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Environmental impacts of urban sprawl: a survey of the literature and proposed research agenda

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Abstract. 'Urban sprawl' has recently become a subject of popular debate and policy initiatives from governmental bodies and nonprofit organizations. However, there is little agreement on many aspects of this phenomenon: its definition, its impacts—both nonmonetary and monetary—economic and policy models that predict the presence of sprawl, and decision-support models that could assist policymakers in evaluating alternative development schemes that may have characteristics of sprawl. In particular, there is relatively little research on urban sprawl that focuses specifically on measurement and modeling of environmental impacts. The purpose of this paper is twofold: to survey the literature on urban sprawl, with a focus on environmental aspects and to identify a research agenda that might result in a greater number of anaytical tools for academics and practitioners to characterize, monetize, model, and make planning decisions about sprawl.

1 Introduction

This paper is a review of current research and applications regarding the environmental impacts of urban sprawl. The motivation for this review is, first, the increased popular attention given to undesirable aspects of urban development, primarily in suburban areas, referred to as 'sprawl'. Recently, voters in many areas have attempted to pass measures to limit the rate of development in suburban areas and to preserve green space (USHUD, 1999). Reports by nonprofit organizations such as The Sierra Club (1999) have highlighted negative impacts of sprawl such as increased traffic congestion and air pollution. Popular research by authors such as Orfield (1997) has drawn attention to the negative political and fiscal impacts of suburban sprawl, not just in the areas that are experiencing sprawl but also in the inner cities and inner-ring suburbs that are losing population to farther-out suburban areas. The second motivation for this review is the increased quantity and quality of academic research that has attempted to quantify sprawl and to assess impacts of alternative development paths. Although researchers have done valuable work in designing tools to visualize alternative development paths and to design models that incorporate current knowledge of urban growth dynamics and environmental change, more work needs to be done to unite disparate research areas related to sprawl.

There is no common agreement either on the defining characteristics and impacts of urban sprawl or on the ultimate desirability or undesirability of urban sprawl. Thus, the scope of this paper will be limited to specific environmental impacts, desirable or not, of development strategies or to outcomes that may be classified as 'sprawl', as distinguished from normal urban, suburban, and exurban development. In addition, the scholarly literature used to frame the discussion of sprawl will focus on the fields of land-use planning, transportation planning, urban planning, economics, landscape architecture, geography, and other related areas.

My goal is to define urban sprawl and, specifically, the environmental impacts of sprawl in a consistent way and to identify and classify models and decisionmaking methodologies associated with the environmental impacts of sprawl through a survey of the academic and practitioner literature. I will also identify areas associated with environmental impacts of sprawl that require further research. Such research may ultimately assist policymakers and decisionmakers in creating and implementing specific policies to ameliorate undesirable impacts of sprawl or prevent those impacts from occurring.

In the next section I present alternative land-use strategies that are given various names: 'sprawl', 'smart growth', and so on, and list characteristics of these strategies. In section 3 I formally define environmental impacts of urban sprawl and explore the difficulties inherent in identifying specific environmental outcomes associated with a particular development strategy. In section 4 I present a variety of economic models that have been developed to explain and predict impacts associated with urban sprawl, with a focus on the efficiency of specific land-use decisions. In section 5 I survey efforts to apply valuation methodologies to environmental impacts of urban sprawl. In section 6 I identify decision-support methodologies that allow evaluation of environmental impacts associated with alternative development scenarios. The paper is concluded with the identification of key areas of research on environmental impacts of sprawl that require more attention from researchers.

2 Alternative development strategies

'Sprawl' can be defined in a variety of ways. According to The Sierra Club (1999, page 1), sprawl is

> "low-density development beyond the edge of service and employment, which separates where people live from where they shop, work, recreate and educate—thus requiring cars to move between zones".

Ewing (1997, page 32) defines sprawl as the combination of three characteristcs:

> "(1) leapfrog or scattered development; (2) commercial strip development; and (3) large expanses of low-density or single-use developments—as well as by such indicators as low accessibility and lack of functional open space".

The US Department of Housing and Urban Development (USHUD, 1999, page 33) defines sprawl as

> "a particular type of suburban development characterized by very low-density settlements, both residential and non-residential; dominance of movement by use of private automobiles, unlimited outward expansion of new subdivisions and leapfrog development of these subdivisions; and segregation of land uses by activity".

The Chester County Planning Commission (as quoted in PTCEC, 1999, page 16) defines sprawl as

> "a spreading, low-density, automobile-dependent development pattern of housing, shopping centers and business parks that wastes land needlessly".

Richmond (1995) adds the following indicators of sprawl: decentralised land ownership and fragmentation of governmental land-use authority, and disparities in the fiscal capacities of local governments. Downs (1998) adds two more characteristics of sprawl to those presented above: widespread commercial strip development, and no low-income housing outside central cores.

All of the definitions presented above have been the subject of extensive debate. For example, as Hayward (1998) and O'Toole (1999) point out, increases in automobile usage is not synonymous with increases in commuting times, and neither of these is necessarily synonymous with low-density development. Burchell et al (1998) synthesized forty years of research on the impacts of urban sprawl and concluded that the three conditions that define the *negative* impacts of sprawl—leapfrog development and low-density and unlimited outward expansion—are the same as those that define the *positive* aspects of sprawl. Definitions of sprawl are difficult to quantify, as metropolitan areas may have some but not all of the characteristics of sprawl and to varying degrees.

In any case, it seems clear that sprawl as a phenomenon is of interest because of the high level of automobile usage, segregated land uses, disparities in fiscal capacities of local governments, and development that alternates relatively low-density land uses and undeveloped land in a rather haphazard fashion. Finally 'sprawl' and 'nonsprawl' are more likely to be directions on a continuum than fixed categories.

