortfalls in applying the concept of urban metabolism to an assessment of regional resource efficiency. The idea of an urban metabolism, 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' (Baccini and Brunner, 1991; Haberl, 2001). While this is 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 land patterns or their associated resource efficiency. Particularly in the case of a sprawling land pattern, it is extremely difficult to define the boundary between what is urban and what is exurban (defined here as the suburban and rural land outside an urban area). It is also difficult to delineate an outer boundary for a functional region to enable a regional resource efficiency analysis using metabolism methods.

A third method, the ecological footprint (EF), 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. 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, etc. 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'). Usually, the EF of a population is compared to the actual land area the population occupies, with an EF larger than the occupied area implying an unsustainable condition.

Ecological footprint analysis is a powerful tool in that it results in an easily communicated estimate of human impact that does not require expertise or special training to understand (Costanza, 2000). However, the EF has two main drawbacks in its application to regional land pattern. While the method involves calculating separate ecological resource inputs and use, the final footprint measure is highly aggregated and does not explicitly consider impacts within the target population's region. The more serious fault is disconnection from local ecosystems, since it is vital to understand specific impacts to ecological resources and how these impacts change with a change in land pattern. While recent work of Luck et al. (2001) and other investigators has acknowledged and attempted to address these constraints in the EF without compromising its positive traits (Borgström Hansson and Wackernagel, 1999), the inherent lack of spatial relationship in the ecological footprint concept reduces its utility in the measurement and assessment of regional land patterns.

While each of these methods have their own, they have limited applicability to the issue of measuring the regional resource efficiency of land patterns. First, these measurement methods have a primarily urban focus and require that an urban or regional boundary be defined a priori. This boundary delineates a land area or a population of interest and highlights the separation of the area (or population) under study from its ecological basis. Although these methods' theoretical basis relies on an urban focus to define the region of interest, they lack an acknowledgment and accounting of the interconnections with the region and, in the case of indicator frameworks and the ecological footprint, have issues of interpretability related to aggregation. Finally, these methods all lack the spatial specificity that is essential in comparing the relative effects of various land patterns on the resource efficiency of a region. In order to advance the state-of-the-art in assessing the regional resource efficiency, this paper explores the development of a method specifically for the analysis of a regional land use/land cover pattern's resource efficiency.

1.1. Regional measurement method development and test case evaluation

Most of the difficulties inherent in existing measurement methods (urban focus, boundary issues, loss of spatial information) result from a theoretical construct that defines the urban area apart from its exurban matrix. Historically, typologies for urban systems have focused on the outline of the urban area. Lynch (1954) and Bacon (1976) defined four urban forms—nuclear, linear, stellar, and constellation—that have become common in discussion of urban land patterns. Since they are based on historical growth patterns, they are defined by their pattern of expansion from a small central locus, outward to a larger urban entity.

These four urban patterns have regional form analogues, and it is the regional characteristics of that form that are key to the development of a regional measurement method. For example, the classic urban form is a compact, nuclear urban center growing more or less uniformly outward. Applied to a regional context, the higher density nuclear urban center is surrounded by a low density, rural matrix with a well-delineated boundary between the two. The second and third forms, the linear and stellar, exhibit their characteristic shape as a result of two or more fingers of growth extending out from the central locus into the rural matrix. The boundary remains clearly defined by the break between urban and rural land uses. This type of expansion typically occurred along

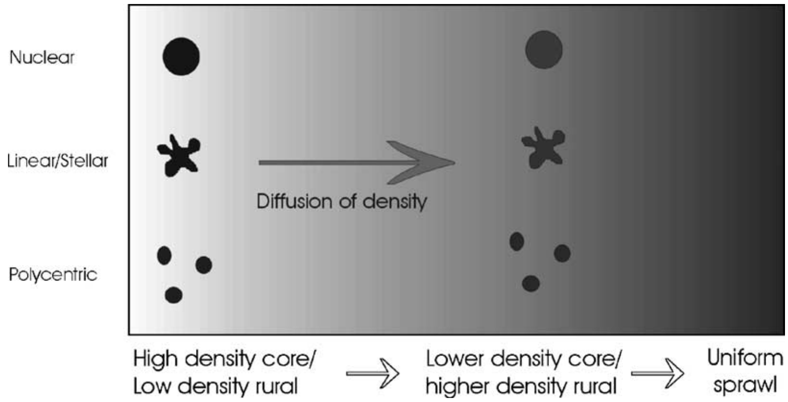

Fig. 1. Extended typology of regional form illustrating the continuum from high density urban cores of various types (dark) in a rural matrix (light) on the left to uniform sprawl (gray) on the right. Degree of darkness in the figure relates to density of settlement on the land.

a railroad, mass transit, or highway corridor and is exemplified by early railroad towns across the US.

Lynch's constellation city provides the basis for the fourth type of regional land pattern. This is the polycentric city, defined as a series of interrelated nuclear cities joined by transport and proximity to form a functional whole (Lynch, 1954). Growth patterns in the latter half of the 20th century have created a regional form of this pattern, exemplified by a series of core areas embedded in a matrix of urban sprawl (Gordon and Richardson, 1996). This pattern may have developed with low-density residential growth engulfing existing nuclear urban areas, or through the development of dense service nodes within a sprawling matrix.

While these four urban forms remain identifiable in the American landscape, 20th century growth patterns have had a tendency to dilute their unique signature. The tendency of growth to thrust outward at a lower density than that exhibited in the urban core has obscured the boundary between urban and rural to the point where in many cases it has become a density gradient or has disappeared completely in a largely undifferentiated pattern of sprawl. A fifth regional form, sprawl, exhibits largely uniform land uses and densities in its purest expression. In most cases, however, the former nuclear, linear, or stellar urban core expands at a lower density, with little further differentiation in either density or land use, to cover the formerly rural land matrix.

