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Urban Sprawl: Definitions, Data, Methods of Measurement, and Environmental Consequences

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Abstract: Like sprawl itself, writing about sprawl is scattered in a vast multidisciplinary literature. In this paper we provide a map of what is increasingly known about urban sprawl in emerging literature. This review of progress includes four main parts—definition, data, methods of measurement, and environmental consequences of urban sprawl. The focus of this literature review is to determine whether the aforementioned parts are elements of a connected system in which progress in any one part reflects in others, thereby enhancing knowledge of urban sprawl's environmental consequences through a cross-fertilization with progress in how sprawl is defined, data are used, and phenomena are measured. We conclude with a discussion of areas of further research that surmounts the shortcomings of a disconnected, epistemic (knowledge) system of definitions, data, and methods, and points toward an explanation of urban sprawl's environmental consequences. The implications for the education of urban sustainability are noted.

Key Words: Urban Sprawl, Definitions, Data, Methods of Measurement, Environmental Consequences, Sustainability Education

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1. Introduction

In an era of the world population's unprecedented urbanization, discussions of climate change are linked to the spatial organization of cities and regions. The subject of urban form is receiving increased attention in both popular media and scholarly literature about climate change, with discussions of the sustainability of both the natural and built environment frequently arising. One particular characterization of spatial form called urban sprawl is considered as a contributor to climate change, with environmental consequences from land to water and air. The way urban sprawl is measured is determined by how it is defined. Similarly, the methods used to measure urban sprawl are determined by spatial data. Arguably, knowledge of the urban sprawl's consequences depends on the manner in which urban sprawl is defined in concept, method of measurement, and data. Our focus is a progress review of how development in each of these dimensions—from definitions to methods of measurement—interrelate, and what knowledge of environmental consequences is gained as a result. This review, then, is not an inventory of progress in concepts, methods, and data as independent parts. We review progress in concepts, methods, and data as elements of one epistemic (knowledge) system and identify how an understanding of environmental consequences is enhanced by the connected system. We conclude with a discussion of areas of further research that surmount the shortcomings of a disjointed epistemic system of definitions, data, and methods toward a connected system in which explanation of environmental consequences of urban sprawl is facilitated.

Federal, state, and local legislation that anticipates or mitigates urban sprawl is not included in this review. State laws that proactively empower cities and counties to prevent urban sprawl—such as Oregon's law empowering Portland to designate an urban growth boundary and Maryland's smart-growth legislation that funnels state funding for development in "priority" areas with existing infrastructure—are the exemplars. [For a thorough review including federal legislation,—such as the Intermodal Surface Transportation Efficiency Act (ISTEA1991) and the Transportation Equity Act for the 21st Century (TEA21,1998)—that heed land use/transportation connection and multi-modal regional mobility options that include public transit, see Calthorpe and Fulton (2001).] However, we do include the impact of legislation through subsequent data and methods used to guide urban development that averts sprawl. For example, Tennessee's Growth Management Act (TACIR) (2000) calls for local (city and county) analysis of land suitability to avoid adverse consequences of urban sprawl (Tennessee's Growth Management Law was enacted in the 1990s, when the federal government shifted the responsibility for planning cities and regions sustainably from the national to the state and local level.) State legislation provides the impetus for the analysis of urban-built and natural environments by using spatial data with methods like geographic information systems (GIS) and remote sensing. For example, Hasse and Lathrop (2003b) used a combination of census and land-cover/land-use change data with GIS-aided suitability mapping to determine compact growth that avoids urban sprawl for 566 local governments in New Jersey.

We identify the progress that enhances our knowledge of environmental consequences through developments in definitions, methods of analysis, and spatial data. Our focus here is to highlight the "ripple effect" of advances in any one dimension across all others, if such an effect exists. For example, advances in GIS and other hybrid spatial-analysis methods reviewed later in the paper, have facilitated morphological measurement of urban development and change.

