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Paving over paradise: how land use regulations promote residential imperviousness

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Abstract

This paper examines the influence of residential zoning and subdivision regulations on the extent and distribution of impervious land cover in Madison, WI. Specifically, an analysis of approximately 40,000 single-family residential parcels in the Madison region is presented to assess the impact of land development regulations governing lot size, lot frontage, front yard setbacks, street width, and the neighborhood street network configuration on total parcel impervious cover. The results of this research suggest that lower density patterns of single-family development are associated with a larger area of impervious cover per unit of occupancy than higher density patterns. The paper argues that parcel-based analyses of environmental impact are needed to evaluate the role of specific land use planning policies on regional environmental quality. Based on the results of the analysis, we identify three specific strategies for reducing residential impervious area through municipal land development regulations.

Keywords: Impervious surface; Stormwater runoff; Urban ecology; Environmental planning

1. Introduction

Consuming prime agricultural land at a rate of over 20 ha per day, America's urbanized regions have been characterized as the most rapidly spreading human settlements in history (Benfield et al., 1999; Lacayo, 1999). While a half-century of decentralization has been credited with stimulating regional economic growth and facilitating one of the highest rates of home ownership in the world, sprawling development patterns have often degraded regional air and water quality and displaced ecologically valuable wetlands, forests, and wilderness areas. With the global urban population projected to double over the next 25 years (United Nations Environment Program, 1999), there is a critical need for planners to articulate a vision of ecologically sound urban growth. Yet there exists within the planning literature a clear divergence among those who call for high and low density models of sustainable design (Troy, 1996; Roseland, 1998; Newman and Kenworthy, 1999). In the interest of advancing this debate, this paper examines the relationship between residential development patterns and a primary determinant of environmental impact: impervious land covers.

The rapid growth of impervious land covers within urbanizing regions holds many negative implications for environmental quality (Arnold and Gibbons, 1996). The displacement of cropland, grassland,

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and forested areas by the impervious surfaces of streets, driveways, and buildings greatly intensifies stormwater runoff, enhances stream channel erosion, and diminishes groundwater recharge. Identified as the most significant threat to water resources by the U.S. Environmental Protection Agency, the toxic and pathogenic pollutants transported from impervious surfaces to watersheds in the form of non-point source water pollution have been shown to substantially degrade streams, rivers, and lakes (USEPA, 1994). In addition to a wide range of hydrological impacts, the conversion of vegetated land covers to impervious material also has been found to influence regional climate and air quality. Through a climatological phenomenon known as the urban heat island effect, the displacement of natural land covers by impervious materials diminishes evapo-transpiration and enhances the absorption of radiant heat energy at the Earth's surface, elevating the summer air temperatures of large cities by an average of about 3–4.5 °C (U.S. Department of Energy, 1996).

While the environmental effects of impervious surfaces are well documented, few studies have sought to evaluate how specific land development regulations influence the extent and distribution of impervious materials throughout urbanized regions. To facilitate the development of planning strategies to minimize the negative impacts of future growth, this study correlates alternative development patterns with the impervious surface area of approximately 40,000 single-family residential parcels in the City of Madison, WI. The results of our analysis demonstrate that modest changes to municipal land development regulations could yield significant reductions in the total impervious cover of new and existing development. Based on these findings, we identify a number of planning strategies that may be employed to reduce the impervious surface area of residential development. To advance these ends, we recommend specific changes to municipal zoning codes, subdivision regulations, and stormwater utilities.

2. Urban design and impervious cover

To date, the literature on urban form and environmental quality remains formative. Although a number of studies establish linkages between various forms of ecosystem stress and urbanization, the precise relationship between land use patterns and regional ecological functioning is not clearly understood (Alberti, 1999; Pauleit and Duhme, 2000; Brabec et al., 2002). As concluded by Alberti, "[planners] have not resolved questions concerning the correlation between changes in ecological conditions and changes in urban patterns ... yet the answers to these questions are critical to predict the impacts of future urban development and to design planning strategies to mitigate them" (1999, p. 151). A principal limitation of the current literature on urban form and environmental quality is an emphasis on the physical rather than the policy bases of regional environmental problems. For example, the physical relationship between regional impervious cover and stream water quality is well established. As concluded by a number of studies, once the impervious area of a watershed exceeds 10%, aquatic ecosystem health tends to decline; at 30% impervious cover, the watershed will become severely impaired (Arnold and Gibbons, 1996; Booth and Jackson, 1997; Schueler, 2000).

The total impervious area of a watershed thus provides a key physical indicator of aquatic ecosystem health. Yet, while such analyses demonstrate a significant relationship between urbanization and environmental quality, they provide little substantive direction for land use policy. Beyond the general prescription to reduce impervious cover, several important policy questions must be addressed to inform targeted land use strategies. For example, what classes of land use are most directly associated with watershed impervious cover? What types of land development regulations governing density, configuration, and materials usage are in place within the watershed? How much of the watershed is privately owned; how much is public land and street rights-of-way? Prior to the development of planning strategies to mitigate non-point source water pollution, we must know not only *how* impervious land covers impact stream water quality (a question of science), but also *why* such surfaces are distributed in various patterns within a particular watershed (a question of policy). In short, we must assess both the physical and policy bases of the stormwater issue.