In the regional context, it is important to view this typology of five regional forms not as individual prototypes, but as a continuum. Fig. 1 depicts such a typology continuum with well defined urban centers in a rural matrix represented by dark forms on a light background at one extreme on the left side of the figure and the undifferentiated land cover associated with sprawl represented by a uniform gray tone on the right. A region may be defined at any point along the continuum within the context of measuring and comparing the resource efficiency of various regional land patterns. Regions may be obvious in form, with dense core and surrounding rural matrix, or may be administratively defined ad hoc, without a distinct center, at the desire of several political jurisdictions to compare alternate future land patterns. Thus, the measurement method must be able to respond to both the existence and lack of an identifiable center in a region under study. It is also incumbent upon a viable regional measurement method to read and reflect the differences in these development patterns, presenting a 'picture' of the relative resource efficiency displayed by a land pattern located at any point along the continuum of regional forms.

1.1.1. Developing an approach to regional measurement

Considering the foregoing analysis of current measurement methods and the characteristics of regional land patterns, it is critical for the regional measurement method to have three characteristics: (1) ability to accommodate a region of any size and shape, with or without one or more defined loci; (2) preservation of spatial information and a sense of scale to permit comparison between regions with different existing patterns or between different potential land patterns within a particular region; and (3) independence from political boundaries. These desired properties are in large part determined by the choice of the shape and size of the area over which metrics are evaluated.

Inspiration for this choice comes from the field of spatial statistics. The study of spatial statistics is concerned with the description and explanation of processes and patterns for which location is an important factor (Cressie, 1993; Bailey and Gatrell, 1995). Three functions used in spatial statistics provide a basis for the development of a regional measurement method: the *K* function, the variogram, and the correlogram. The *K* function is used in the analysis of point data patterns. It estimates the mean number of point events per unit area in a region by using a series of concentric circles centered on each point and counting the number of other points within each circle. After normalizing for regional area and edge effects, the *K* function value is plotted against circle radius. The variogram is used in the analysis of continuous data to estimate the dependence of spatially separated measurements on each other. A variogram is calculated from samples of the underlying continuous data, and values of the function are plotted against spatial lag, another term for distance or range of distances between samples. Similar to the variogram, the correlogram is used to display spatial dependence information against lag, however the correlogram is used with area data.

These functions characterize spatial data in a region as a function of distance. This central idea, combined with the use of concentric circles as a basis for evaluation and plotting of function values against distance, informs the structuring of a regional measurement method. By repeatedly evaluating a given metric over a series of concentric circles, a corresponding series of metric values is generated, as in evaluating regional *K* functions. Each circle is used as the basis for calculating an aggregate value of the metric. This series of metric values, one for each circle, is plotted against the corresponding values of circle radius as points in an *X*–*Y* plot, just as in plots of *K* functions, variograms, and correlograms. The first point results from evaluation over the smallest radius circle, the second point corresponds to the next larger radius circle, and so on. This process results in the creation of a graphical image that is characteristic of the measured region for a given metric. This image is termed a regional characteristic curve. Characteristic curves contain features useful for categorization and comparison: inflection points, minima, maxima, plateau values, and slopes. The presence of these features and the evaluation circle radii at which they occur are all condensed data that are characteristic of the region and provide a basis for comparison with other regions.

The use of concentric circles is reminiscent of the theories of Johann–Heinrich von Thünen (Kolars and Nystuen, 1974). In 1826, von Thünen published *Der isolierte Staat* in which he presented an economic argument that explained patterns of agricultural land uses (von Thünen, 1826). He concluded that these patterns arose out of the interaction of the value of agricultural products (their economic rent) and their transportation cost. The simplest case assumed an equally productive landscape devoid of obstacles, and the resulting pattern in this case was a series of concentric circles around the central market, with intensity of use decreasing with distance from the center. More recent investigators have revisited von Thünen considering the expansionary nature of modern urban areas (and attendant effects of changing economic forces) and concluded that, while the intensity of agricultural use still changes with distance, it generally becomes more intensive farther away from the center (Sinclair, 1967). This inversion of the classic von Thünen pattern is traced to speculation in land values nearer to urban areas and more available and widespread transportation.

While this theoretical construct connects circular form with land patterns, there is a significant difference between von Thünen's concentric circles and those used in this evaluation method. von Thünen developed his theory to explain circles visible in the pattern of land use as a result of economic forces. However, the evaluation circles used in the regional measurement method serve only as the geographic basis for the evaluation of a chosen metric and are often not apparent on the landscape.

The regional characteristic curve method described above accommodates regions of different spatial extent and shape by using a series of concentric circles of graduated size and, as long as the underlying data are available, is independent of political boundaries. By using the same shape regardless of the form of the region under study, different regions can be compared without measurement method bias. The presence or absence of loci in the region is immaterial to the operation of the method, though the presence of a single locus provides an obvious center for the evaluation circles. A single locus also provides an anchor for interpretation of the regional characteristic curves by tying them to a known point on the landscape.

1.1.2. The test region: Ann Arbor, Michigan and surrounding land area

The first step in the evaluation of the measurement method was the selection of a test region. The Ann Arbor, Michigan region was chosen as a 'test of method' case for two primary reasons. First, it forms an identifiable region of interest, containing characteristics of an historic urban nucleus while also exhibiting sprawling growth. Due to its growth history and current land pattern, the Ann Arbor area also forms a functional region, with the city of Ann Arbor serving as a political and economic center for the surrounding areas. Although a particular center may be suggested by the metric being evaluated—a farmer's market as the center for an agricultural land metric or a central business district for a commuting/transportation metric—in this case the historic economic center, the intersection of Huron and Main Streets in Ann Arbor, provided a readily identifiable central point for the study.