Compared to the earlier generation of methods that used coarse, zonal level data, spatial methods now facilitate the measurement of urban form at even parcel level (Lin et al 1997, Landis and Zhang 1998, Wegener 1998). The relevance of analytical methods that aid in mapping the changing urban form—such as urban sprawl at both local neighborhood and regional scale—is suggested (see section on methods). Technological advances have facilitated the mapping of the consequences of sprawl's environmental impacts to a previously unattainable degree (Green et al., 1994). The knowledge of environmental consequences is gained through discussions that articulate definitions of sprawl, advances in procedures for collecting data, and developments in the technologies and methods of measurement. The implications of an approach that stresses four connected parts—how urban sprawl is defined, how it is measured; how the data are used and analyzed; and the environmental consequences of the definition-data measurement and analysis process—are noted not just for theoretical and policy research but also for the education of urban sustainability that similarly emphasizes holistic knowledge in both problem-framing and problem-solving. The review of progress is in four sections. We begin with definition(s) of sprawl.

2. Definitions of Sprawl

Before a problem is solved it must be defined; however, there is ambiguity in defining exactly what urban sprawl is and how it should be measured (USHUD 1999, Johnson 2001, Bourne 2001, Galster et al. 2001, Hayden 2004, Hasse, 2004; Hasse and Lathrop, 2003a; Hasse and Lathrop, 2003b; Schneider and Woodcock, 2008). (For a comparison of the spatial from and growth of cities globally, see Schneider and Woodcock, 2008). “Sprawl means different things to different people” Calthorpe and Fulton, (2001, 2) note. While some view sprawl as an unintended consequence of a lifestyle in suburban house and auto commute to work, others consider it a waste of resources—land, water, air, and energy—and, above all else, inimical to civic life if not the economy and society (Kunstler 1993, Duany et al. 2000).

Why so much contention and even confusion about sprawl? Expert views of what sprawl connotes, given different professional and disciplinary orientations, are a contributing factor. . Each specialization has its own “language” of sprawl (see Hayden, 2004). While professionals from different specializations shed lights on various aspects of urban sprawl, the differences in language and perspectives (e.g. architects, planners, real estate agents, bankers, land-use regulators) contributes to the lack of a cohesive definition. This ambiguity negatively impacts what data should be collected, what method should be deployed, what technology should be used, and what consequences of urban sprawl might be anticipated and mitigated in advance.

Hayden (2004, 8) defines sprawl as “a process of large-scale real estate development resulting in low-density, scattered, discontinuous car-dependent construction, usually on the periphery of declining older suburbs and shrinking city centers.” Bourne (2001, 26) recounts observations about sprawl, such as “any extension of the suburban margin, the spread of development onto sensitive greenfields and agricultural soils, increases in highway congestion, the proliferation of new subdivisions of homogeneous and low density, single-family housing.” A “suburban development” that is “haphazard, disorganized, poorly serviced, and largely unplanned.” Notwithstanding the contentions, the definitions suggest the sprawl indicators, among which are the density of population and dwelling unit (dwelling units per acre). Attention should be given to commercial, industrial, and residential uses, since, as Bourne (2001) emphasizes, lower-density commercial and industrial uses contribute to sprawl more than higher-density residential uses, even when the larger share of urban land use is residential. In contradistinction to Bourne (2001), Galster et al. (2001) discount commercial land use due to economies of agglomeration. Other indicators are consumption versus conservation of land (for an example of per capita consumption of land as an indicator of sprawl, see Masek and Lindsay's 2001 comparison of Portland OR with an urban growth boundary (UGB) and Washington D.C. without one). [Portland—with a planned UGB to limit its sprawl—has been growing at an annual rate of 1.2 square miles, compared to 9.5 square miles in UGB-less Washington D.C. Per capita consumption of land (land area divided by population) is used as an indicator of "efficient" growth—for example, Washington D.C. consumed 480 square meters/person compared with Portland's 120 square meters/person (Calthorpe and Fulton 2001, page 125). The lower per capita consumption of land indicates a more compact development and less sprawl, other dimensions of sprawl noted in this paper notwithstanding. Residential and non-residential consumption of land and density are also factors. With population and jobs spreading beyond urban and suburban (i.e., exurban) areas, the regional balance of jobs and housing, and the connection of land use with transportation are critical indicators of whether urban growth resembles compact or connected polycentric urban growth in a network of multi-modal regional transportation, or "haphazard" sprawl. For Galster at al. (2001, 685), sprawl is "low levels of some combination" of "density, continuity, concentration, clustering, centrality, nuclearity, mixed uses, and proximity" in a so-called urban area rather than a metropolitan region. However, toward a definition of sprawl, the regional scale is arguably plausible not just because the region is the location of jobs, housing, and services that spur commuter and communication flows of a wide-ranging variety in the region's physical infrastructure network (Banai and Wakolbinger 2011, see also, USHUD 1999,Wheeler 2000), but also because the natural corridors of the physiographic region (valleys, rivers, streams, creeks and the like), which are likely impacted by sprawl, transgress municipal or "urban area" boundaries. The regional scale, then, must be regarded in defining and measuring sprawl if the natural environmental consequences of sprawling urbanization are to be fully realized. The regional scale also suggests the relevance of commuting distance as an indicator of sprawl. Next, we review progress in technologies and methods of collecting data that represent the various indicators of sprawl.