There are a number of land-use strategies that include sprawl as well as certain alternatives to sprawl. 'Edge cities' (Garreau, 1991) are essentially regions with sprawl-type development that are dense enough and populous enough to be considered 'cities' even though these regions may comprise a number of autonomous municipalities. Edge cities are defined by the concentration of nonresidential clusters at the intersection of major beltways and interstates outside the central city that are eventually joined by high-density residential development and that become relatively self-sufficient.

'Transit-oriented development' is defined as "walkable, livable, mixed-use communities built around transit stops in feasible locations in both urban and suburban areas" (PTCEC, 1998, page 26). Transit-oriented development does not require that mass transit be used for all trips but that residents have mass transit as a reasonable alternative to the automobile and that mass transit stations and the areas around them allow riders to combine work and nonwork trips.

Urban growth boundaries, one antidote to sprawl, have been defined by Stoel (1999, page 11) as "a line drawn around a city at a distance sufficient to accommodate expected urban growth. Beyond the boundary, urban development is prohibited". Areas beyond the urban growth boundary that are off-limits to suburban development include farms, environmentally fragile watersheds, and parks. Urban growth boundaries are intended to preserve the diversity of natural resources around cities and to funnel development into areas with existing infrastructure (The Sierra Club, 1999). For example, Oregon has enacted a law requiring the use of an urban growth boundary around the Portland metropolitan area. This growth boundary has three goals: to manage the rate of growth of residential and commercial development, to increase use of mass transit, and to encourage 'infill' development of inner-ring suburban areas as opposed to developing as far away from the central city as possible.

Other states have explored variations of urban growth boundaries under the rubric of 'smart growth'. Smart growth plans are focused on revising land-use controls to make them more sensitive to problems of lack of housing diversity, traffic congestion, and environmental degradation. The intended result of these land-use changes is greater growth in areas that have existing infrastructure, acquiring certain open spaces and increased social equity (Burchell et al, 1998; O'Neill, 1999; Stoel, 1999). Smart growth incorporates the transit-friendly, mixed-use design of transit-oriented development. These plans may be more appealing politically than urban growth boundaries because there is no fixed limit to growth; instead, incentives are designed to produce results that are similar to those derived from an urban growth boundary.

The 'sustainable development' strategy, derived in large part from the World Congress on Sustainable Development held in Rio de Janiero in 1992, is designed to "limit growth to the degree that public facilities and services are in place to accommodate this growth" (Burchell et al, 1998, page 37). Some twenty-one communities in the USA have passed sustainable development ordinances, which are basically growth-management programs under another name. Various federal commissions and agencies have designed sustainable development objectives that funded programs must observe, ensuring that capital projects respect the local environment as well as limiting associated growth to locations that have infrastructure to support that growth (Burchell et al, 1998).

Another development strategy lies in stark contrast to the ones listed above; it relies on land-use deregulation, reductions in fuel taxes, and local control of land-use and transportation investment decisions. This strategy assumes that residents and businesses can best make land-use decisions without interference from planning agencies or state and federal bodies (Hayward, 1998; O'Toole, 1999). This is in direct opposition to the model of directed growth and is most similar to the edge-city strategy. In a sense, it is the locally oriented status quo drawn to its logical conclusion.

Downs (1994) has defined four regional growth regimes that incorporate the policies listed above and that are useful in generalizing the discussion of development alternatives. The first, which can be considered the status quo, is called 'unlimited low-density growth'. In this regime, local zoning and building codes alone define market provision of housing and jobs, the dominant residential pattern is owner-occupied, single-family detached homes, transportation is almost exclusively provided by private automobiles, low-rise workplaces dominate employment alternatives and affordable housing is available almost entirely through the trickle-down effect. Edge cities and the extreme free-market approach listed above would fall under this planning scheme.

The next regime, a moderate alternative to the status quo, is called 'limited-spread, mixed-density growth'. Here, urban growth boundaries are encouraged but not mandated, and the dominant residential pattern is clusters of high-density housing amid larger areas of lower-density housing, with some affordable housing made available through housing subsidies and lower regulatory barriers. Transit use is encouraged primarily through ride-sharing, and employment may be concentrated in nodes through voluntary incentives. Local governments have limited cooperation in land-use planning.

The third regime, incorporating more aggressive planning initiatives, is called 'new greenbelts and communities'. Here, growth boundaries are designed and enforced, but only for certain corridors, new towns, and metropolitan areas. Residential growth is concentrated in a few planned communities featuring mixed-use, mixed-density development, and there is an explicit emphasis on mass transit as an alternative to the automobile. Regulations and incentives encourage jobs to cluster in new centers and encourage municipalities to plan for growth in a regional framework. Transit-oriented development, sustainable development, and smart growth all incorporate aspects of these two alternatives to the status quo.

The last regime, called 'bounded high-density growth', incorporates extensive land-use and employment planning to achieve four goals. First, future growth is limited to an urban growth boundary. Second, residential densities are raised both in new and in existing communities. Third, a regional government supercedes many local government functions. Fourth, mass transit is strongly emphasized through subsidies and transit-oriented development. Affordable housing is available in this regime as entitlement, counteracting the effects of higher housing prices brought about by a restricted supply of developable land.

Pendall (1999) has constructed a model to test certain policy-related hypotheses regarding sprawl. He defines sprawl as the change in county population between 1982 and 1992 divided by the change in urbanized acres of land over the same period. This measure is regressed upon a variety of independent variables representing: percentage of land area under formal control, farm characteristics, metropolitan fragmentation, housing values, local government spending, transportation infrastructure, and minority population. Dependent and independent variables were gathered for 1168 counties in the twenty-five largest metropolitan areas of the USA. Pendall hypothesizes, among other things, that land use will be more dense (less sprawling) if appropriate land-use controls are in place, municipal fragmentation is limited, housing prices are high, local governments do not rely heavily on property taxes to finance public services, and infrastructure and transportation accounts for smaller proportions of public spending. Regression results indicate that the model supports all of these hypotheses. However, more sophisticated statistical models are necessary to refine these results. For example, it may be that high housing prices are a consequence of limited supply of land owing to natural features, as for example in San Francisco or Boston.