The second important reason for selecting the Ann Arbor region as an initial case was that high resolution digital geographic data layers were readily available for the region. Data were collected for all of Washtenaw County, which includes Ann Arbor, for two time periods (1975 and 1998). Also, county scale data enabled an investigation of edge effects on the measurement method since the political boundary of Washtenaw County provided a sharp edge with no data for adjacent counties.

As part of the larger, seven-county southeast Michigan region, Washtenaw County is located approximately 30 miles west of downtown Detroit. The county comprises 24 primary political divisions including Ann Arbor (2000 population 114,024), Ypsilanti (pop. 22,362), the smaller towns of Saline (8034), Chelsea (4398), Dexter (2338), and Manchester (2160) and portions of the towns of Whitmore Lake (6574) and Milan (4775) (Fig. 2). Ann Arbor's economic activity relies heavily on the University of Michigan as a major employer, with a strong research and development sector related to the university. The surrounding more rural area's historical growth pattern is characterized by small market towns serving the agricultural land base. Residential growth has been strong in the last decade, leading to residential sprawl primarily to the east and south of Ann Arbor.

Ecologically, the Huron River watershed dominates the region. The Huron flows into the county from the north, bisects the city of Ann Arbor, and eventually empties into Lake Erie to the southeast. The northwestern portion of the region is distinguished by greater topographical relief, less arable glacial soils, and a large area of state-owned recreation land. In contrast, the southwestern and southeastern portions of the region contain the most productive agricultural land and expanding rural residential areas.

1.1.3. Selection of test metrics

Resource efficiency, as defined in this paper, describes the impact a region has on its ecological basis through the use and alteration of fundamental water, land and energy resources. To be of the greatest value in measuring the resource efficiency of a land pattern, a test metric must be closely tied to both the intensity of the built environment and the degree of impact on the resource. Three metrics at the core of the resource efficiency concept were chosen for evaluation in this regional analysis: impervious surface (a water quality metric), agricultural land (a food production metric), and open space (a habitat availability metric). These metrics were chosen primarily due to the availability of data for the test site. In the case of agricultural land and open space, there was a simple (positive) correlation between the amount of the land use type present and the quality rating of the resource. With respect to impervious surface, it was also chosen as a metric since it has a high level of acceptance in the literature as a water quality metric (Morisawa and LaFlure, 1979; Arnold et al., 1982; Bannerman et al., 1993; Brabec et al., 2002). Impervious surfaces influence the quantity and quality of water resources by altering the partitioning of rainfall between surface water runoff and groundwater recharge. As such, they are a physical manifestation of a land pattern's spatial properties, as both the density and location of the impervious surfaces will differ between various regional patterns, from compact to sprawling. The area of impervious surface in a region is measured from aerial photos or inferred from existing land cover/land use classification data (Martens,

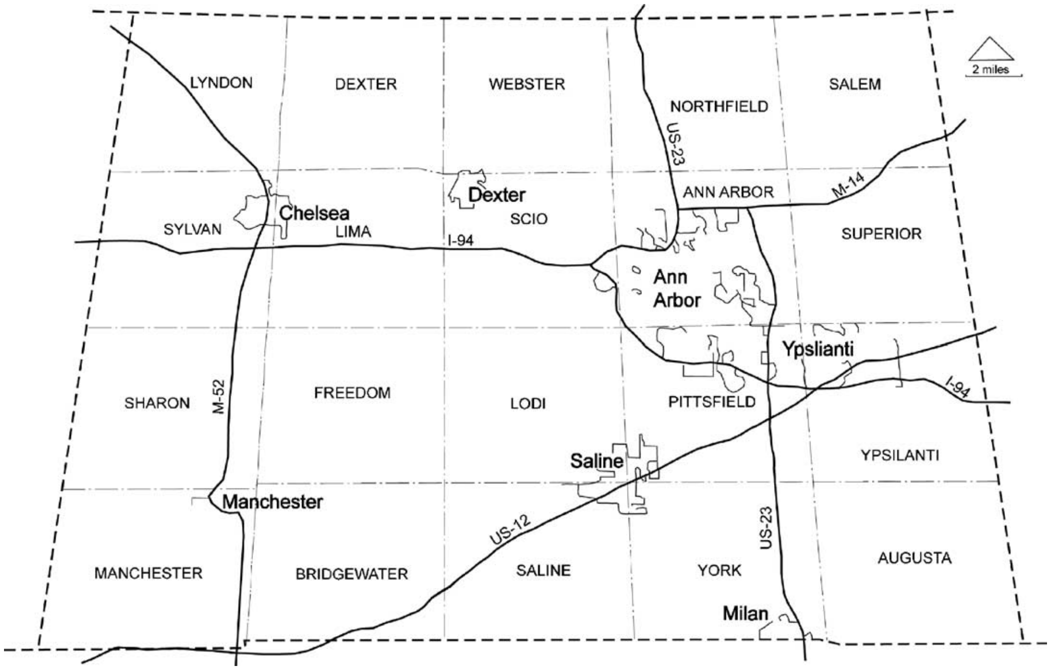

Fig. 2. Washtenaw County, Michigan, townships, towns, and major highways.

1968; Hammer, 1972; Graham et al., 1974; Gluck and McCuen, 1975; Ragan and Jackson, 1975).

All of the selected test metrics are readily measured from land cover data, and the data sets needed to characterize these metrics were available for Washtenaw County at multiple points in time. Vector data sets used in this analysis included 1995 land cover/land use from the Southeast Michigan Council of Governments (SEMCOG) and 1978 land cover/land use from the Michigan Resource Information System (MIRIS). Although separated by almost 20 years, these data sets were developed using comparable methods, photo quality and land classifications. The 1995 edition of the data was developed directly from the 1978 layer. Land cover/land use categories were coded as standard two-digit (SEMCOG) and three-digit (MIRIS) values using the generic classification system developed by Anderson et al. (1976) and published by the US Geological Survey. The metrics are presented as a percentage of total land area.