The intent of this research is to understand more clearly why impervious materials are distributed in various patterns throughout a metropolitan region

and to identify design-based strategies that may be employed to reduce the impervious area of new and existing development. To do so, this research will build upon the current literature in three important respects. First, we will develop a policy-relevant unit of analysis. Second, we will distinguish between the various impervious components of residential development. And, third, we will account for the design capacity of the residential structure in assessing the relative impervious effects of alternative development models.

2.1. Deriving a policy-relevant unit of analysis

Research on the environmental implications of impervious land covers has tended to adopt an ecological (e.g. a watershed) or geometric (e.g. a square kilometer) unit of analysis. For example, each of the stormwater management studies referenced above quantifies the water quality impacts of impervious materials at the level of the watershed. The limitation of an ecological unit of analysis for planning research pertains to the spatial dimensions of land use regulation. Because land use is regulated at the legal dimensions of land parcels or planning districts, rather than at the ecological dimension of watersheds, analyses conducted at the watershed level may yield only limited insights for planning policy. For example, as watersheds generally consist of more than a single land use class and set of land development regulations, it may not be possible to identify which policies are most directly associated with watershed imperviousness. Because impervious surface inventories derived from aerial photography do not reveal the underlying land use policies at work within the watershed, a disconnect is created between a potential regulatory cause, such as a minimum street width requirement, and an environmental effect, such as stormwater runoff.

In light of this fact, this research quantifies impervious surface area at the unit of the residential land parcel. By measuring impervious cover at the legal dimension of the parcel, it is possible to associate directly various land development regulations enforced at the parcel level with residential imperviousness and associated impacts. In short, a parcel-based assessment of impervious cover is needed to fully bridge the gap between science and policy.

2.2. Measuring the components of impervious cover

In contrast to previous studies focused on aggregate measures of impervious cover, this research quantifies the individual components of parcel impervious area. The ability to distinguish between distinct impervious components is essential to understanding how various land development regulations influence total impervious cover, and what classes of cover constitute the majority of residential impervious surfaces. As illustrated in Fig. 1, the distinct impervious components measured in this project include the footprint of the house, garage, and other parcel buildings; the paved area of the driveway; and the paved area of the sidewalk.

In addition to these surfaces, the local street network may also account for a significant proportion of the total area of neighborhood impervious cover. In a study of impervious land cover in Olympia, Washington, street surfaces were found to account for over a third of a neighborhood's total impervious area (City of Olympia, 1995, Table 1). As a result, reductions in street width may provide a viable strategy for mitigating the environmental impacts of future development. In order to capture these extra-parcel areas within a parcel-based measure, the "street allotment," or the area of the street immediately adjacent to the parcel, is incorporated into a measure of total parcel impervious cover. Calculation of the street allotment permits both the private and public components of neighborhood impervious areas to be captured within a single variable. As illustrated in Fig. 1, it is hypothesized that parcels characterized by larger lot sizes, longer front yard setbacks, and wider street frontages (Parcel A), require significantly more impervious surface area than alternatively configured parcels designed for an equivalent residential capacity (Parcel B).

2.3. Accounting for design capacity

A final important shortcoming of the current literature on urban form and environmental quality is a common failure to account for the "design capacity" of alternative development models. By design capacity, we mean the number of residents or workers that a structure is designed to accommodate. The failure to account for variability in design capacity has biased statistical comparisons in previous work. For example,