Pendall's work demonstrates that public policy affects sprawl and that requiring developers to pay the incremental cost of new infrastructure is preferable to policies such as low-density zoning and building-permit caps. These results form a response of sorts to antisprawl critics who promote the primacy of consumer preferences and minimize the potential of government to modify growth patterns.

Powell (1998) addresses the underside of the common argument that sprawl is simply an expression of consumer preferences and that government should respond to these preferences rather than attempt to control them. He hypothesizes that 'white flight', associated with a desire for local control and population homogeneity, leads to sprawl. Powell further proposes that explicit opposition to affordable or subsidized housing, more likely to be occupied by minority groups than are the larger single-family detached housing common in suburban sprawl-type development, leads to segregated uses and transit-dependent lifestyles. This transit-dependent lifestyle is reinforced by the opposition of suburban residents to pay for mass transit, which again is more likely than private automobiles to be used by minority groups in suburban areas. These hypotheses are justified by anecdotal evidence rather than formal models and seem deserving of closer scholarly examination.

To summarize, there are a variety of definitions or characteristics of sprawl, having in common:
(a) segregated land uses,
(b) emphasis on the automobile for transit,
(c) a push for growth at the boundary of the metropolitan area,
(d) residential and employment densities that are generally lower than those in further-in suburbs or in the central city,
(e) populations that are homogeneous in terms of race, ethnicity, class (to a lesser extent), and housing status,
(f) the inability of local governments to work together to devise common policies to address perceived negative characteristics of the current growth regime.

These characteristics are often described rather than quantified in the literature. Thus it is difficult to determine the extent to which sprawl actually exists in a certain area and whether certain attributes of sprawl are associated, in a statistical sense, with values of other explanatory variables that represent the demographic and spatial characteristics of an area. There is also significant disagreement among popular and academic commentators as to whether these characteristics of suburban growth are inherently desirable or undesirable. Settling this question would require determining the extent to which groups of residents and business owners in various regions are positively or negatively affected by the sprawl characteristics listed above, properly quantified.

3 Environmental impacts of sprawl

Researchers generally focus on those communities whose development is the source of the sprawl phenomenon in order to identify environmental impacts of urban sprawl. From this perspective, the following environmental impacts have been identified:

loss of environmentally fragile lands,
reduced regional open space,
greater air pollution,
higher energy consumption,

decreased aesthetic appeal of landscape (Burchell et al, 1998),
loss of farmland,
reduced diversity of species,
increased runoff of stormwater,
increased risk of flooding (Adelmann, 1998; PTCEC, 1999),
excessive removal of native vegetation,
monotonous (and regionally inappropriate) residential visual environment,
absence of mountain views,
presence of ecologically wasteful golf courses (Steiner et al, 1999),
ecosystem fragmentation (Margules and Meyers, 1992).

These impacts can be divided into those that pose immediate human risk as opposed to those for which the associated human risk will not be fully known for years. These risks can also be divided into those that primarily affect the aesthetic appeal of an area as opposed to those that affect the viability of ecosystems.

An alternative viewpoint for environmental impacts of sprawl is that of *environmental justice*, whereby poor and minority communities suffer disproportionately from urban disinvestment and/or hazardous land uses. Both of these outcomes can be viewed as correlates of urban sprawl, inasmuch as urban sprawl incorporates a transfer of people and resources from the inner city and inner-ring suburbs to more distant suburbs, and such transfer is performed with very tight local control over land uses (Downs, 1994). Such impacts include:

toxic and hazardous wastes from abandoned brownfields,
toxic and hazardous wastes from landfills located in least-desirable areas,
toxins such as lead and asbestos persisting in older buildings because of disinvestment in inner cities (Bryant, 1995; USHUD, 1999).

These impacts may pose a more direct threat to human health than those associated directly with suburban development yet conceivably they are less likely to be remedied in a timely manner than those associated with suburban development. This is because the costs of remediation must be borne by those who own land in these areas. Owners of inner-city sites such as urban municipalities, factories who have relocated, and so on generally have fewer available resources than do growing suburban municipalities.

Although environmental impacts of sprawl are seemingly numerous and in many cases straightforward to *observe* they are much more difficult to *measure*. One way to address this problem is to define a *baseline level* of particular environmental quantities that may be affected by sprawl. Markandya (1992b) has suggested defining a set of "indicators of environmental resources", for example physical stocks of resources, but it is not clear what a baseline level of, say, species diversity ought to be.

Second, it may be difficult to measure environmental impacts *directly* in physically meaningful units (for example, in terms of measuring the extent to which a particular impact is present). If an environmental impact is associated with environmental toxins then it is especially important, according to Lippman (1992), to identify the levels of toxins, their proximity to citizens, and the physiological effects of these toxins, yet in many cases such measurement is an open research issue.

Third, it may be difficult to construct *aggregate measures* of multiple environmental impacts occurring together and at different levels. For example, identifying the human health outcomes associated with multiple toxins acting together is complicated by the fact that these toxins can be present in the workplace, at home, and outdoors (Head, 1995). Even for nontoxic environmental impacts it is not easy to devise a single scale that incorporates aesthetic impacts and impacts with specific ecological effects. Moreover, when different stakeholder groups are affected by sprawl (for example, lower-income city dwellers rather than higher-income suburban dwellers), the calculation of aggregate impacts requires intergroup comparisons of utility.