In order to calculate the amount of total impervious surface in the region, land cover/land use codes were grouped into categories based on their imperviousness properties. Values for the percentage of total impervious surface area (TIA) were assigned to each land category based on measurements conducted by the Wayne County Rouge River Program Office (Rouge Program Office, 1994) (Table 1). The Rouge watershed is adjacent to and north of the Huron and has a comparable variety and intensity of land covers.

The imperviousness values for each land cover category (as %TIA) were used as shown in Eq. (1) to estimate the total impervious area percentage on a regional basis. Note that surface area covered in water was included in the imperviousness metrics because water land cover types were assigned an imperviousness value in the Rouge watershed data.

$$\%\mathrm{TIA}_{\mathrm{region}} = 100 \times \frac{\sum_{\mathrm{cat}}(\mathrm{Area}_{\mathrm{cat}} \times \%\mathrm{TIA}_{\mathrm{cat}}/100)}{\sum_{\mathrm{region}} \mathrm{Area}} \qquad (1)$$

Eq. (1): calculation of percent total impervious area by land cover category.

The amount of land currently in agricultural use was employed as a metric related to the local (regional) production of food. The presence and location of prime agricultural soils could also be used as an agricultural metric, but this quantity is more closely related

Table 1
Land cover categories and associated total and effective total impervious area (TIA) percentages

Category description	MIRIS land use/land cover codes	SEMCOG land use/land cover codes	%TIA
Forest/rural open	3x, 4xx	3xxx, 4xxx	1.9
Urban open	193, 194	19xx	10.9
Agriculture/pasture	2x	2xxx	2.0
Low density res	1133		18.8
Medium density res	113, 115	1130, 1150	37.8
High density res	111, 112	1110, 1120	51.4
Commercial	12x	12xx	56.2
Industrial	13x, 14x ex. 144, 17x	13xx, 14xx ex. 1440, 17xx	75.9
Highway	144	1440	52.9
Water/wetlands	5x, 6xx	5xxx, 6xxx	51.2

to *potential* agricultural production. For this reason, and since soil maps indicating prime agricultural soils were not available in digital form, this analysis relied on a metric based on existing agricultural land, which is identified in both the SEMCOG and MIRIS data sets. All surface area covered by water (Anderson land use/land cover codes beginning with the numeral 5) were excluded from total surface area in percentage calculations for agricultural land metrics. Percentage of land area in agricultural use (all Anderson land use/land cover codes beginning with 2) was calculated using the sum of agricultural land areas as a fraction of the total surface area (excluding area covered by water).

The amount of land categorized as open space was used in this analysis as a simple metric of habitat availability. Land that is ‘open’ or not built upon (identified in this analysis as percent land area) is easily determined from both MIRIS and SEMCOG land cover data sets. Although this initial analysis used open space as a proxy for available habitat, a more comprehensive analysis of actual viable habitat would disaggregate the open space to assess the habitat quality of these lands. Such a habitat assessment could also employ patch-based metrics (McGarigal and Marks, 1995), including such measures as patch size, density, connectivity, variability, diversity, contagion, and interspersion (Forman, 1995; Turner et al., 2001). Percentage of open land area was calculated using the sum of the land use/land cover codes listed in Table 2 as a fraction of the total surface area. Again, as with agricultural land metrics, all surface area covered by water (Anderson land use/land cover codes beginning with the numeral 5) was excluded from total surface area in percentage calculations.

1.1.4. Basis of comparison—a traditional analysis

A traditional regional planning analysis begins with a map of the study area, often in digital form in a geographic information system (GIS). The GIS usually contains a number of layers of point, line, and area data for the same geographic area, including, for example, survey monument locations, roads, waterways, parcel boundaries and ownership, and land cover. These data layers are generated from data collected over smaller geographic entities, such as municipalities, townships, and counties, but can be combined into metropolitan, state, and larger units depending on the requirements of a particular analysis. Once an area of study has been determined, the GIS is used to analyze and organize layers of data and produce tabular summaries based on the study area boundaries. A study area can be determined by a political or natural boundary (e.g. a watershed), and data can be tabulated by subdivisions of the study area that exist in the original data layers, townships or subwatersheds, for example. If the data are available for more than one date, tables can be generated for these data and used to calculate trends over time.

Table 2
Land use/cover codes included in ‘open space’

Land use/cover code	Description
1930	Outdoor recreation
1940	Cemetery
All 2xxx ex. 2300, 2500	Agriculture ex. confined feeding, farmstead
All 3xxx	Nonforested herbaceous and scrub
All 4xxx	Forested
All 6xxx	Wetlands
7200	Beach
7300	Sand dune

Once tabular data are generated, much of the spatial information has already been lost, either through aggregation over large political or natural areas in the original data layers or through loss of adjacency or connectivity in tabulation. This can be mitigated by dividing the study area into smaller geographical areas, such as multiple political jurisdictions, and relying on the resulting tables to contain more spatial information. A standard planning analysis was completed using the Washtenaw County data set and its 24 component political jurisdictions to provide a basis for comparison with the regional characteristic curves method.

1.1.5. Method refinement test 1—rings versus circles

The first test conducted to refine the method compared the results of using concentric rings (annuli) instead of circles as the basis for evaluation. This test was intended to assess the relative ability of both methods to preserve spatial information. The hypothesis was that rings would preserve more of the spatial information in the underlying data, since circles would result in large-area average metric values that would obscure or obliterate important spatial information.

Metric values for rings were derived from existing results calculated over circles. Each ring was defined as the incremental area between one circle and the next larger one in the series. By subtracting the metric value of the smaller circle from the larger one, metric values were calculated for each ring. Regional characteristic curves based on rings and those based on circles were plotted on the same axes for comparison. Twenty-five circles were used in this analysis, in radius increments of 1 km, and these circles were used to generate 24 rings (the smallest circle was also used as the smallest ring). Washtenaw County's census block boundaries are depicted in Fig. 3 with a series of 1 km radius increment evaluation rings superimposed to allow a comparison of the radius values with underlying features in the county.