3. Data

The progression and the phased spread of urbanism are better grasped when mapped and visualized at the metropolitan-region scale, which provides the "big picture." Since the early 1920s, aerial photography has provided an indispensable method of mapping the state of city development and gauging the continued expansion of urban areas (Hayden, 2004). However, remote-sensing technology increasingly used in combination with GIS provides spatial data that reveal urban sprawl more efficiently than aerial photography. Remote sensing and GIS are commonly used technologies in urban-sprawl research with land-use/land-cover change (LULCC) maps (Green et al. 1994). LULCC maps depict and quantify, among other factors, the change in land form from permeable to impermeable surfaces with urban development. The environmental consequences are immediately suggested with change in the surficial landscape capacity that affects the occurrence of flood events and run-offs with point- and nonpoint-source pollution, water quality, and micro-site climate (as in so-called heat islands in urban areas with limited green open space), among other environmental consequences (for example, Tan et al. 2010; see also Green et al. 1994). The same information is obtained from conventional aerial maps, but the method is much more cumbersome. Remote sensing and GIS have provided the technology that figures prominently in collecting, visualizing, and quantifying spatial data about urban sprawl toward assessing the environmental consequences.

Introduction of new and improved technology has been a driving factor in the use and popularity of remote sensing over time (Green et al. 1994). The usefulness of remote sensing technology is thus realized in mapping the changed landscape. For example, Klemas (2001) reports that remotely sensed images for coastal areas from the current Landsat Thematic Mapper ™ cost less than $1,000.00 per scene compared to former cost of $4,500.00 per scene. Klemas (2001) also indicates that with the launch and release of new satellites, the images will be of higher quality and lower cost [1]. Satellite imagery has proven useful in depicting the bigger picture of sprawl. Kulash (2009) points out that night-time satellite images of the Earth indicate the magnitude of "light pollution" is greater in the archetypal auto-dominated sprawling small towns in North Carolina's Piedmont Crescent, than in large metropolitan regions of New York, California, or Texas (see also National Geographic 2008).

Tan et al. (2010) investigated LULCC (1999-2007) in Penang Island, Malaysia and explain that changes to the landscape occurred during this time period due to urban sprawl. Highly built-up areas increased (109.03%), minimally built-up areas decreased (4.61%), barren land decreased (77.69%) due to urbanization, forested lands decreased an average of 16.89% grasslands increased (12.67%), and water areas showed a modest increase (0.75%). As well, highly built-up areas experienced an increase in land surface temperature (LST) from 45.07^0 C to 45.19^0 C. Advances in technology and the application of new and improved remote-sensing techniques and user-friendly GIS facilitate detailed mapping and analysis of sprawl with urban growth and change. Studies of this sort are useful toward an appreciation of the environmental consequences of "urban expansion," to use terminology from Tan et al. (2010), due to the change in land use and land cover. By using the term "urban expansion," however, and focusing on quantity of land use/cover change, little is conveyed about formal quality—that is, whether or not the urban expansion resembles urban sprawl. Discussions of urban form at a finer level of resolution (i.e. land parcel) with perspectives from new urbanism and new regionalism fill this void by focusing on the quality of the built and natural environment, from the rooftop to the region (Calthorpe 1993, Calthorpe and Fulton 2001, Wheeler 2000 and 2002, Duany and Talen 2002, Talen 2008, Wheeler and Beatley eds. 2003, Birch and Wachter eds. 2008).