Fourth, even if environmental impacts of sprawl may be measured, alone and in combination, and associated with specific human outcomes, perceptions of the *risk* associated with these environmental impacts may vary widely among individuals (for example, experts versus ordinary citizens). Thus, the desire of the populace to address specific environmental impacts of sprawl, or to address such impacts at all, is a function of common perception of the relative danger to life and limb of these impacts (Upton, 1992). These perceptions may be inconsistent with known probabilities of certain outcomes.

Fifth, for planning purposes it is not enough to measure environmental impacts of sprawl; one must construct *models* in order to evaluate potential environmental impacts of alternative development strategies, including the status quo, both in the current region of interest as well as in other regions in which the impacts of sprawl are currently absent. Such models models require a variety of assumptions, with which different observers may disagree, and require a presentation mechanism, such as geographic information systems (GIS) to enable meaningful communication of results.

I have shown that urban sprawl is agreed to have a set of specific environmental impacts that vary according to the stakeholder group affected, the immediacy of human risk, and the aesthetic versus physical effects, and that some of these effects may be meaningful to ordinary citizens. However, there is less information on how relative levels of these impacts ought to be expressed in terms that are understandable to the public at large as well as policymakers and analysts.

4 Modeling environment-related sprawl outcomes

In this section I survey research in economics and related disciplines in order to give a behavioral justification to urban sprawl, evaluates the economic efficiency of various development strategies, identity remedies to environmental impacts associated with sprawl, and highlight the difficulties inherent in applying traditional microeconomic models to this phenomenon.

I start by presenting some definitions from Tietenberg (1996) to enable analysis of environmental resource allocations arising from policy decisions. The *full-cost principle*, based on the assumption that humanity has a right to a safe and healthy environment, states that "all users of environmental resources should pay their full cost" (Tietenberg, 1996, page 554). Designing policy to enforce the full-cost principle is quite difficult; thus an alternative, less-than-perfect criterion, the *cost-effectiveness principle*, is useful. Here, the aim is to achieve a given policy goal at the least possible cost; for example, through market mechanisms such as pollution-rights trading. Often, well-intentioned policies cannot be implemented because of confusion over ownership rights of resources. The *property-rights principle* addresses this issue by endorsing the ownership of local communities over environmental resources within their borders and allowing local communities to share in local benefits resulting from policy decisions. The *sustainability principle* requires that resources be used in such a way as to respect the needs of future generations. This principle is difficult to implement, however, as it requires detailed knowledge of the total level of environmental resources and group preferences over time.

In the following discussion I present a number of economic models that may be applied to the phenomenon of urban sprawl. Perhaps the most famous of these models is 'the tragedy of the commons', developed by Hardin (1992). This model has influenced discussion of environmental impacts of policy decisions since it was originally published more than thirty years ago. In his paper, Hardin presents a problem in cattle grazing in which herders create externalities that are not internalized: herders let their cattle graze anywhere they like because there is no incentive to conserve land; if one does, then one will not maximize one's own return. Hardin does not use economic models to make his argument or to propose solutions. Instead, he appeals to conscience or coercion to solve the problem.

Baumol and Oates (1992) have designed economic incentives that require polluters to pay for the cost of their actions through taxes. They consider, but reject, the classical method in economics for internalizing externalities, that is, Pigouvian taxes. This is because such taxes, requiring the generator of the externality (the 'polluter') to pay a tax equal to the marginal net damage caused by its activity *if the activity had been adjusted to its optimal level* (that is, not at its current level), are very difficult to implement because of lack of information. They propose, instead, a method called 'pricing and standards'. Here, government determines, a priori, a certain level of pollution that polluters must not exceed, and then devises taxes (or subsidies) on a unit decrease in the particular pollutant. Moreover, these taxes could be adjusted to reflect ease or difficulty in achieving the predefined environmental impact goals.

Although Baumol and Oates admit that this scheme may not lead to Pareto-efficient levels of activities under dispute, these measures are relatively easy to design and inexpensive to implement, inasmuch as those polluters who can most afford to reduce activities will do so. This method is most appropriate in situations where the externalities in question have significant and unambiguous effects on human life and where reductions in the activities that produce these externalities do not entail huge resource costs.

Gerking and Stanley (1992) have measured the amount that individual consumers are willing to pay to avoid exposure to air pollution, a sprawl by-product. A consumer's utility, assumed to be a function of own stock of health capital and other nonhealth goods, is maximized subject to an income constraint incorporating time lost because of illness. Derived first-order conditions of the model result in an equation in which marginal improvements in health can be associated with monetary bids. These bids correspond to willingness-to-pay (WTP) values. Gerking and Stanley found that decreases in physical measures of pollution (for example, in ozone concentrations) are associated with certain yearly WTP estimates.

Recently, economists have designed models that explicitly address issues associated with urban sprawl. Lee and Fujita (1997) have created an economic model to determine whether alternative locations of greenbelts that may define urban growth boundaries and are characterized by the level of service they provide are efficient. They found that when the greenbelt is a pure public good the only optimal location is outside the urban fringe. However, when the greenbelt is an impure public good then, under certain reasonable assumptions about utility, income, and type of service, it may be optimal to locate the greenbelt inside the urban area.

Farrow (1999) addresses the issue of optimally timing the conversion of land from one use to another. Typical conversions of interest relevant to the study of sprawl are from farmland or forest uses to residential or industrial uses. These conversions are irreversible, delayable, dependent on uncertain future prices for capital and other services, incorporate scale economies, and generate positive or negative externalities. Thus, Farrow introduces from the finance literature the notion of an *option*, or a choice to convert land from one use to another at some time in the future when expected net benefit exceeds a given threshold. A model of a price threshold for investment is developed that depends on the discount rate, the marginal product of capital, and an option value multiplier inversely proportional to the discount rate. The model is extended to address the notion of externalities, particularly relevant to environmental impacts in which negative externalities result in nonconvexities associated with the first project in an area. Computational results indicate that real-world actors may not acknowledge the irreversibility of projects, lending support to government policy intervention in land development.