1.1.6. Method refinement test 2—ring radius increment

The second test of the method evaluated the impact of altering the ring radius. Radius increments of 1 and 5 km were evaluated using the same center point and test region data. The expectation for this test was that more information would be displayed in a curve based on 1 km rings than in one based on 5 km rings.

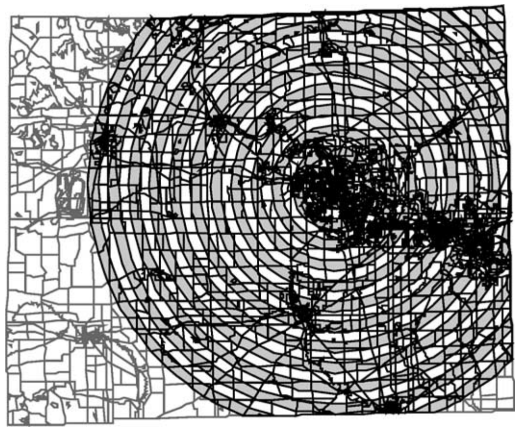

Fig. 3. Example of circles/rings used to generate regional characteristic curves for Washtenaw County, MI superimposed on census block boundaries and centered in downtown Ann Arbor.

Increased features and details within a characteristic curve translate into improved function in quantifying and comparing regions.

2. Results

2.1. Basis of comparison—a traditional analysis

A traditional regional planning analysis of the test region based on tabular data summaries provided a basis for comparison with the results of the characteristic curve method. Tabular summaries were obtained from the same data sets used to create the characteristic curves. The planning analysis detailed the total number of acres of resource lands (agricultural and open space), and their change between the available 1978 and 1995 data sets (Table 3). Additional detail was obtained from the data sets by disaggregating the data into the minor civil divisions of townships and municipalities comprising Washtenaw County. Tabular summaries provide spatial information only through use of geographic divisions and are typically compiled at the level of the smallest recognized political unit. In this case, the political divisions were the 20 townships and 4 largest municipalities in Washtenaw County (Fig. 2). Each township contains approximately 9065 ha, and the aggregate area of the entire county is roughly 183,890 ha.

Table 3 illustrates the growth and land conversion trends in the region arising from the acreage analysis.

Table 3
Conventional planning perspective on change in metrics by minor civil division between 1978 and 1995

Minor civil division	Agricultural land (ha)			Open space without agricultural land (ha)			Open space with agricultural land (ha)			Total impervious area (%)		
	1978	1995	%Change	1978	1995	%Change	1978	1995	%Change	1978	1995	%Change
Ann Arbor	193	118	−38.86	5239	4408	−15.86	5432	4526	−16.67	34.05	37.05	8.81
Milan	104	102	−1.92	55	53	−3.64	159	155	−2.36	33.45	34.29	2.51
Saline	790	794	0.51	1062	763	−28.15	1852	1557	−15.93	20.09	28.97	44.20
Ypsilanti	28	1	−96.43	454	444	−2.20	482	446	−7.50	40.79	42.43	4.02
All Municipal	1115	1015	−8.97	6810	5668	−16.77	7925	6,684	−15.65	32.10	35.69	11.19
Ann Arbor Twp	3771	3598	−4.59	5621	5075	−9.71	9392	8673	−7.66	12.07	15.68	29.91
Lodi Twp	14560	14028	−3.65	5772	4540	−21.34	20333	18567	−8.68	5.28	10.31	95.27
Pittsfield Twp	8333	7000	−16.00	6106	5248	−14.05	14438	12247	−15.18	12.41	19.49	57.05
Scio Twp	8209	6764	−17.60	9316	8013	−13.99	17526	14777	−15.68	12.41	18.59	49.80
Superior Twp	9753	9453	−3.08	9882	9321	−5.68	19635	18774	−4.39	8.9	11.21	25.96
Ypsilanti Twp	5790	5003	−13.59	6682	6320	−5.42	12472	11322	−9.21	20.35	23.93	17.59
Adjacent to Municipal	50416	45846	−9.06	43379	38517	−11.21	93796	84,361	−10.06	11.90	16.54	38.91
Augusta Twp	14999	14948	−0.34	6617	5971	−9.76	21616	20920	−3.22	5.59	7.58	35.60
Bridgewater Twp	15681	15603	−0.50	6848	6217	−9.21	22528	21820	−3.14	3.95	7.34	85.82
Dexter Twp	6371	5654	−11.25	11573	10739	−7.21	17944	16393	−8.64	14.32	18.55	29.54
Freedom Twp	14143	14150	0.05	7671	6977	−9.05	21814	21128	−3.15	5.06	7.58	49.80
Lima Twp	13973	13290	−4.89	7763	6994	−9.91	21736	20284	−6.68	8.52	11.12	30.52
Lyndon Twp	5084	4812	−5.35	14882	14335	−3.68	19966	19147	−4.10	17.82	20.3	13.92
Manchester Twp	12087	11909	−1.47	11185	10383	−7.17	23272	22292	−4.21	7.62	10.34	35.70
Northfield Twp	10909	10773	−1.25	10133	8970	−11.48	21042	19743	−6.17	9.74	15.14	55.44
Salem Twp	10746	10227	−4.83	9303	8408	−9.62	20049	18635	−7.05	8.43	10.99	30.37
Saline Twp	18161	18104	−0.31	3781	3214	−15.00	21942	21317	−2.85	3.01	6.20	105.98
Sharon Twp	14342	14250	−0.64	9139	8085	−11.53	23482	22335	−4.88	5.41	8.28	53.05
Sylvan Twp	8501	8315	−2.19	9945	10073	1.29	18446	18388	−0.31	20.66	20.38	-1.36
Webster Twp	10364	9982	−3.69	11012	9791	−11.09	21376	19772	−7.50	7.4	11.47	55.00
York Twp	14930	14549	−2.55	5300	4510	−14.91	20230	19058	−5.79	6.14	10.84	76.55
Rural	170291	166566	−2.19	125152	114667	−8.38	295444	281,234	−4.81	8.83	11.87	34.32
Total	221822	213427	−3.78	175341	158852	−9.40	397164	372,279	−6.27	13.48	17.00	26.15