Besides remotely sensed data and images, studies of urban sprawl have used readily available census data that are retrieved and visualized with thematic maps and are compatible with widely used GIS. Nasser and Paul's (2001), and Lopez and Hynes's (2003) studies, described later below, are examples of the use of census population and density data, which are defining elements of urban sprawl. We noted jobs/housing balance as an additional factor in discerning urban sprawl. The distance/direction data with work-census block to home-census block facilitates this mapping (see census origin-destination employment statistics). Furthermore, location and density of jobs data are useful in determining whether the urban structure resembles the polycentric pattern of linked centers or sprawl.

4. Operational Methods of Measurement

Just as sprawl is defined in varied ways, so too are there multiple ways to measure sprawl. Different methods are used to capture the various dimensions of sprawl. Galster et al.

(2000) identify eight measurable dimensions: density, continuity, concentration, compactness, centrality, nuclearity, diversity, and proximity. The dimensions are measured by dividing "urban areas" into one-mile grids and by using a combination of GIS and field survey. However, Lopez and Hynes (2003) identify some limitation of the dimensions in application, particularly in comparative evaluation of sprawl of metropolitan areas. Population density, dwelling unit density, or a gauge on how many jobs have decentralized are among simple measures of sprawl in the literature. However, as Bourne (2001) notes, demographics that identify cohorts of population in urbanization or suburbanization are even more important measures of the changing urban form. The distance that the population is located from the central part of the city is another measure of sprawl. As long as a standard definition of sprawl remains undetermined, an eclectic repertoire of methods—the efficacy of which will be debated—is expected to approach different concepts of sprawl.

Nasser and Paul (2001) measure sprawl by the change in population density, called the *USA Today* Sprawl Index. Basically, the sprawl index compares population density changes throughout the 1990s and the early part of the new century. The sprawl index indicates that a general rise in population does not always signify an increase in sprawl, and that some of the smaller cities (with populations under 250,000) sprawl more than larger cities (see also Kulash 2009).

Lopez and Hynes's (2003) definition of sprawl is measurable, objective, scale-invariant, interpretable, and easily replicated. U.S. census definition of a metropolitan area with a population of 50,000 or more, which includes geographic and demographic data is used. The definition itself must be all-encompassing for wide-ranging applicability.

The Farmland Protection Policy Act (FPPA) of 1981 aimed to protect farmland from the possible adverse effects from the implementation of federal programs and public (capital) projects, gauged by a numerical system called land evaluation and site assessment (LESA) (Steiner 1987). The site-assessment component of LESA aids in site-development suitability. However, whether agricultural land that ultimately yields to private sector, real estate development pressure at the urban fringe assumes a spatial form that resembles sprawl or compact urban development is not determined within LESA. (For the purposes of land use planning, see Hamerlinck et al. 2003 for an application of LESA used in combination with GIS).

Urbanization and suburbanization are world-wide phenomena. Land-use planning and decision-making is aided by GIS in multi-criteria analysis (MCA) (Lin et al. 1997, Wu 1998, AbuSada and Thawaba 2011). AbuSada and Thawaba (2011) describe the rationale to plan for continued urban development sustainably in Palestine, given that the current rate of urbanization (65%) that is greater than the international rate of urbanization (50%). GIS is used in combination with MCA to determine suitable areas for future urban expansion. Furthermore, the methods are guided by the concept of a compact urban form. Studies of this kind use hybrid methods that proactively anticipate sprawl with unplanned urban growth, much like the legislation that aims to prevent sprawl from occurring in the first place. AbuSada and Thawaba's (2011) study is an example of *ex-ante* rather than *ex-post* methods that measure consequences of urban sprawl.