Kahn (1999) uses economic models to address from another angle the impacts of sprawl: he attempts to measure the environmental damage associated with dispersion of development as represented by increases in automobile miles driven, home energy consumption, and land consumption. In turn, environmental damage is disaggregated into likelihood of global warming, local air pollution, farmland destruction, open space reduction, wetland destruction, and decreases in water quality. Kahn models environmental damage generally as a production function of individual household consumption of resources and emissions per unit of resource consumption; household resource consumption itself is a function of household attributes, location choice, and the price of market inputs. Kahn finds that, although household travel, energy consumption, and land consumption have increased as a result of suburbanization and migration, environmental impacts have been largely mitigated by regulations such as the Clean Air Act and the ability of individuals to provide incentives to developers not to develop on environmentally rich land. However, Kahn recognizes that measuring the social damage in dollars (rather than in physical units) represented by suburban growth requires environmental valuation measures, which are explored in more detail in the next section.

Efforts in this area to model sprawl are complicated by a number of difficulties associated with the policy environment, economic environment, and characteristics of the actors. As Burnet (1999) acknowledges, users of natural resources are both numerous and anonymous thus making measurement of individual benefits and costs difficult. Moreover, the shared resource itself is extensive and abstract, making it difficult to determine how much of it is used by various groups. More than one group may contribute to the degradation of the resource, making it difficult to determine how responsibility for remediation should be apportioned.

Another modeling complication is the presence of *market failures*, that is, an inability of a free market to "allocate resources efficiently among uses and over time" (Panayoutou, 1992, page 326). For example, externalities may make it difficult to determine prices to charge consumers for use of a public good. Also, one participant in an exchange of property rights may exercise monopoly power, limiting the amount of information about the environmental resource available to others. Private and social discount rates may differ, resulting in firms being excessively aggressive or conservative in the use of resources with respect to a socially efficient level of resource usage. And, as Farrow (1999) has demonstrated, although actors in development may incorporate uncertainty, irreversibility, and risk associated with land-use decisions, current real-options models are insufficient to capture these dynamics.

Government or policy failures regarding environmental policy are defined by Panayoutou (1992) as government interventions that do not outperform the market or improve its function or that result in benefits from the intervention that are exceeded by the costs of planning, implementation, and enforcement as well as by indirect and unintended costs. These failures can have the effect of "distort[ing] incentives in favor of overexploitation and against conservation of valuable and scarce resources" (Panayoutou, 1992, page 340).

In reality, policy and law associated with environmental resource allocation must be made and enforced whether or not models that describe such actions are sufficiently rich to inform decisionmaking. Tietenberg (1996) notes that this can be done through the court system or the legislative system.

This survey of the research regarding economic models of environmental impacts of urban sprawl indicates that such models must incorporate: multiple stakeholders; multiple periods; multiple, interacting environmental impacts; asymmetric information; nonconvexity in environmental externalities and risk; and irreversibility and delayability of land-use decisions. In addition, policy initiatives based on economic models should incorporate economic incentives linked to measurable externalities and risk associated with development, deterrence strategies such as monitoring and enforcement, and longer-term strategies and investments.

5 Monetizing the environmental consequences of sprawl

In the previous section I focused on methods to model the economic behavior of individuals and groups whose activities result in or are affected by environmental impacts that are or can be associated with urban sprawl. In that context, what is most important is showing that physical outcomes of sprawl as defined in section 3 are linked to specific behavioral models. Here, I wish to move from measuring physical impacts of sprawl and defining behavioral models to associating dollar values with the various impacts of sprawl. Such dollar values can be used, along with other, less quantifiable measures, to evaluate benefits and costs of various development alternatives.

Markandya (1992a) presents four main methods of evaluating environmental amenities and disamenities. *Hedonic price* models use statistical methods on time-series, cross-section, or pooled data to determine the differential in prices for various locations arising from the presence or absence of an environmental amenity and to determine the amount people are willing to pay for an improvement in an environmental amenity. *Contingent valuation* (CV) asks people directly the maximum that they would be willing to pay for a particular environmental amenity (that is, their *willingness to pay*) or, alternatively, the minimum that they would be willing to accept to avoid a particular environmental amenity. The latter quantity is defined as *willingness to accept* (WTA)]. The *travel cost* method measures, via surveys, the value of an amenity to which people travel (for example, a national park). *Dose-based* approaches attempt to verify specific impact values associated with environmental amenities without investigating individual revealed preferences.

It is useful to focus more closely on properties of WTP and WTA measures as these correspond to fundamental economic quantities of consumer surplus and producer surplus, used to measure welfare impacts of certain policies. Coursey et al (1992) presented results in experimental economic research that suggest that WTA values are much higher than WTP values. There are two possible explanations for this result: individuals may use value functions rather than utility functions to measure gains or losses, or consumers may behave irrationally, undervaluing potential gains or overvaluing potential losses. Coursey et al performed experiments to measure WTA and WTP, and found that after repeated iterations of the experiment the two values converged.

Brookshire et al (1992) compared consumers' WTP values (derived from a survey) to avoid air pollution with WTP values derived from a traditional hedonic model. They presented a theoretical model that predicts that survey responses will be bounded below by zero and above by rent differentials derived from the hedonic method. To test this model a survey and a hedonic analysis of housing markets in the Los Angeles metropolitan area were performed; it was determined that neither of the two hypotheses listed above can be rejected. As a result, researchers may use either the survey method or the hedonic method to monetize environmental impacts associated with sprawl, whichever is easier.