Focusing first on agricultural land, the incorporated municipalities of Ann Arbor, Milan, Saline, and Ypsilanti all had modest total of 1115 ha of agricultural land within their boundaries in 1978, with Saline accounting for 790 ha of the total. These 4 municipalities lost fewer than 9% of their agricultural land resources between 1978 and 1995, down to a total of 1015 ha. The heaviest losses in agricultural land were in Pittsfield, Scio, Ypsilanti, and Dexter townships. All of these townships except Dexter are directly adjacent to the cities of Ann Arbor or Ypsilanti. Losses in open space were also significant during the 1978–1995 period. The incorporated municipalities lost an average of just under 17% of their open space. Again, losses in townships adjacent to the cities were high, with Lodi sustaining the highest losses at just over 21%, followed by Pittsfield and Scio. Loss of open space resources in rural townships was also over 10% in a number of instances, notably Northfield, Saline, Sharon, Webster, and York townships.

Examining total impervious surface area percentage, change was apparent almost across the board. In 1995, only five townships had less than 10% impervious surface area. Although urban change was not drastic in any municipality with the exception of Saline, all townships adjacent to Ann Arbor and Ypsilanti, and half of all townships in the county showed more than a 50% increase in their impervious surface area between 1978 and 1995.

While this level of analysis is useful for planning purposes, it does have its limitations. The data indicate in which political jurisdiction change occurred and the relative magnitude of that change. Growth trends and drivers (e.g. pro-growth planning policies in one jurisdiction eschewed by a neighbor) can be identified from this information. While insight into the land pattern can result from a review of the data presented in graphical form, as a choropleth map for example, this insight is significantly limited to qualitative statements regarding trends. The data do not translate well into a picture of the region as a whole, irrespective of political boundaries, nor do they provide a picture that is functionally comparable with other regions.

2.2. Evaluating regional characteristic curves

The regional characteristic curve results agree with the general analysis of the Ann Arbor region provided by traditional map and tabular data. However, the characteristic curve plots track and analyze changes in the land pattern in a way that is clearer from a regional standpoint than traditional planning methods. For example, the 1995 regional characteristic curve for percent agricultural land in Washtenaw County, Fig. 4, illustrates the general pattern of a compact downtown Ann Arbor (at the left) with virtually no agricultural land. At about 3 km from the center, the amount of agricultural land increases dramatically, transitioning quickly through the suburbs (the steep portion of the curve), into a rural/urban fringe at about 7 km from the center, and then grading into a bumpy rural portion of the curve characterized by a level of

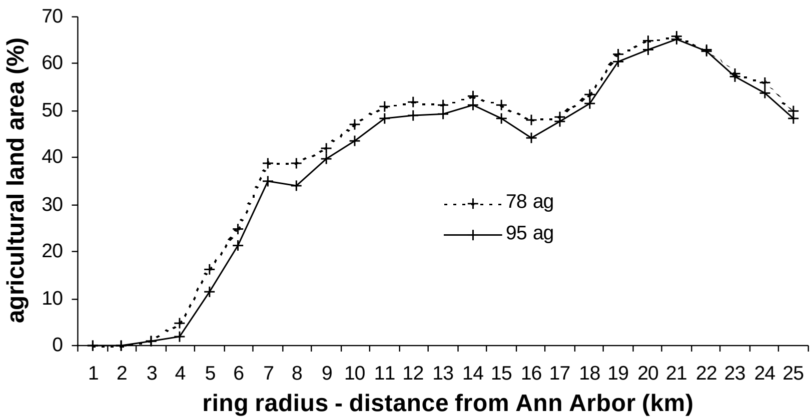

Fig. 4. Percent agricultural land, 1978 and 1995, calculated using rings.

approximately 50% agricultural land. This rural portion of the plot tells a rich story, showing a dip in agricultural land where the rings intersect Ypsilanti and the built-up US-23 corridor and where there is a relative increase in non-agricultural land cover starting 16 km from the center. The percentage of land in agriculture then gradually increases as the predominantly agricultural areas in the south central parts of the county are encountered, peaking 21 km from the center and then grading into the less arable land in the northwestern and western portion of the county where much of the land is either public recreational land or inactive farms.

These characteristics of the 1995 land cover data are heightened by comparison with conditions in 1978. The plot shows a consistent reduction in agricultural land between the two dates, with an exaggeration of the plateau at 8 km from the center where the city has been sprawling to suburban developments and the dip at 16 km, indicating the expansion of existing towns. There is a less significant loss of land in the highest portions of the curve between 17 and 25 km from the core, illustrating a more stable land cover in both private agricultural and state land.

The characteristic curves for open land plotted in Fig. 5 tell a story complementing that told by the agricultural land curves. Between 10 and 25 km from the center, the open land curve is nearly a mirror image of the agricultural land curve. This is a reasonable result in these primarily unbuilt areas since most land falls into either agricultural or open land categories. Inside 10 km in 1978 there is a steep rise in open land between the downtown core of Ann Arbor (at just over 5% open) to over 40% open land 4 km from the center, providing a picture of the suburban ring in which the availability of open space increases with distance from the center. There is a plateau at this level, with a notable peak at 8 km that reflects an area of lower density between Ann Arbor and Ypsilanti and a mostly rural section of Pittsfield Township. At 10 km, the percentage of open space gradually drops as agricultural land area increases. The most dramatic reduction in open lands between 1978 and 1995 occurs between 4 and 10 km from the center, especially 5 and 6 km out, graphically illustrating the expansion of the built areas close to Ann Arbor and their appropriation of formerly open land area.