Wu (1998) developed a simulation model to visualize land use and conversion through the implementation of a hybrid methodology: GIS, cellular automata (CA) and multi-criteria evaluation (MCE). Cellular Automata, is "viewed as a self-organizing system in which the basic element—land parcels—are developed into various land uses" (Wu, 1998, 63). The SimLand method used a GIS to map multiple data layers in conjunction with CA. The hybrid methodology describes likely development patterns, though the MCA does not provide criteria with which urban sprawl is assessed. For a sustainability assessment of land resources with multicriteria analysis, see Banai (2005). However, hybrid methods like those by Lin et al. (1997), Wu (1998), Banai (2005), AbuSada and Thawaba (2011) are helpful if used to also determine if land-use conversion is an outcome that resembles urban sprawl or compact sustainable development.

New urbanism, sustainable urbanism, landscape urbanism, and smart growth are labels that have gained popularity by drawing attention to consequences of urban sprawl. Mitchell (2001) reports that the principles of smart growth are catching on in the sprawling suburb, with legislation to collect taxes in order to fund land conservation and urban renewal; to aid in the preservation of farmland and green spaces and encouraging the renewal and reuse of deserted industrial sites.

The U.S. Green Building Council (usbc.org) developed the Leadership in Energy and Environmental Design (LEED-ND) rating system to assess neighborhood development (usgbc.org; see also smartgrowthamerica.org, cnu.org). The rating system incorporates neighborhood walkability, mixed land use, and access to public transit among its criteria—features that are generally lacking in the sprawl city's typical suburban, auto-dependent neighborhood with mainly residential land-use. The Sustainable Sites Initiative (SITES) uses a similar approach in developing a building-site rating system (Steiner, 2011). Other studies provide city-wide rankings that are based on a set of urban-sustainability indicators (e.g. sustanelane.com). These rating systems do not supply any consequences of low rankings which are linked to sprawl.

` To promote smart growth, the Environmental Protection Agency (EPA) developed the smart growth index (SGI) which is used with a GIS (EPA, 2003). The smart growth index (SGI) maps environmental impacts of existing building and infrastructure. The SGI aids in local government investigations of possible future scenarios by assessing changes in new development and transportation (EPA, 2003).

Commercially available software accomplishes tasks similar to the SGI. The spatial analyst in GIS (ArcGIS Spatial Analyst Esri.com) is used in city design (Barnett, 2011, ESRI references). Spatial Analyst is an ArcGIS program that aids urban planners and designers in using spatial data to gain a better understanding of complex decisions such as where to build and expand (see Barnett 2007). Useful applications include the identification of best location for conservation in the city. The plan for future transportation and population growth of the City of Orlando and its seven counties with an eye towards protecting the environment used this GIS approach (see Barnett 2007).

5. Environmental Consequences

We know about the consequences of drained wetlands or embanked rivers for the inhabitants of cities and regions. Recall Hurricane Katrina in New Orleans, and, more recently, Hurricane Sandy in Staten Island. Seminal mappings, like those by McHarg (1969/1995) that determined land suitability for urbanization and conservation, anticipated consequences of not heeding the natural world, such as in Staten Island (see also McHarg and Steiner 2006). The environmental consequences of urban sprawl are the subject of scholarly publications as well as popular reports and documentaries in the media (e.g. Breheny ed.1992, Ewing et al. 2008, Farr 2008, UN Habitat 2009, Calthorpe 2011; see also Journey 2011,). Technology, including Internet use, has facilitated the collection, analysis, and reporting of data about environmental consequences of urban sprawl—storm water runoff, water and air pollution, soil degradation, and urban heat islands. Advances in data-collection technology, which also spur development of methods of analysis and visualization, inform scientific studies toward determination of environmental consequences of sprawl. An expansive definition of the ecosystem--both natural and human built environment--informs the consequences of urban sprawl in greater scope (see also Lynch 1984). In addition to the natural environmental consequences are those in the built environment of urban sprawl—ecology, economy, equity, the so-called 3Es of environmental sustainability. However, the literature gives greater attention to the concept of 3Es, compared to discussions of the consequences of urban sprawl in ecologic, economic, and equity terms. Calthorpe and Fulton (2001) identify economic and social inequality as both cause and effect of urban sprawl (see also Barnett 2003).

