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Land resource impact indicators of urban sprawl

John E. Hasse [a,*], Richard G. Lathrop [b]

[a] *Department of Geography and Anthropology, Rowan University, 201 Mullica Hill Road, Glassboro, NJ 08028, USA*

[b] *Rutgers University, Center for Remote Sensing and Spatial Analysis, College Farm Road, Cook Campus, New Brunswick, NJ 08901, USA*

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Abstract

Sprawl has been loosely defined as dispersed and inefficient urban growth. We propose a series of five indicators that examine the per capita consumption of land taken in new development in relation to several critical land resource impacts associated to sprawl including: (1) density of new urbanization; (2) loss of prime farmland; (3) loss of natural wetlands; (4) loss of core forest habitat; and (5) increase of impervious surface. These *Land Resource Impact (LRI)* indicators were measured for each of New Jersey's 566 municipalities using a 1986 to 1995 land use/land cover digital database along with US Census population data. By integrating population growth with land resource loss a more nuanced interpretation of land use change is provided than in previous analyses of sprawl.

Keywords: Urban sprawl; Environmental indicators; Urban impacts; Land use/land cover change

Introduction

The phenomenon of sprawling urban development is one of the major forces driving land use/land cover change in the United States. The US Department of Agriculture Natural Resource Conservation Service estimates that over 12 million hectares of land were converted to developed land in the United States during the 15 year period between 1982 and 1997, with over half of newly developed land

* Corresponding author. Tel.: +1-856-256-4500x3977; fax: +1-856-256-4670.
E-mail address: hasse@rowan.edu (J.E. Hasse).

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coming from farmland and another third from forest land (Natural Resources Conservation Service, 1999). This dramatic expansion of development at the expense of open space and natural resource lands has sparked intense interest and debate over the problems and benefits of 'urban sprawl.'

The literature on sprawl, with a tinge of irony, is broadly dispersed and multi faceted. A variety of definitions for sprawl have been put forth that describe sprawl as a specific form of urban development with low-density, dispersed, auto-dependent and environmentally and socially-impacting characteristics (Ewing, 1997; Downs, 1998; Burchell & Shad, 1999). The costs and negative externalities of urban sprawl have been widely studied and documented (Duncan et al., 1989; Frank, 1989; Kunstler, 1993; Burchell et al., 1998; Kahn, 2000; Freeman, 2001). Others have pointed out the benefits incurred from sprawl-style development (Gordon & Richardson, 1997; Carliner, 1999; Easterbrook, 1999). Of particular concern is the land-consumptive and inefficient nature of this new urban growth and the increasing amount of critical land resources lost in relation to human population growth (Anon,1994, American Farmland Trust, 1997, Burchell et al., 1998; NRCS, 1999; Sierra Club, 1999).

Urban sprawl, as implied by its name, is an inherently dynamic spatial phenomenon. A number of recent studies have attempted to develop a means of characterizing sprawl by measuring particular spatial characteristics associated to sprawl and comparing between metropolitan areas (Galster, Hanson, Wolman, Coleman & Freihage, 2001; El Nasser & Overberg, 2001; Ewing, Pendall, & Chen, 2002). These studies have helped to break new ground in characterizing a challenging and elusive concept (Galster, Hanson, Wolman, Coleman, & Freihage, 2001). However, from both a research and practical management standpoint, there is a great need to further our understanding of the spatial and temporal patterns of urban land use change, especially in dynamic suburban and exurban areas. To keep up with this change, agencies from all levels of government and private companies spend millions of dollars per year obtaining aerial photography and other forms of remotely-sensed data to extract detailed, up-to-date information about urban/suburban infrastructure (Jensen & Cowen, 1999). Even so, there is still often a dearth of consistently interpreted, appropriately detailed land use/land cover change (LU/LCC) data at sufficient time intervals to characterize and monitor urban growth over broader geographical extents, i.e., larger than a county (Theobald, 2001).

While sheer magnitude of low-density new growth is often pointed to as sprawl, we suggest that a more nuanced analysis is required. Fine scale information is needed to directly link 'from-to' land use changes and to more closely evaluate land use change in relation to population change. Unfortunately, most of the current discussions of urbanization and sprawl in exurban areas are limited by the use of coarse scale of data aggregated at the state or county level. These aggregated data and current urban-based definitions poorly capture the fine-grained pattern of land use change, especially beyond the dynamic urban-rural interface (Theobald, 2001).