The regional characteristic curves for total impervious surface area plotted in Fig. 6 illustrate changes combining those for agricultural land and open land above. The highly built up core of Ann Arbor is once again visible in the left hand portion of the plot, where very high values of impervious surface area change little between 1978 and 1995. Continuing to the right along the *X*-axis of the graph, suburban and fringe built areas come into play. As areas were converted from relatively pervious agriculture and open (approximately 2% TIA) to more built-up, more impervious land covers, there was a constant degradation (i.e. increase) in impervious surface properties across the test area. There are two significant plateaus in the 1995 curve, one between 3 and 5 km and one between 7 and 9 km from the center. These plateaus can be interpreted as signaling a transition in land pattern from urban at 5 km

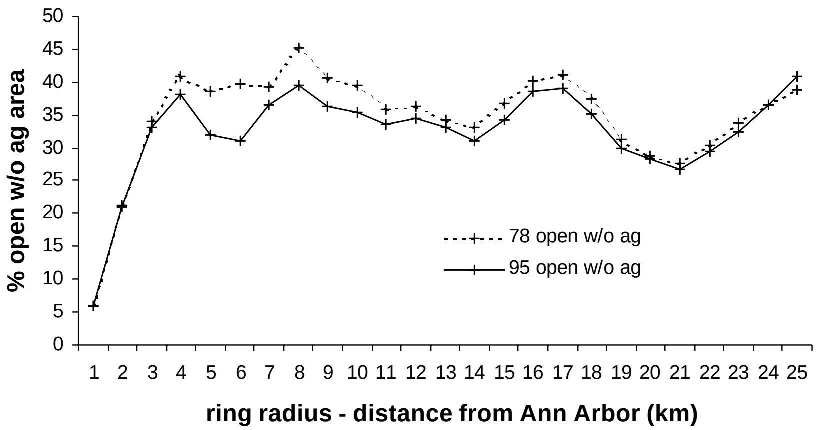

Fig. 5. Percent open space (not including agricultural land), 1978 and 1995, calculated using rings.

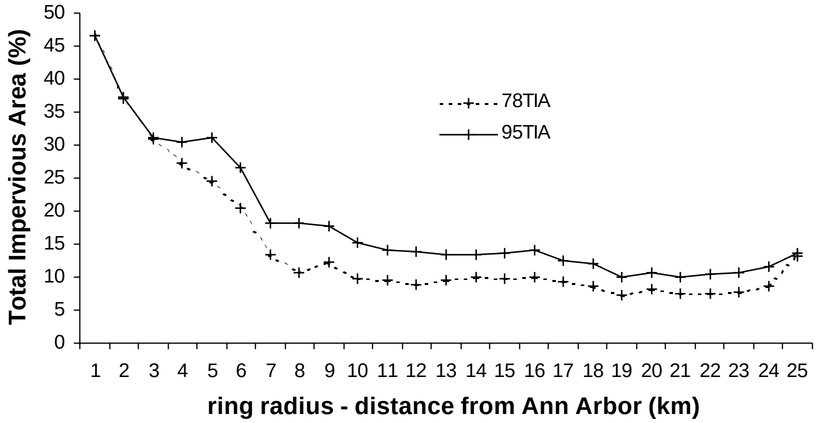

Fig. 6. Percentage total impervious surface area, 1978 and 1995, calculated using rings.

to suburban at 9 km. These plateaus are nonexistent in the 1978 curve, indicating a change in the regional land pattern between these two periods, with the plateau between 3 and 5 km especially illustrative of increased intensity of use adjacent to downtown Ann Arbor, just as in the open land plots. The other significant change in the curves lies in the fact that the impervious surface percentage does not fall below 14% in 1995 until 16 km from the center, while that level of imperviousness occurred at 7 km in 1978, indicating the sprawling increase in land cover conversion. In 1978 total impervious area was below 10% by 10 km from the center, the figure generally accepted to signal an impact to surface water quality (Brabec et al., 2002). However the total impervious value does not fall to this level at all by 1995, indicating degradation in regional water quality.

2.3. Method refinement test 1—rings versus circles

As hypothesized, when circles were used as the basis for evaluation, the resulting characteristic curve averaged the metric value over a larger and larger area, smoothing the curve and tending to obscure spatial detail related to distance from the center. Fig. 7 illustrates different characteristic curves that result from using circles and rings as the basis for evaluation of the agricultural land metric. The ring curve showed a greater degree of variation, indicating that the use of rings preserved more spatial information and provided

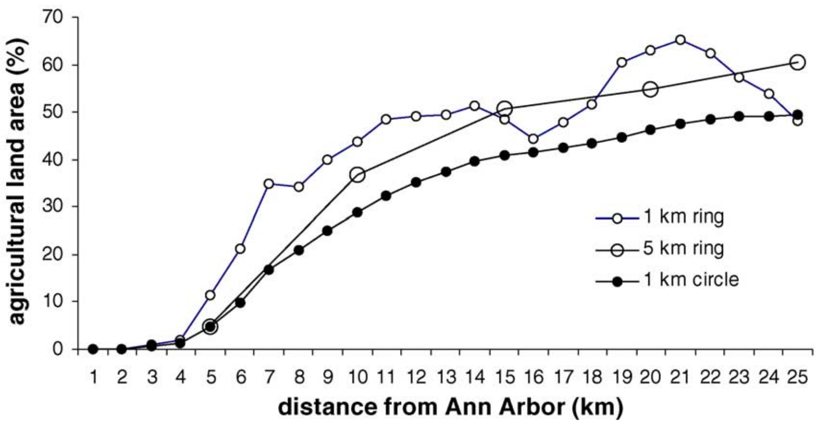

Fig. 7. Percentage agricultural land, 1995, calculated using 1 and 5 km rings and 1 km circles.

a richer understanding of metric variation across the region. The ring curve results illustrated both *how* a metric varied and *at what distance* from the center by plotting metric values at each incremental step in ring radius along the way.