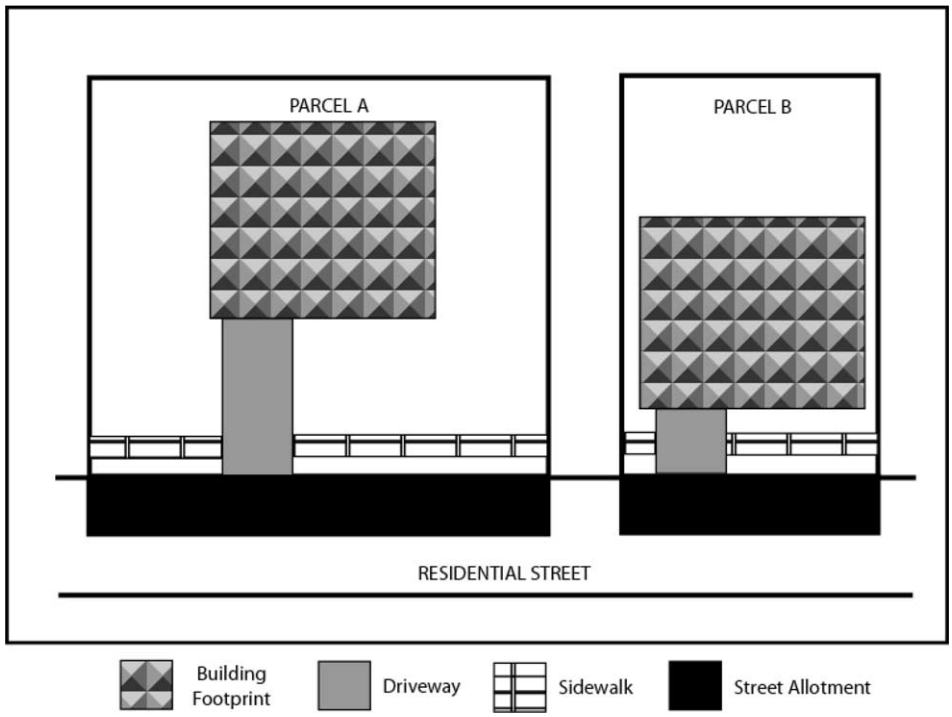

Fig. 1. Impervious components of two single-family parcels.

in one of the few studies of land use class and impervious surface area, the Soil Conservation Service (1975) reports that low density residential development is associated with a lower percentage of impervious cover per parcel than high-density residential development. While undoubtedly accurate, the limitation of this analysis is a failure to account for the design capacity of each model. Designed to house many more residents than a single-family district, a multi-family district should be expected to exhibit a more extensive impervious coverage per parcel. A more useful analysis would control for the number of housing units and/or bedrooms per parcel in comparing dissimilar residential models. If the residents living within a multi-family parcel were dispersed into a larger number of a lower density, single-family parcels, would total regional impervious cover be increased or reduced? To answer this question, this study incorporates the design capacity of the residential structure into the analysis as a control variable, permitting the relative impervious impacts of alternative single-family models to be reliably compared.

3. Developing a parcel-level measure of impervious cover

The objective of this study is to estimate the area and type of impervious cover for approximately 40,000 single-family residential parcels in the City of Madison, WI. Two criteria informed the selection of the single-family residential parcel as the unit of analysis for this research. First, the legal dimension of the land parcel provides a direct link between the distribution of an environmental stressor, such as impervious land covers, and the planning policies in place to control the character of new and existing development. Second, single-family development often constitutes the leading edge of peripheral urban growth and, as such, holds significant implications for the direction and extent of new development. Related to this point, single-family residential development occupies the majority of total urban land conversions in the study region, accounting for approximately 52% of the total developed land area in the City of Madison.

To quantify the type and area of parcel impervious materials, high-resolution aerial photography and parcel attribute information were obtained from the Dane County Land Information Office and the City of Madison Engineering Division, respectively. Collected in April of 2000 at a ground resolution of 6 in. (2.5 cm), the aerial imagery is of sufficiently high resolution to permit the surface features of high-density residential parcels to be accurately measured. In addition, the tax attribute database maintained by the City of Madison provides a range of information on parcel characteristics, such as the size of building footprints and the number of bedrooms in the residential structure. In combination, these datasets were used to quantify four components of residential parcel impervious surface. These include the footprint of parcel structures, the driveway area, the sidewalk area, and a parcel street allotment. In addition, four regulated dimensions of the residential parcels were measured and incorporated into the database. A detailed description of each parcel attribute and the methods employed in its derivation is provided in the following paragraphs.

3.1. Residential design attributes

Four parcel attributes were quantified to associate impervious cover with planning regulations: lot size, lot frontage, front yard setback, and, to be used as a control variable, the number of bedrooms in the residential structure. What follows is a brief description of each attribute and the method employed in its estimation.

- *Lot size*: The area of the parcel measured in square meters. The lot size serves as a direct measure of housing density and was obtained from the City of Madison Engineering Division. Lot size is used in the analysis to assess how different levels of housing density influence the area of parcel impervious surfaces and the area of street surfaces immediately adjacent to the parcel.
- *Lot frontage:* The width of the parcel in meters at the point of its adjacency to the street. The lot frontage is a direct determinant of the length of street paving required to service the parcel. This variable was also obtained from the City of Madison Engineering Division.
- *Front yard setback:* The front yard setback is the linear distance in meters between the street curb and the residential structure. Because driveways are required to extend at least the distance of the front yard setback (as discussed below), this regulated parcel attribute is related to the area of driveway paving. As the length of the front yard setback is not recorded for property tax purposes, this variable was manually digitized with the aid of the high-resolution aerial photography and a parcel-based geographic information system.
- *Residential capacity:* The number of bedrooms in the residential structure. This measure is used as a control variable in the analysis to account for the variation of housing capacity throughout the study region. As discussed above, in evaluating the relative impacts of alternative development models, it is essential that the intensity of development be held constant; this variable enables such comparisons. These data were obtained from the University of Wisconsin-Madison Land Information and Computer Graphics Facility.

In addition to these four parcel design variables, two attributes of the neighborhood street network were quantified to assess the contribution of extra-parcel infrastructure to total residential impervious cover. As noted above, streets can account for a significant percentage of total urban impervious area. The inclusion of the following two variables permits impervious road surface to be incorporated into a parcel-based measure.