Nelson (1999) attempted to develop a series of indicators to examine the efficacy of growth management policies in Florida, Georgia and Oregon to limit urban sprawl and the loss of farmland. Nelson relied on spatially aggregated figures of urbanized population from the US Census and area of farmland lost from the US Census of Agriculture. In a later comment, Kline (2000) discussed the weakness of Nelson's indicators as providing only an indirect means of comparing land use change relative to population growth. Kline suggested that a better alternative is to directly examine rates at which lands in either farm or forest use are converted to developed uses. He goes on to use the initial National Resources Inventory estimates of developed land change along with population data from the US Bureau of Census to compare areas of developed land gained per new resident. While this approach may be useful for comparisons at the state, or even county level, it does not provide the ability to examine more fine-scaled impacts on important land resources due to sprawling forms of development.

In this paper, we examine New Jersey as a case study in the development of land use change indicators as a tool for identifying localities where the least efficient and most highly impacting forms of urban growth are occurring. As suggested by Nelson (1999) and Kline (2000), these indicators will aid in assessing the success or failure of growth management policies designed to control sprawl and/or protect specific natural resource lands such as wetlands or prime farmland. The New Jersey Department of Environmental Protection (NJDEP) has included measures of land use change as environmental indicators to assess the degree to which the state is meeting its goals for land, natural resources, and water related key issue areas (Kaplan & Ayers, 2000; Kaplan & McGeorge, 2001). For example, land use change data are being used to assess whether the state is meeting its milestone of a net increase in wetlands quantity or no net loss of forested land statewide, as well as, for each of the state's watershed management areas (NJDEP, 2000, 2001). Impervious surface cover is also used as an additional indicator of the intensity of urban/built-up land use due to its relationship to water quality. However, only recently has the multi-temporal land use/land cover data set needed to calculate and map these indicators become available statewide, allowing the state to move from the conceptual development phase into implementation.

We exploit New Jersey's recently compiled land cover/land use change dataset along with US Census, and other environmental data to measure the percent as well as per capita amount of urban growth and change in selected land resources. Using the NJDEP's indicators as a starting point, we propose a series of five indicators to better identify the spatial characteristics and qualities of urban growth that are especially problematic. These Land Resource Impact (LRI) indicators were developed for identifying the impact of new urban growth on five specific critical land resources including: (1) efficiency of land utilization (i.e. density); (2) prime farmland; (3) forest core area; (4) natural wetlands; and (5) impervious surface. As New Jersey is renowned as a 'home rule' state with much of the land use decision making authority vested in its 566 local municipal governments, it was deemed vital to track these indicators at a municipal level.

Methods

Study area

As in many other places throughout the nation and around the world, sprawling urban development and the associated conversion of suburban and exurban lands have become an important issue facing the state of New Jersey. Located in the middle of the larger Boston-Washington megalopolis, New Jersey shows a bipolar distribution of population with dense urban centers adjacent to the New York City in the northeast and Philadelphia in the southwest (Fig. 1a,b). Outside of this 'inner ring' of dense urban areas (both north and south) is an 'outer ring' of medium density suburban areas (e.g., population density of approx. 1.5–10 people per hectare) that also spans the central neck of the state and extends along the Atlantic coast and low density rural or exurban areas (e.g., population density of $<$ approx. 1.5 people per hectare) in the northwestern, central western, southwestern and Pinelands areas of the state. Examination of recent US Census data reveals the classic symptoms of urban sprawl with stagnant population growth or even loss in these older 'inner ring' urban centers and moderate to high growth in the 'outer ring' suburbs, as well as hotspots of high growth in some exurban areas (Fig. 1c).

Land use/land cover change dataset

The New Jersey LU/LCC is a statewide digital coverage utilizing a modified Anderson, Hardy, Roach, & Witmer (1976) classification system for two points in