A different perspective on monetizing environmental impacts of sprawl is that of determining the value of environmental resources so that dollar-valued benefits and costs can be compared with a baseline. Repetto et al (1992) presented a methodology to redefine national income accounts—the official measure, at the national level, of consumption, savings, investment, and government expenditures—to explain misspecification arising from the absence of values associated with natural resources. These expenditures could be estimated by computing the present value of future net resources, the transaction value of market purchases and sales of the resources, and the net price, or unit rent, of the resource, multiplied by the relevant quantity of the reserve. Although the authors' focus is on national accounts, it is possible that similar calculations could be done for a metropolitan area, thus allowing the valuation of all goods, including environmental resources, as they are affected by various development patterns.

Monetizing environmental impacts of urban sprawl is a specific application of benefit–cost analysis (BCA). Farrow and Toman (1999) have presented a comprehensive overview of this well-studied discipline, which has become more important given requirements of recent laws and executive orders mandating use of BCA to justify policy proposals. General steps in the BCA process identified by Farrow and Toman include: defining a baseline, identifying policy alternatives, identifying potential changes in outcomes and risks, assessing the economic costs and benefits of identified policy alternatives, calculating overall net benefits, and performing sensitivity analysis.

Farrow and Toman acknowledge criticisms of BCA, including that it: ignores equity concerns, uses imprecise benefit–cost measures, and is unable to monetize environmental benefits and risks. In response, the authors offer three justifications of BCA. First, BCA can be used to highlight distributional effects of benefits and costs and trade-offs between cost and equity considerations. Second, the act of performing a BCA can serve to identify uncertainties, the impacts of which on dollar-valued impacts can be estimated via sensitivity analysis, as well as to give analysts a clearer idea of impacts that can be monetized and those that cannot. Third, monetizing the environmental impacts of sprawl highlights the fact that trade-offs between different groups are necessary and that these trade-offs can be done more consistently by using dollar values of impacts as opposed to using general sentiments.

In the previous section I introduced recent work by Farrow (1999) on the use of real options to evaluate the decisionmaking process associated with land conversion. This work is also relevant to BCA because it attempts to incorporate externalities associated with land use, and the uncertainties, nonlinearities, and time dependence inherent in these externalities, into the BCA methodology and the net present value decisionmaking criterion.

The literature on BCA applied specifically to environmental impacts of urban sprawl is sparse. The book by Burchell et al (1998) is noticeably incomplete in this area. That portion of the sprawl literature reviewed by Burchell et al that focuses on environmental impacts contains no references to work that contains dollar-valued benefit and cost estimates of environmental impacts of sprawl. Instead, they evaluate a limited set of environmental impacts that are measured in physical units and that are not based on explicit economic models of stakeholder behavior or preferences.

Bezdek (1995) has addressed the common wisdom that increased environmental protection efforts will cost jobs. He did this by presenting anecdotal evidence that increased environmental protection efforts will actually create jobs, supported by econometric simulations. This work, although lacking a behavioral economic basis, provides some evidence that efforts to remedy negative environmental impacts of sprawl—both on the urban fringe as well as in the inner city—may have dollar-valued and employment benefits that offset the operating costs. Maynard (1998) estimates that there will be US $328 billion generated annually in wages and taxes associated with homebuilding and maintenance. Maynard acknowledges, but does not estimate, costs associated with homebuilding, such as roads, schools, sewage treatment facilities, and public services. Moreover, she takes demand for 'greenfield' construction as given—an indication that the status quo has not been adequately defined.

Research already presented in this review could easily be incorporated into a benefit–cost framework. The pricing and standards approach of Baumol and Oates (1992) could be used to augment the costs portion of an analysis; the work on national income accounts of Repetto et al (1992) could be used to define baselines for BCA as well as dollar-valued effects of environmental resource depletion; the estimates by Gerking and Stanley (1992) of consumer willingness to pay to achieve marginal improvements in health arising from reductions in air pollution levels could be used to augment benefits to consumers (if they were to move from affected areas) or costs associated with compensation for living with environmental disamenities (if they were to remain).

Although robust methodologies exist for monetizing the environmental impacts of sprawl, and although these methodologies can easily be incorporated into a BCA framework, relatively few studies have been done to estimate the dollar value of *environmental* impacts of sprawl or to perform a formal BCA. However, I have identified a variety of strong research related to valuation of environmental impacts that could be adapted to a BCA of urban sprawl.

6 Decision-support models that address environmental impacts of sprawl

I now turn to research on decision-support models intended to incorporate some or all of the previous aspects of environmental analysis of urban sprawl. These models allow analysts to identify and rank development alternatives (including those associated with urban sprawl), based, in part, on environmental impacts, and allow decisionmakers to choose specific development alternatives.

Decision-support systems (DSSs) are tools that assist analysts and/or decision-makers to define and analyze alternatives and to make decisions based on the attributes of these alternatives. A decision-support model to evaluate sprawl-related environmental impacts must include criteria to determine if: (a) a particular development scheme has characteristics of urban sprawl; and (b) whether a particular development scheme is optimal (or most preferred). In section 3 a number of criteria were identified to address issue (a). In addition, Tietenberg (1996, pages 33–34) has identified a number of criteria, each of which could determine if a development scheme is sustainable or not:

> "Future generations should be left no worse off than current generations;
> Resource use by previous generations should not exceed a level which would prevent future generations from achieving a level of well-being at least as great;
> The value of the remaining stock of capital should not decrease;
> For selected resources the physical service flows should be perpetually maintained."

Tietenberg has also defined alternative principles to determine if a given allocation of resources is preferable: the full-cost principle, the cost-effectiveness principle, and the property-rights principle.

There are a number of models previously examined in this paper that can be used in a decision-support context. The pricing and standards model of Baumol and Oates (1992) could be used to infer costs to be paid by a stakeholder responsible for an adverse economic impact associated with sprawl. The national accounts framework of Repetto et al (1992) could be used to estimate the dollar value of baseline, or status quo, levels of environmental resources. The real options framework of Farrow (1999) could be used in a multiperiod context to determine whether a risky decision is made at a point in time and at a scale so as to maximize expected net benefits.