Continued sprawl's environmental impact is increasingly realized by state and local governments, and citizens. Local government programs, codes, and incentives that aim to protect the environment range from greener planning and the implementation of green areas of established urban areas to improved/greener construction methods. One of the ways that states aim to control or limit the spread of urbanism is through the implementation of UGB (Calthorpe and Fulton 2001, Barnett 2011). Oregon—which began to restrict growth by strategically establishing an urban-growth boundary that effectively limits urban development of agricultural land—is a well-known example. The designation of green/park areas in established downtown regions, and zoning codes that regulate street tree planting and landscaping, rooftop landscaping, and green building practices are additional examples of reinserting nature into the built environment (see Birch and Wachter eds. 2008). The challenges of the environmental consequences manifest beyond the green building, the street, and even the neighborhood to the region, with sprawling location of jobs and residences, the mismatch of jobs and housing, and limited multi-modal mobility options (see also Wheeler 2000, Duany and Talen 2002, Talen 2008, Banai 2013).

The concept of ecosystems services elucidates the relationship between humans and the environment holistically (Steiner, 2011, see also McHarg 1969). New York City’s water quality management, which targeted point- and non-point- source water pollution generated from suburban towns throughout the watershed that collects rain and snow, is an example of the ecosystems-services approach. In partnership with multi-county agencies and local stakeholders, the comprehensive, long-term, cost-effective watershed-management program mitigated water pollution at its source in the ecosystem and avoided construction of an even more costly water-filtration facility in the city (for elaboration, see Calthorpe and Fulton 2001).

Making the land use-transportation-air quality connection (LUTRAQ) is an exemplary holistic (epistemic) system that links environmental consequence of urban form with alternative land use and transportation options, increasing density or intensity of land use that supports "walking, biking, and transit use," contrasting auto-dependent sprawl (Calthorpe and Fulton 2001). LUTRAQ effectively fills a void in environmental "analysis of transportation options" like highway or transit that are commonly considered independently of urban form in "major investment studies," due to the political sensitivity of changes in the land use at the "corridor or subregional level" (Calthorpe and Fulton 2001 page 109). LUTRAQ prediction: highway congestion, air pollution, greenhouse gas, and energy consumption is reduced; transit use is increased and auto-use decrease in a metropolitan region with transit-oriented development and connected mixed-use jobs and service centers (Calthorpe and Fulton 2001, 111).

Not all above-defined dimensions of sprawl are used inclusively in determining environmental consequences, due in part to achieve analytical tractability or to surmount data availability. For example, Ewing et al. (2008) use residential density to measure greenhouse-gas emission associated with per capita vehicle miles traveled (VMT) in sprawling vs. compact urban form. Environmental consequences of sprawl are implied rather than measured directly. For example, Newman and Kenworthy's (1989) studies of fuel consumption is cities should be noted for the environmental implication of the use of non-renewable resource—fossil fuel--with automobile dependence in cities. Stone and Frumkin (2010) observe that "extreme heat events," which are associated with climate-related fatalities, increased in sprawling cities at an annual rate of more than twice as large when compared to compact cities during 1956-2005, even controlling for the size and growth of the population. The sprawling metropolitan region is characterized by "geographic expansion over large areas, low-density land use, low land-use mix, low connectivity, and heavy reliance on automobiles relative to other modes of travel" (Squires 2002 in Stone and Frumkin (2010). Just as the dimensions of sprawl are expanding with fine-tuning definitions, so are methods of measurement, as in US Environmental Protection Agency's smart growth index (SGI) noted above, combining population density, land use mix, activity center, and road network (for elaboration and application to measure sprawl in large metropolitan areas, see Ewing et al. 2002, 2003).