- *Street width:* The width of the primary residential street in meters. In combination with the lot frontage, this variable is used to estimate the area of the residential street allotment. As discussed below, the street allotment is the portion of the residential street immediately adjacent to the single-family parcel. Wider street widths and lot frontages require a greater area of street paving in residential zones, with direct implications for stormwater runoff and surface heat retention.
- *Street intersection density:* The number of street intersections located within 1 km^2 of the residential parcel. As illustrated in Fig. 2, this measure provides a quantitative variable that may be used to differentiate standard grid-based street networks from dendritic (i.e. based on cul-de-sacs) street

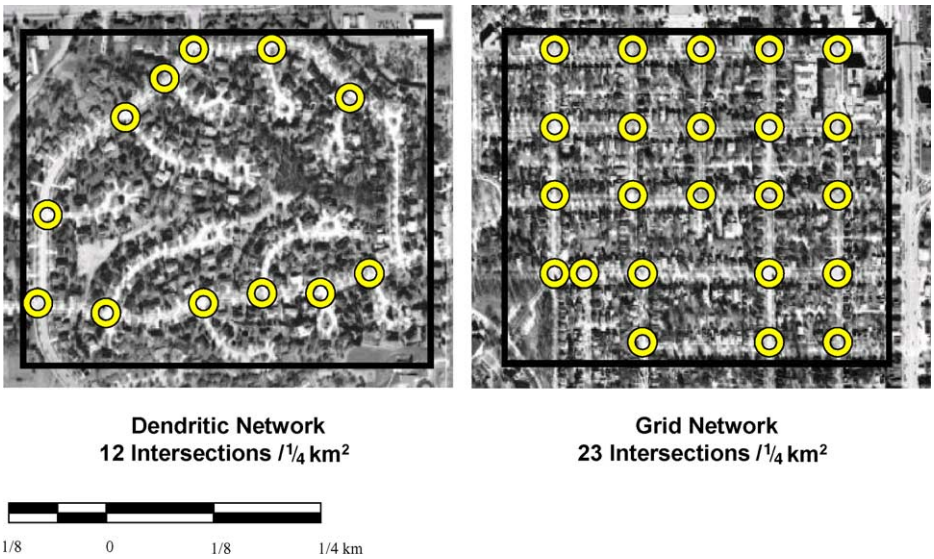

Fig. 2. Street intersection density in dendritic and grid network types (circles denote street intersections).

networks. As cul-de-sacs are not considered to be intersections, dendritic networks tend to have a much smaller number of intersections per unit of area than a grid-based network. Derived with the aid of a geographic information system, this variable is used to evaluate the effects of the street network pattern on parcel impervious cover, holding the other parcel design attributes constant.

3.2. Parcel impervious cover

As discussed above, the parcel impervious cover consists of the horizontal surface area occupied by residential structures, such as the house, garage, storage sheds, and other ancillary structures; the driveway area; and the area of sidewalks. Obtained as part of the routine property tax assessment process, the area of all parcel structures is maintained by the City of Madison and was made available for this research. In addition, property tax assessors record information on the presence of sidewalks and garages. For parcels coded as having sidewalks, the sidewalk area was estimated based on the lot frontage (the width of the parcel at the street adjacency) and an average sidewalk width of 1.5 m. The product of these two dimensions (lot frontage × 1.5 m) yielded an estimate of sidewalk impervious surface area for those parcels containing sidewalks.[1] With the aid of aerial photography, a random sample of over 100 parcel sidewalks was measured and found to comport well with these width and area estimates.[2]

Similar to the dimensions of sidewalk paving, the City of Madison records information on the presence of garages but does not survey driveway areas. To derive an estimate of driveway paving, an equation based on the front yard setback and number of garage stalls was employed for each residential parcel coded as having a garage. As specified in the Madison Code of Ordinances, all driveways must lead from a street and traverse the length of the front yard setback (Madison Code of Ordinances §28.04, 28.11). In light of this requirement, the setback distance was used as the minimum length dimension for estimating all driveways in the study region. To estimate driveway width, a ran-

[1] Because there is an overlap between sidewalk and driveway paving, a uniform area of 4.5 m^2 was subtracted from all parcel sidewalk estimates to avoid a double-counting of paved areas. This area is based on an average sidewalk width of 1.5 m and an average driveway width of 3 m.

[2] A random sample of 100 single-family parcels was found to be sufficient to achieve a 95% level of confidence in predicting sidewalk area within 10% of the population mean. The sidewalk area of 100 randomly selected parcels was measured through the use of high-resolution aerial photography and found to vary from the sidewalk area estimates by an average of 2%.

dom sample of residential parcels was selected and the driveway widths measured with aerial photography.[3] On average, sample driveways were found to be approximately 3 m in width for each garage stall. Based on these parameters, parcel driveway areas were estimated with the following simple equation:

$$\text{Driveway area } (\text{m}^2) = \text{Front yard setback (m)} \times 10\,\text{m} \times \text{Number of garage stalls}$$

To gauge the accuracy of this estimation routine, a random sample of 100 single-family parcels was selected and the driveway areas measured with the aid of the aerial photography.[4] The results of this sampling process were compared to the driveway area estimates derived with the above equation and found to correspond closely. On average, the difference between the measured and estimated driveway areas was approximately 6%, a level of error deemed acceptable for this type of analysis. It should be noted, however, that this estimation routine fails to assign any driveway area to parcels with driveways but no garage. An additional random sample of 100 parcels found that less than 1% of those surveyed have driveways without garages.[5] Nevertheless, this limitation of the study methodology is a source of potential error that should be considered in evaluating the results.