2.4. Method refinement test 2—ring radius increment

The cost of a small starting radius and small radius increment are both the same: increased computation. The benefit is a smoother characteristic curve that captures the greater small-scale variation present in the underlying data. Fig. 7 also illustrates characteristic curves for the agricultural land metric calculated over both 1 km and 5 km radius increment rings. The curve generated from 1 km rings contains much more detail than the curve generated from 5 km rings, clearly illustrating the plateau at 7–8 km from Ann Arbor, the dip at 16 km, and the peak at 21 km, all of which are invisible in the 5 km ring curve. In short, the 1 km ring curve illustrates much more of the spatial structure of the variation in the land pattern than the 5 km ring curve. A further hypothesis suggested by these results is that characteristic curves will better capture underlying variation as evaluation ring radius increment shrinks to the resolution of the underlying data. Conversely, characteristic curves will obscure spatial structure if ring radius increment is larger than the scale of that underlying structure.

3. Discussion and conclusions

While each of the regional characteristic curves presented for the sample case convey a great deal of information individually, when these curves and the stories they tell are considered together, a much more comprehensive picture of the region emerges. Even though the sample case examined only a subset of the metrics that would be included in a comprehensive resource efficiency analysis, information about Ann Arbor and Washtenaw County is available and visible in the curves. The characteristic curves provide a visual summary of the region that can be used to analyze the relative sustainability of a given land pattern through the concept of resource efficiency. This visual format is accessible to both researchers and laypersons in the form of a ‘picture’ or signature of the region, while also containing sufficient richness to allow an analysis of trends and comparison between regions.

By comparison with land use/land cover maps and tabular data employed in traditional planning analyses, both the shortcomings and the additional value of the regional characteristic curves and the information contained within them becomes apparent. The characteristic curves preserve spatial information without having to define a regional boundary a priori. However, that information is presented in relationship to a single central point, a relationship that is important in tying the curves to the place they are measuring and providing a context for their interpretation. Since each metric value is an aggregate over the entire area of each ring, detailed information apparent in the tabular data can be obscured as ring radius (and area) increase. An obvious example of this effect lies in the impervious surface data. The tabular data indicate that in 1995, five townships had impervious surface percentages below 10%. However, the characteristic curve indicates that imperviousness does not fall below 10% anywhere in the region.

Based on this analysis, a primary constraint of the regional characteristic curve method as described is that it has limited ability to discriminate asymmetric forms. Characteristic curves illuminate the spatial structure of the region, but may not capture all of the underlying information since they are blind to spatial variations at any given radius. For example, high values of imperviousness in the north can be counteracted and obscured by low values to the east. Future tests of modifications to address this difficulty with individual curves should include the construction of characteristic curves separately for sections of evaluation rings (quadrants, octants, etc.). Generating four or eight curves for each quantity of interest adds discriminatory power at the cost of some loss of interpretability.

Another area of future testing should explore variations on the process used to select the rings’ center point. An alternative to the rigorous selection of a single point is the use of multiple randomly placed centers. The resulting multiple characteristic curves, when plotted on the same set of axes, outline an envelope of variation for the region. For example, if all of the characteristic curves for a particular region vary little as the evaluation rings are placed randomly, it could be concluded that the region is essentially centerless and displays a sprawling pattern. Conversely, curves that all vary greatly at small ring radii but that converge to similar shapes at larger radii might indicate multiple concentrations, related to that particular metric, in a background matrix, i.e. polycentricity. The use of multiple centers may also address the issue of insensitivity to asymmetric forms, though compromising the interpretability that results from the use of a single center.

The strength of characteristic curves, when considered as a set, lies in the fact that they present a signature of a region that can be used for direct comparisons with other regions. While tabular data can provide comparable metric results for subsets within a region of interest, they do not provide readily comparable signatures of the region as a whole. With common ring radii and basis for choosing a center point, characteristic curves enable equitable comparison of various regions via graphical signatures based on common metrics. These comparisons illuminate critical commonalities and variances between different land patterns, patterns that arise in separate regions or in a single region at different points in time.

The regional characteristic curve method demonstrates significant progress towards the realization of a regional method for evaluating various land patterns when compared to existing methods used for assessing sustainability. This method for measuring regional resource efficiency metrics preserves spatial information from the underlying variations across the landscape and is not bound by urban, ecosystem, or political boundaries, the two major constraints in existing measurement methods. The characteristic curve method allows the calculation of any metric based on areal data and produces a graphical regional image for each metric evaluated, a regional characteristic curve that can then be used to examine change over time or to compare various land patterns and their relative resource efficiencies. Regional characteristic curves also provide additional value over the information supplied by a more traditional, tabular presentation of land cover data. The curves spatially illustrate how land cover varies across the region in a continuous and detailed fashion, simultaneously providing both richer detail and a more comprehensive regional overview.

There are several significant contributions resulting from this research. The characteristic curve method allows boundary-free regional measurements of any area-based metric of interest and so allows individual components of resource efficiency to be investigated as the first step in sustainability assessment. These curves allow both spatial measurement of change over time and comparisons between regions, and provide the basis for substantive discussions on the topic of sustainability. The method has the potential to provide guidance in the form of a visual image of the spatial variation in regional resource efficiency metrics and their temporal change, guidance which can be used by decision makers and planning professionals in the ongoing sustainability debate.

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