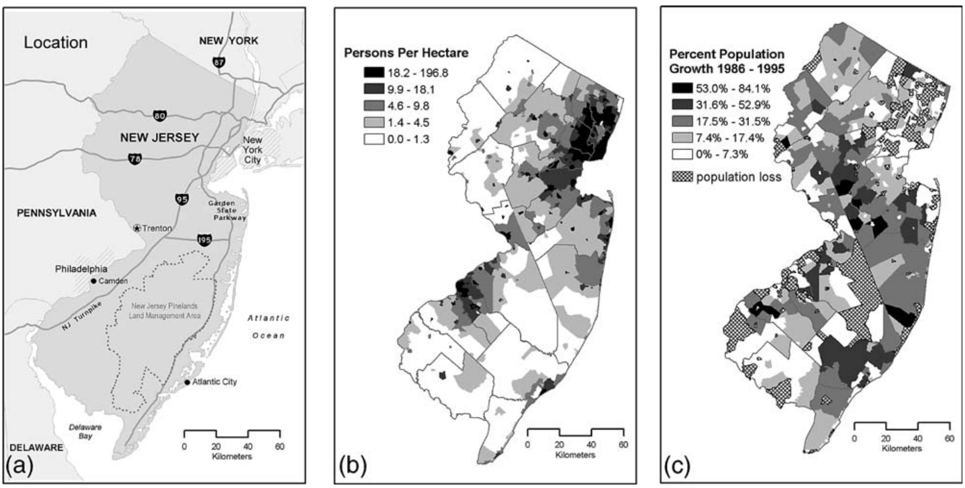

Fig. 1. New Jersey's geographical context. Located between the metropolitan areas of New York and Philadelphia (a), New Jersey is the nation's most densely populated state. Population densities are greatest adjacent to the metropolitan areas (b). However the most rapidly growing areas are in the outer ring and coastal regions (c). Extensive development pressures have elevated urban sprawl to become one of the state's top issues of concern.

time, 1986 and 1995 (Thornton et al., 2001). The NJ dataset was produced from an original 1986 land use/land cover dataset delineated from 1986 orthophotoquads. The dataset was updated to 1995/97 and enhanced in spatial accuracy through 'heads-up' on-screen digitizing and editing techniques. The 1995/97 digital imagery were color infrared USGS digital orthophoto quarter quads (DOQQs) (1:12,000 scale) with 1-m grid cell resolution. Data were delineated to a spatial accuracy of ± 60 ft (18.3 m) in the original 1986 data and further adjusted in the 1995/97 update. A minimum mapping unit of 1 acre (0.40 ha) was utilized for delineating features as well as a 60 ft (18.3 m) minimum width for mapping linear features. Each polygon of the LU/LC has multiple attributes including: LU/LC1986, LU/LC1995, impervious surface percentage, text descriptor and more. Analysis for LU/LC can be made using GIS for any 'area of interest': municipalities, counties, watershed management areas, sub-watersheds, administrative boundary, buffer, or any other boundary created by the user. Since the dataset was compiled by expert photo-interpretation, the level of accuracy exceeded that which is possible from other computer-classified remote sensing-based datasets available for New Jersey (Lathrop & Hasse, 2003), and has a high degree of reliability for analyzing detailed land use/land cover change along the rural-urban fringe. Data are freely available in ESRI shapefile format at www.state.nj.us/dep/gis.

Land resource impact indicators

The vector LU/LCC coverage was rasterized to facilitate spatial tabulations at both the statewide and municipal level. The grid cell size selected was 25 m rendering a spatial extent of 10,783 rows by 5680 columns. Municipal population estimates were calculated from 1980, 1990 and 2000 census counts (NJSDC, 2001) by simple linear interpolation for 1986 and 1995 to coincide with the dates of the LU/LCC dataset delineations. The percent as well as per capita amount of urban growth and change in selected land resources were measured for each of New Jersey's 566 municipalities.

The LRI indicators examine the impact of new development on five specific critical land resources including: (1) efficiency of land utilization (i.e. density); (2) prime farmland; (3) forest core area; (4) natural wetlands; and (5) impervious surface. The individual LRI indicators provide useful metrics for focusing on individual resource impacts. To locate more problematic overall trends of land resource impacts attributable to sprawling urban growth, the five LRI indicators were summed by municipality to provide a *combined*-LRI indicator. The combined-LRI indicator was calculated in two forms, as percent cumulative rank and as per capita cumulative rank.

Density—Land is a limited resource, especially in a densely populated state such as New Jersey. The density index provides a measure of land consumption for new urban growth. Percent population change ($\mathrm{Pop}\Delta_{pct}$) was calculated by comparing the difference in population between 1995 and 1986 over the population in 1986. The urban density LRI indicators were generated by tabulating the area of all non-urban land use categories in 1986 that became urbanized by 1995 within each municipality. The percent growth metric (UG_{pct}) was calculated by normalizing the area of new growth by the total municipality area. The per capita metric (UG_{percap}) was calculated by normalizing the area of new growth by the concurrent change in population.

Farmland loss—As its 'Garden State' nickname implies, agriculture is an important component of the New Jersey economy. New Jersey has a multi-faceted farmland preservation strategy that includes both legislated right-to-farm provisions, tax incentives and an ambitious acquisition program (New Jersey Future, 2003). Of particular concern for the long-term competitiveness and sustainability of agriculture is the loss of the prime farmlands. These are agricultural areas endowed with Class I and Class II prime soils which are suited for long-term agricultural viability.