3.3. Estimating impervious street allotments

As discussed above, in addition to the impervious surface area of individual land parcels, alternative residential development patterns can degrade regional environmental quality through the area of street paving required to service residential dwellings. In order to better capture this extra-parcel imperviousness within a parcel-based measure, this study quantifies an area of the residential street called the "street allotment." For parcels situated on linear street segments, the street allotment is a polygon bounded by the parcel frontage, the centerline of the street, and an extension of the parcel side lot lines to form a rectangular section of street paving (see Fig. 1). This street allotment area is easily calculated by multiplying the length of the parcel frontage times one half of the residential street width. In the Madison study region, 96% of all single-family residential parcels are situated on linear street segments.

For parcels situated on terminal street segments or cul-de-sacs, no street centerline exists and thus a different method was required for estimating the street allotment. For these parcels, the area of the cul-de-sac was manually digitized with the aid of the aerial photography and then equally allocated to each parcel bordering the cul-de-sac. In essence, each of the approximately 1400 parcels bordering a cul-de-sac was allocated a wedge-shaped area of street paving defined by the number of neighboring parcels and the radius of the cul-de-sac.

4. How parcel design influences impervious cover

Once constructed, the parcel attribute and impervious cover database was analyzed to identify land use planning strategies that may be adopted to reduce the impervious area of new residential development. Specifically, the data analysis was designed to associate the parcel design attributes of the lot size, lot frontage, front yard setback, and design of the street network with total parcel impervious cover of all single-family residential parcels in the City of Madison. In addition, the number of bedrooms in the residential structure was used as a control variable to permit comparisons of high and low density parcels designed to accommodate the same number of residents. In the first component of the analysis, descriptive statistics are presented to illustrate the distribution of the various parcel design attributes throughout the study region. In the second component, multivariate regression analysis is used to assess the magnitude of benefits that may be achieved through modifications to current zoning and subdivision regulations.

4.1. Descriptive analysis

Table 1 presents a series of descriptive statistics for each of the independent variables and impervious surface measures. Within the Madison study region, the average single-family residential parcel is approx-

[3] Similar to the sidewalk sample, a random sample of 100 parcel driveways was found to be sufficient to achieve a 95% level of confidence in predicting driveway width and area within 10% of the population mean.

[4] Ibid.

[5] Ibid.

Table 1
Descriptive statistics

Variable	Minimum	Maximum	Mean	Standard deviation
Lot size (m^2)	74	8146	911	487
Frontage (m)	3.7	131	22.3	8.7
Setback (m)	1.5	137	12.6	3.9
Number of stories	1.0	4	2.0	0.64
Street width (m)	3.1	26	9.4	2.9
Intersection density (intersections/km^2)	1.9	77	35.4	12.5
Number of bedrooms	1.0	10	3.10	0.78
Total impervious cover (m^2)	52	1786	354	121

imately 900 m^2 in size; is characterized by three bedrooms, a 22 m frontage, a 13 m front yard setback; and is two stories in height. As suggested by the standard deviation, parcel size varies greatly throughout the region, indicating a range of housing densities.

Fig. 3 presents the percent coverage of the four primary impervious components: the house/garage footprint, the driveway, the sidewalk, and the street allotment. For the average parcel (as noted in parentheses), the street allotment and house/garage footprint each account for roughly one third of the total impervious cover, with the driveway and sidewalk accounting for smaller percentages. Yet these relative percentages vary greatly by lot size. As depicted by the line drawings, the contribution to total impervious cover of the house/garage footprint and the street allotment tend to decrease with increments in lot size, while the contribution of the driveway increases with increments in lot size. The percent coverage of sidewalks remains relatively constant from 1000 m^2 to over 4000 m^2 in size. These findings suggest that the effectiveness of various design-based strategies to reduce impervious cover may vary by density class. In high-density zones, standards addressing the street width and lot frontage may prove to be most effective in reducing total impervious cover, while a reduction in the front yard setback, a variable associated with the driveway length, may prove most effective in reducing the