6. Conclusion

We began our review to address the question of whether definitions, data, methods of measurement, and environmental consequences of urban sprawl are elements of one connected knowledge system in which progress in any one part reflects in all others through a cross-fertilization. Even though the environment is a crucial element impacted by urban sprawl, the links to definitions, data, indicators, and methods of measurement are not readily or ubiquitously apparent in literature about sprawl. We observed a knowledge system with *some* interconnected elements. We also identified the elements of a disconnected system. We observed some common indicators on how sprawl is fundamentally defined, such as population, dwelling unit and employment density, regional balance of jobs/housing, mix of residential and commercial land use, and multi-modal mobility options. The definitions that appear as indicators with data in methods of measurement, and environmental consequences such as SGI and are examples of the connected system. Like legislation to prevent sprawl, the "index" methods are predominantly of the *ex-ante* rather than *ex-post* variety, descriptive or proactive rather than normative or reactive measures of the environmental consequences. Stated differently, methods of the *ex-post* variety measure the type or magnitude of environmental consequences once sprawl occurs. Measurement methods lacking a definition of sprawl and a nebulous connection to environmental consequences are examples of a disconnected system. Progress in one part is not reflected in other parts of the same system. For example, cutting-edge cellular automata methods of mapping urban growth, land use, and land cover change are commonly lacking in definition—notwithstanding the implications—of sprawl. However, there are exceptions where environment is an explicit link in the method of analyzing urban sprawl. Progress in these areas can tip the balance in favor of knowledge of environmental consequences.

The environmental consequences of urban sprawl are determined in varied ways. Aerial photography is a method of collecting spatial data, depicting, and defining urban sprawl qualitatively if not quantitatively as elements of one connected system as Hayden (2004) illustrated, although environmental consequences are implicit rather than explicit, and the measure of the magnitude of impact even more cumbersome. The dynamics of urban sprawl is a concept better captured by using satellite imagery/remote sensing as Masek and Lindsay (2001) have shown with Landsat data, comparing the urban growth of metropolitan regions. The calculated per capita (annual) consumption of land provided a comparative measure of growth in a metropolitan area with and without growth control. This is an example of a limited connected system of data and a simple method of measuring sprawl. Environmental consequences are not considered as elements of one system of definition, data collection, and method of measurement.

Environmental sustainability is commonly conceptually illustrated in the literature by three interconnected elements: ecologic-economic-equity—3Es. The idea of the central importance of environment is due, in part, to the social and economic consequences of urban sprawl. As noted above, with economic and social inequality considered as both causes and effects of urban sprawl (Calthorpe and Fulton 2001), future research plausibly expands the concept of 3Es with discussions of consequences of urban sprawl in ecologic, economic, and equity terms. Further research thus surmounts the shortcomings of a disconnected epistemic system of definitions, data, and methods of measurement toward explanation of environmental consequences of urban sprawl in one connected ecologic-economic-equity system.

The idea of a connected (epistemic) system that defines, measures, and identifies the environmental consequences of sprawl synergizes holistic urban-sustainability education, as noted above. But how could urbanization as a process synergize with the education of urban sustainability? As an example, Envision Utah was a community workshop (learning) example that enabled its participants to decide how the future of a region might be thought of and planned differently from past practice, responding to the increasing urbanization of population while mindful of the environmental consequences of growth (Calthorpre and Fulton 2001). Compact urban form that prevents sprawl and conserves natural resources is decided in place of sprawl and its ecosystem, social-equity, and economic-efficiency consequences. The compact urban form accommodates multi-modal mobility with public transit, bike and walk options that reduce auto-dependency and thereby congestion and tail-pipe pollution. The relevance of research paradigms that define, measure, and determine environmental consequences of urban sprawl as elements of one connected whole is implied for practice and education of urban sustainability. However, a final education and practice challenge is determining whether the paradigms accommodate not only systemic knowledge but also communicative, collaborative, and reflective modes of decision-making that are hallmarks of effective pedagogies as well as democracies (Banai 2012, 2013). Emerging web-based technologies that provide a public participation component to designing and planning alternative sustainable futures for cities and regions affirmatively indicate paradigm responses [2].

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Notes

1. A constellation of small satellites photographs the entire planet daily with high resolution and in "near-real-time." (See W. Marshall http://www.ted.com/talks/will_marshall_teeny_tiny_satellites_that_photograph_the_entire_planet_every_day)
2. See Barnett (2011a, 2011b), Keranen and Kolvoord (2011), McElvaney (2012)

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