A model, based on work by McDaniels and Thomas (1999) and focused on preference elicitation from individuals regarding specific development alternatives, could also be integrated into a DSS. McDaniels and Thomas investigated the use of a *structured value referendum*, in which alternatives are presented to voters with contextual information on consequences associated with fundamental objectives. In this model, approval voting is utilized, in which voters may choose more than one alternative. Each land-use alternative is evaluated according to a set of fundamental objectives, and this information is presented to the voters. McDaniels and Thomas found a high level of satisfaction with this referendum procedure as well as a high incidence of voters choosing only one of the available alternatives.

There are a number of research results intended to stand alone as decision-support applications. Forkenbork and Schweitzer (1999) have developed a GIS-based application that integrates models of air pollution, vehicle emissions, pollution dispersion, and noise to estimate potentially disparate impacts, by race and class of affected populations, of transportation development. The use of GIS is particularly important for present purposes since urban sprawl has a spatial extent, populations affected by urban sprawl live in differing regions, and data on these populations can be examined at varying areal units.

Another GIS-based decision-support model, developed by Landis (1995), is called the California Urban Futures (CUF) model. CUF is a simulation model that allows planners and decisionmakers to visualize and evaluate various land-use scenarios at the regional, subregional, and local levels. CUF uses two units of analysis—political jurisdictions and developmental land units (DLUs)—and four submodels—regression models to estimate future population, database layers that describe developmental land units and display model results, an allocation model that matches demand and supply of developable sites, and decision rules that govern annexation or conversion of DLUs to cities.

The key assumption of CUF is that

> "it is profit-maximizing, private land developers who make the key development location and timing decisions that ultimately shape urban areas. These decisions are subject to governmental regulation ... and may also be influenced by public infrastructure investments" (Landis, 1995, page 441).

Although CUF gives a detailed representation of the supply side of urban land and housing markets and allocates growth to individual sites it is not a transportation planning model and therefore uses travel times only indirectly; in contrast, a critical role is played by development policies. Also, CUF does not model commercial or industrial growth and is not an equilibrium model in which excess demand feeds back into housing prices or land costs and in which all individuals have the same utility in all regions. CUF models environmental policies through allocation rules governing development prohibitions. Environmental outcomes can be represented as characteristics of developed land. CUF appears to be a robust model that generates results understandable by and of real interest to decisionmakers.

Another GIS-based decision-support tool for community planning with applications to urban sprawl is the Smart Growth Index, produced by Criterion Planners/Engineers, in association with Fehr and Peers Associates (CPF, 1999). This software model allows the user to visualize land-use plans and transportation-usage outputs together with a variety of indicators, including population density, vehicle usage, and air pollution levels. This DSS suffers from a sparse theoretical foundation. There appear to be a number of environmental applications for this software: brownfield usage, air pollution levels, climate change, and residential use of water and energy. Other measures could be related to environmental impacts through regression models.

A GIS-based modeling package called the urban ecological model (UEM) (Alberti, 1999) is a research framework as much as a practical decision-support tool. UEM is designed to quantify human-induced environmental stresses over time and space, relate these stresses to land uses, and predict the changes in these stresses as a function of changes in management practices.

The modeling framework has four main components, which feed back to one another in order to deal realistically with dynamic spatial behavior at a local level:

drivers, consisting of demographics, economics, policy, technology, and environment;

human systems, consisting of actors, markets, resources, and institutions;

urban processes and environmental stressors, consisting of production and consumption and land development and use, feeding into resource usage, land conversion, and emissions and waste;

natural systems, consisting of climate, ocean, and atmosphere, biogeochemical cycles, hydrology, and the terrestrial biosphere.

The UEM uses as inputs household factors, developer actions, business processes, governmental interventions, and infrastructure, and generates as outputs land-use changes, land-cover impacts, resource usage, and emissions generation.

A non-GIS-based decision-support model containing a substantial visualization component is BLUEPRINTS (Best Land Use Principles and Results, Interactively Shown) (Foster and Johnson, 1997; 1999). This software is primarily a presentation package without a strong quantitative theoretical component. BLUEPRINTS presents visual representations and text explanations of alternative land-use design outcomes in six major areas—agriculture, community character, natural systems, sign control, streetscapes, and trees and woods—and in three contexts—town, city, and rural. This software is best seen as a complement to more analytically oriented tools that generate numerical outcomes associated with alternative development strategies.

A decision-support application with a more abstract visualization component is a desktop urban simulation laboratory developed by Batty (1998). This model allows the user to visualize urban evolution by using a combination of a simulation package, a graphics and statistical analysis package, and a movie viewer package. It represents spontaneous growth by using feedback, interaction, and innovation effects represented by locational choices of residences and businesses and is best used to simulate situations with high rates of growth and high levels of innovation or noise. The visualization outputs used in this computer-based simulation are quite abstract compared with actual urban areas that are usually viewed at the tract, lot, or municipality level. By using cellular automata rather than general equilibrium economic models, Batty's model determines how changes in a variety of model parameters result in the generation of urban growth patterns similar to observed general growth patterns. Thus, markets for various factors are not considered. The key modeling notion used is 'potential for development'. Batty's model may be extended to deal with decline as well as growth and with autonomous agents as well as layers that reflect attributes of underlying grids.

A decision-support model with a more traditional graph-based and chart-based interface, but which in addition is Web-enabled, is L-THIA (Long-term Hydrological Impact Assessment) (Purdue University/USEPA, 1999). L-THIA is intended to estimate long-term hydrological impacts of development alternatives accounting for changes in the amount of impervious surfaces. L-THIA requires very little data: location in terms of state and county, area under past, present, and future land uses, and hydrological soil groups for land-use areas. Outputs include: estimated runoff depth by land use and soil group, or only by land use; estimated runoff volume by land use and soil group, or only by land use; and nonpoint-source pollution estimates, including nitrogen, phosphorous, suspended particulates, and lead. L-THIA makes a number of simplifying modeling assumptions and is not designed to estimate requirements for stormwater drainage systems or other urban planning concerns. Nevertheless, L-THIA appears to be a very useful tool for estimating hydrologic impacts of various development schemes, including suburban sprawl.