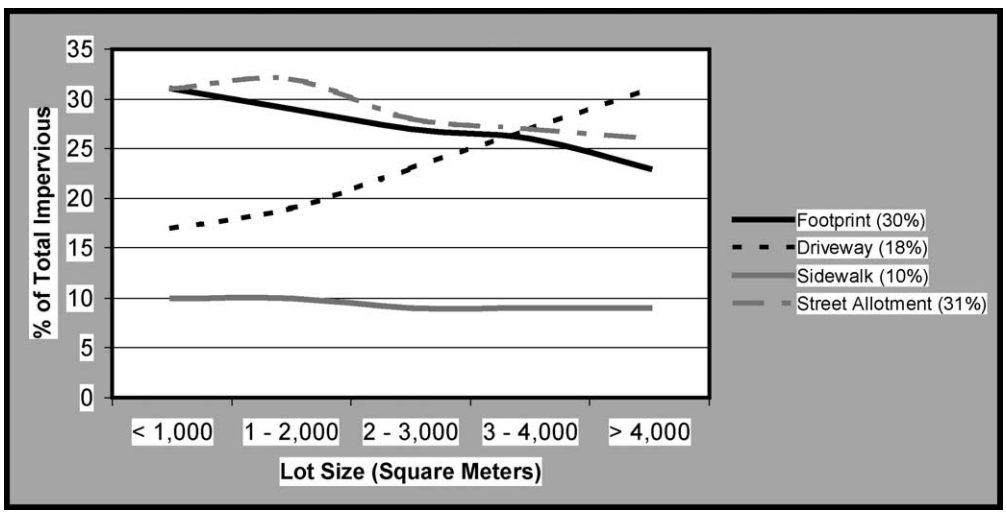

Fig. 3. Percent coverage of impervious components by lot size (mean percent coverage in parentheses). *Note*: Line drawings depict the mean percentage of impervious component coverage at different levels of lot size. Negative changes in slope indicate a reduction in the percentage coverage with increments in lot size; positive changes in slope indicate an increase in the percentage coverage with increments in lot size.

impervious cover of parcels greater than 4000 m^2 in area. Presented in the following section, the results of a regression analysis further illustrate the potential for modifications to land development regulations to reduce significantly residential impervious cover.

4.2. Explanatory analysis

In order to quantify the potential benefits of specific design-based strategies, ordinary least-squares was used to develop a predictive model linking parcel design and street network design to total parcel impervious cover. In addition to regulated parcel and street network attributes, the number of bedrooms in the residential structure was incorporated into the model to control for the distribution of housing capacity throughout the study region. The resulting model included the following dependent and independent variables:

Y	Total impervious cover
X_1	Lot size
X_2	Lot frontage
X_3	Front yard setback
X_4	Street width
X_5	Intersection density
X_6	Number of bedrooms

With the aid of the Statistical Package for the Social Sciences (SPSS), a set of parameter estimates and model summary statistics was generated for the approximately 40,000 single-family residential parcels located in the Madison study region. These results of this modeling process are presented in Table 2.

Table 2
Regression analysis results

Variable	*B*-coefficient	Standardized coefficient	Significance
Lot size	0.059	0.235	<0.001
Frontage	6.85	0.495	<0.001
Setback	6.43	0.205	<0.001
Street width	5.90	0.140	<0.001
Intersection density	−1.16	−0.120	<0.001
Number of bedrooms	20.70	0.128	<0.001
Summary statistics	Adj. *R*-square 0.765	*F*-statistic 20,997	*F*-significance <0.001

The results of the regression analysis indicate that the various parcel and street network design variables are significantly related with the area of impervious materials. The parcel area exhibits a significant positive relationship with impervious cover when controlling for other parcel design attributes believed to be associated with the dependent variable. As indicated by the positive *B*-coefficient of 0.059, impervious surface area increases by over 0.06 m^2 for each square meter increase in lot size when holding the other independent variables constant at their mean values. Significantly, this relationship was found to hold when controlling for the number of bedrooms in the residential structure, suggesting that the greater impervious coverage of lower density parcels is not solely attributable to variation in residential capacity.

Perhaps surprisingly, lot size is not the strongest determinant of impervious cover. With a standardized regression coefficient of 0.495, variation in the dimension of the lot frontage was found to have the greatest influence on impervious surface area. Specifically, an increase of one standard deviation in lot frontage is associated with an increase in impervious surface area of approximately 0.5 standard deviations. This standardized effect on the dependent variable is more than double that of any other independent measure. In terms of observed units, a one meter increase in the lot frontage was found to be associated with an increase in total impervious cover of about 6.85 m^2. Although not as strongly related, the front yard setback was also found to have a significant positive relationship with total impervious cover. As denoted by the *B*-coefficient on this variable, a 1 m increase in the front yard setback was found to be associated with a 6.43 m^2 increase in total impervious cover, holding constant all other model variables. As discussed above, the front yard setback influences total parcel impervious cover through its effects on the length of driveways.

In concert with the parcel design attributes, the two street network attributes of street width and intersection density were found to have a significant influence on parcel impervious cover. As to be expected, additional increments in street width are associated with an increase in the area of the street allotment, enlarging total impervious cover. The *B*-coefficient on this variable indicates that a 1 m increase in street width is associated with a 5.9 m^2 increase in total

impervious cover. The negative coefficient found for the intersection density variable suggests that as the street network more closely approximates a grid pattern, total parcel impervious cover tends to decrease. As discussed in the concluding section, this relationship is likely attributable to the expansive paved area of residential cul-de-sacs.

Overall, a regression model incorporating the four parcel design and two street network design attributes was found to explain approximately 77% of the variation in residential impervious cover within the Madison study region. As such, this model provides a reliable basis for assessing the potential implications of various planning policies governing the size and configuration of residential parcels. Based on these results, the following section of the paper will explore three recommended policy changes to reduce the area of impervious surfaces within new and existing residential areas.

5. Planning policies to reduce impervious cover

The results of this analysis suggest a direct linkage between land development regulations governing the dimensions of residential land use and the surface area of impervious materials. In this concluding section of the paper, we discuss three sets of strategies that may be adopted by municipalities seeking to reduce the growth in regional impervious materials through zoning codes, subdivision regulations, and stormwater utility fees.

5.1. Think small: reducing impervious land area through zoning

The most effective approach to reducing the area of residential impervious surfaces is through reducing the size and dimensions of new single-family parcels. In contrast to studies focused on impervious materials as a percentage of parcel size, this research suggests that total parcel impervious area increases significantly with increments in lot size. This relationship holds true even when accounting for the greater residential capacity of lower density parcels. In short, moderate to high-density residential development is associated with a smaller area of impervious materials per bedroom than lower density models. As a result, a reduction in the average housing density of the region can be expected to result in an increase in total regional impervious land area.

Perhaps the most straightforward approach to minimizing the growth in impervious land covers is through reducing the average lot size of new development. Yet, current zoning codes in the Madison region and in cities throughout the country specify lot size minimums rather than maximums. While many codes do specify impervious coverage maximums, these standards are often set too high to measurably influence development. Importantly, such percentage-based impervious standards place no ceiling on total lot impervious area (i.e. as the lot size increases, the permissible impervious surface area increases) and do not limit the area of the residential street allotment. Our results suggest that a reduction in the average lot size of new development from 2000 to 4000 square meters, in the absence of other regulatory measures, would reduce total parcel impervious area by about 12%.

More effective than constraints on lot size would be a reduction in the lot frontage. Directly tied to the area of the street allotment, the lot frontage could be reduced without mandating a reduction in lot size, resulting in a smaller street allotment. In addition to its clear relationship with the area of paving required to service a parcel, the lot frontage also appears to be related to the size of the building footprint. When controlling for the lot size, front yard setback, and number of bedrooms in the residential structure, the lot frontage has a significant and positive correlation with the area of the building footprint and the number of stories in the residential structure. This finding supports the hypothesis that a reduced frontage places upward pressure on the residential structure, resulting in multistory construction and a reduction in the horizontal footprint of the house.

Thinking small in terms of the lot size, frontage, and front yard setback can significantly reduce the area of impervious surfaces without requiring reductions in the square footage of the house. As suggested by our results, a reduction in lot size from 2000 to 4000 square meters, a reduction in the frontage from 21 to 15 m, and a reduction in the front yard setback from 12 to 8 m would reduce total impervious area by approximately 30%. These benefits could be achieved with modest revisions to municipal zoning

codes and with no reduction in the average size of new houses.

5.2. Constrain the public domain: street design and subdivision regulations

Street paving constitutes a significant proportion of the total impervious surface area of residential development. As indicated in Fig. 3, the street allotment is the single largest component of total impervious cover, accounting for almost a third of the average parcel imperious area. This finding suggests that municipal governments can substantially reduce the impervious cover of residential zones through the modification of subdivision regulations governing the dimensions of street widths and neighborhood block sizes.

The significance of street widths to regional environmental quality is widely recognized in the literature (City of Olympia, 1995; Arnold and Gibbons, 1996). In concert with previous work, our findings suggest that a reduction in the average residential street width from 9.8 to 8.5 m, a dimension sufficient to accommodate two lanes of slow moving traffic and on-street parking, would reduce the average parcel street allotment by approximately 13%. Less appreciated is the influence of neighborhood block structure on impervious surface area. Block size is directly related to street intersection density: as block sizes decrease, intersection density increases. In combination with a reduction in street width to 8.5 m, an increase in street intersection density to 45 intersections per square kilometer, consistent with a 150 m block size, would reduce average residential parcel impervious cover by almost 10%.

Block size and intersection density appear to influence impervious surface area through two mechanisms. First, as noted above, grid networks lack expansive cul-de-sac areas, which, when controlling for the lot size and frontage. As there is no need within a grid network to facilitate 360° turning movements by emergency vehicles, this expansive and wasteful use of impervious surface is avoided.