One may summarize the requirements for a DSS with visualization capability designed specifically to model environmental impacts from urban sprawl as follows. First, it should generate environmental impacts associated with various development alternatives that are both physical and quantified, incorporating hydrological impacts, landcover changes, air pollution, noise, and other outcomes. Second, such a model should allow the user to visualize environmental impacts of sprawl development at the tract, lot, or municipality level via GIS, at the level of actual land-use design choices by means of multimedia and by using charts and graphs. Third, the DSS should incorporate monetized environmental impacts of sprawl. Fourth, the DSS should incorporate the economic principles of efficiency and sustainability. Fifth, the DSS should incorporate risk, nonlinearities of externalities, and irreversibility of development decisions.

Other desirable features of DSSs, not present in the literature surveyed above, are group negotiation of stakeholders to generate a list of alternatives, and a mechanism to rank alternatives that might lead to group consensus on preferred development alternatives. The work of McDaniels and Thomas (1999) is useful in this regard, but even more desirable might be operations research and management science models for group decisionmaking (for example, Jankowski, 1997).

7 Key research priorities

In this section I identify specific areas in the study of environmental impacts of urban sprawl in which more research is necessary. Burchell et al (1998) have made a number of suggestions in this vein. First, new data-collection efforts must be initiated to alleviate the problem of small datasets repeatedly analyzed. Second, rigorous econometric analysis of sprawl-related hypotheses requires that pairs of regions be identified for analysis purposes; these regions should differ in only one key respect, the aspect for which significance is being tested (for example, presence or absence of mass transit). Third, new studies should examine impacts of sprawl in areas other than the urban fringe and in older, less-dynamic metropolitan areas that are also experiencing sprawl. Fourth, researchers and advocates must justify, on governmental efficiency grounds, remedies for certain undesirable outcomes associated with urban sprawl. Fifth, benefit–cost analyses of sprawl can be substantially improved by addressing: the entire metropolitan area, changes over time, positive and negative effects of sprawl, and scale economies. Last, sprawl studies need to do a better job of distinguishing between normal suburban development patterns and those associated specifically with sprawl.

In addition, comparisons of measurements of different environmental impacts could be performed by means of multiattribute utility theory in which stakeholders rank impacts based on physical measurements or policy impacts alone. The latter approach seems fruitful especially as diverse environmental impacts of sprawl cannot all be put in dollar measures.

Other areas of sprawl research that could be improved are those associated with a report issued by the US General Accounting Office (USGAO, 1999) concluding generally that there is a lack of known federal influence on urban sprawl. Certain of the GAO's conclusions could be examined more closely if there were more and better quality research on the links between urban sprawl and specific federal policy in areas such as tax-code provisions for owner-occupied housing and transit policy.

Given the potential for BCA to quantify some of the environmental impacts of sprawl, new case studies that follow the recommendations of Farrow and Toman (1999) might yield other BCA insights that might enrich the theory.

The Pennsylvania 21st Century Environment Commission (PTCEC, 1998) has made a number of suggestions for future research that specifically address environment impacts of urban sprawl. These include: the need to measure environmental impacts of 'sound land-use practices', as opposed to those that result in sprawl; the need for the development of a comprehensive catalogue of land-use patterns with use of GIS; the need for identification, modelling, and evaluation of economic incentives that encourage healthy as well as unhealthy land-use patterns and for the measurement and benchmarking of certain indicators of environmental health, specifically those associated with urban sprawl.

Bullard (1995) has examined the link between residential segregation and environmental racism and has identified unregulated growth, ineffective regulation of environmental toxins, public policy decisions authorizing industrial facilities that favor those with political and economic clout, and exclusionary zoning. As indicated in section 2, Downs (1994), USHUD (1999), and others have made the link between urban (suburban) sprawl and urban (inner-city) disinvestment and undesirable land uses. However, recent work by Downs (1999) casts doubt on the strength of this linkage. More research is needed to clarify the nature of this relationship.

Head (1995) has surveyed the fields of toxicology and environmental justice and has identified a number of issues that require increased research, such as identification of causal relationships between levels of one or more chemicals emitted by one or more facilities and the impact on humans, and characterization of aggregate impacts of multiple chemical exposure on humans. Related research by various authors (Lippman, 1992), though not specifically focused on urban sprawl or environmental justice, has resulted in an inventory of the effects on humans of hazardous chemicals such as asbestos, carbon monoxide, chemicals associated with water disinfection, ozone, and more. However, additional research is necessary to address the following questions: Which chemicals are or can be explicitly linked to sprawl? Which chemicals, singly or in combination, arising from sprawl development, can be associated with risks that can be classified as high or low? How can these risks be communicated to citizens in such a way that they can weigh the benefits and costs of alternative development plans with respect to risks with which they are already familiar?

Alberti (1999) develops a decision-support model that has a very different perspective from that of the research areas listed above. His urban ecological model is really the basis for an entire research agenda devoted to linking urban system models and environmental system models through improved treatment of problem definition, multiple actors, time, space, scale, feedback, and uncertainty.

Finally, there is a significant opportunity for research in developing DSSs addressing environmental impacts of urban sprawl. As mentioned in the previous section, such DSSs should incorporate identification, measurement, and monetization (where possible) of environmental impacts of sprawl, generation of easily visualized development alternatives, and group negotiation to choose a most-desired alternative as a basis for policy.

Research that addresses some of the needs mentioned above is likely to yield important and relevant results for those interested in measuring, modeling, predicting, and making decisions about urban sprawl.

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