Second, when controlling for lot size, lot frontage, and residential capacity, building footprints were found to have a significant negative correlation with intersection density. A potential explanation for this finding concerns the variable configuration of parcels within grid-based and dendritic network types. In the rectangular configuration of a traditional grid, the width of the buildable area of the parcel does not change between the front and rear lot lines (i.e. the width of the parcel is uniform throughout its depth). In contrast, parcels situated on cul-de-sacs often assume an irregular shape, with the rear lot line exceeding the length of the frontage by many meters. In this more triangular configuration, the buildable area of the parcel increases with depth, permitting a wider building footprint than a rectangular parcel of equal frontage and side yard setbacks. As a result, the imposition of a rectangular block and parcel structure may constrain the footprint of the residential structure, encouraging multistory development for larger house sizes.

5.3. Perforate the driveway: abating the effects of existing development

Projected to grow by approximately 25,000 residents by the year 2020, the Madison region can expect to add at least 140 ha of additional residential impervious surface area over the next two decades.[6] If the zoning and subdivision regulations governing street width, block size, and parcel design outlined above were adopted, this figure would be reduced by approximately 38%, or about 53 ha.

While the potential to reduce the impacts of new growth are impressive, it is important to note that changes to a city's land development regulations will have little, if any, impact on existing development. As the vast majority of the Madison region's 2020 built area is already in place, changes in future peripheral development will have only limited effects on total regional impervious land cover. In light of this observation, the most effective strategies for reducing regional impervious cover must address both new and existing development. One strategy for doing so would entail the modification of existing residential driveways. Found to account for almost 20% of the total parcel impervious area, driveways constitute a significant source of regional impervious cover, yet this component of parcel imperviousness could be reduced in area

[6] Currently, 48% of all housing units in Madison are single-family dwellings. This statistic assumes that 48% of the projected population growth occupy single-family dwellings at an average occupancy rate of one resident per bedroom.

or modified to facilitate the infiltration of stormwater during the process of periodic resurfacing. For example, several types of porous paving materials, through which up to 80% of intercepted stormwater can infiltrate, have been available for many years (Gburek and Urban, 1980). Other alternatives to traditional driveway designs are paved, semi-paved, or gravel runners.

The use of porous paving in the periodic re-surfacing of driveways could yield substantial benefits to the region. For example, an increase from zero to 80% infiltration on the driveway areas of parcels would be roughly equivalent to reducing the region's total residential impervious cover by approximately 194 ha. Were such materials to be used in the resurfacing of sidewalks, this figure would increase to 297 ha—an area greater than the impervious zone of downtown Madison.

One means of encouraging the use of alternatives to traditional driveway paving is through the creation or modification of a regional stormwater utility. Stormwater utilities are regional taxing districts created to assess a stormwater impact free for all residential, commercial, and industrial development within a stormwater management district. Generally based on the area of impervious land cover materials per parcel, stormwater utility fees create a monetary incentive for developers and property owners to reduce the surface area of impervious materials. In the Madison region, for example, general impervious surface estimates based on the parcel area, square meters of the residential structure, and number of garage stalls are used to assess a stormwater fee semi-annually for residential landowners. Such a fee structure could be modified in two ways to create a greater incentive for retrofitting driveway areas with porous paving alternatives.

First, the taxable impervious area could be expanded to capture the street allotment, creating a greater incentive to reduce impervious areas and assessing a greater impact fee on neighborhoods characterized by wide streets and dendritic networks. Second, driveways could be taxed at a higher rate than building or street surfaces, and porous driveway areas not taxed at all, to create a targeted incentive to redesign driveway areas. The imposition of such a two-tier tax structure would hold the potential to modify existing development over time and would raise additional revenue to fund regional stormwater management.

6. Conclusions

This work demonstrates that, in one rapidly growing metropolitan region of the U.S., lower density models of single-family residential development are associated with a greater use of impervious materials than higher density models. This relationship holds true when controlling for the residential capacity of the parcel. Given the direct mathematical relationship between parcel impervious area and the dimensions of the parcel frontage, front yard setback, and configuration of the street network, among other parcel design attributes, it is reasonable to conclude that the relationships found between parcel design and imperviousness in the Madison study region are largely transferable to any city characterized by North American development patterns. If true, metropolitan regions seeking to reduce the rate and extent of impervious land conversions should revise land development regulations to achieve the greater physical economies of scale associated with moderate-to-high-density residential development. In addition, tax-based incentives should be adopted to encourage a reduction in the area, runoff rate, and thermal capacity of existing impervious surfaces.

This research does not seek to present a direct link between specific land development regulations and regional water or air quality but rather adopts impervious surface area as a surrogate indicator of such problems. Continuing work will model the direct hydrological and atmospheric implications of alternative development models within the Madison region. This work does provide, however, an important methodological foundation for assessing the role of land use policy in the emergence of diffuse, regionalized environmental problems such as non-point source water pollution, smog formation, and climate change. Through the adoption of a policy-relevant unit of analysis—the individual land parcel—it is possible to associate directly the effects of land use policies enforced at the parcel level with regionalized environmental problems produced through the conversion of natural areas to urbanized land uses. In contrast to previous work seeking to model such effects at an ecological or geometric unit of analysis, this research provides a more direct connection between the science of environmental degradation and the policy of land use controls. As such, we hope

this work will contribute to a more complete integration of land use planning policy and environmental management.

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