The prime farmland loss LRI indicators quantify the amount of prime farmland loss to urban growth. The indicators were developed by first creating a raster-based map of prime farm soils from NRCS SSURGO digital soils data utilizing the prime farm soils attribute of the map unit lookup table (NJ NRCS, 2001). NJDEP soils datasets were utilized for several counties that have yet to complete SSURGO datasets. This statewide prime farm soils map was then intersected with the agricultural categories of the NJDEP LU/LCC dataset to produce a digital *prime farmland* map.

The prime farmland loss LRI indicators were generated by tabulating the area of all prime farm land use categories in 1986 that became urbanized by 1995 for each unit of analysis, in this case municipalities. Percent prime farmland loss (PF_{pct}) was calculated by normalizing the area of prime farmland that converted to urban land by the starting area of prime farmland (as of 1986). The per capita metric (PF_{percap}) was generated by normalizing the amount of prime farmland loss by the concurrent increase in population.

Forest core habitat loss—Forest habitat loss is of concern throughout the state as dispersed sprawling development has removed forest habitats and fragmented the remaining forest areas into smaller pieces. While the loss of all forests is significant, the loss of interior or core forest area has significant implications for wildlife habitat sustainability and forest land management. To counteract the loss of core forest habitat, the NJDEP has implemented what it terms the Landscape Project to promote the protection of these contiguous forest areas (Niles & Valent, 1999).

Forest core areas were generated for 1986 by extracting all mature upland and wetland forest land use/land cover categories from the NJDEP dataset while excluding the transitional wooded categories (e.g., scrub/shrub). Consistent with Landscape Project protocols, core forests include patches that are buffered 90 m from peripheral human altered land use classes. In this study, the 1986 mature forested land use patches were buffered 100 m (the buffer was rounded to 100 m to be consistent with the 25 m raster cell size of the dataset) interior from the periphery of all human altered land use classes including all urban, all agriculture and several human-altered barren classes.

The forest core loss was generated by intersecting the 1986 forest core map with a 100 meter buffer from all new 1995 urban growth. The percent forest core loss

LRI indicator (FC_{pct}) was generated by normalizing the area of forest core loss by the area of previous forest core for each unit of analysis (i.e. the amount of forest core in 1986). Per capita forest core loss (FC_{percap}) was generated by normalizing the area of forest core loss by the population increase for each unit of analysis.

Natural wetlands loss—Once thought of as swampland or wasteland, wetlands have become recognized as critical for the ecological and hydrological health of a landscape. Loss of wetlands has implications for water quality/quantity and wildlife habitat. The wetlands LRI indicators were developed by extracting the wetlands categories from the dataset (i.e. 6000 level) that had converted to urban land uses. Only comparatively un- or minimally altered wetlands (i.e., excluding agricultural, urban or disturbed wetlands or wetlands rights-of-way) were used in the analysis. The percent wetlands loss value (WL_{pct}) was generated by normalizing the area of wetlands that became urbanized by the original area of wetlands (as of 1986). The per capita wetlands LRI indicator (WL_{percap}) was generated by normalizing the area of wetlands lost to urbanization by the population growth within the unit area of analysis.

Impervious surface increase—Impervious surface is becoming an important indicator of water quality degradation within a watershed (Arnold & Gibbons, 1996; Brabec, Schulte, & Richards, 2002). Impervious surfaces created by parking lots, road ways and building footprints prevent ground water infiltration, increase stream surges and channel non point source pollution directly into water bodies (Kaplan & Ayers, 2000). Estimates of impervious surface are included for each 1995 land use polygon in the NJ LU/LCC data set and were summarized for areas of new urban growth within the unit area of analysis. In order to estimate the impervious cover that existed in 1986, polygons that became urbanized during the 1986–1995 study period were assumed to have no impervious coverage in their 1986 condition. The percent impervious surface increase metric (IS_{pct}) was generated by normalizing the area of impervious surface estimated for new development by the impervious surface estimated for previously existing 1986 urban areas. The per capita impervious surface metric (IS_{percap}) was tabulated by normalizing the estimated area of new impervious surface by the population growth within the unit area of analysis.

Results

Land Resource Impact indicators were calculated on a municipal scale to identify localities that experienced the most highly impacting patterns of development in relation to the selected critical land resources. While the LRIs are designed to gauge land resource impacts against population growth, a significant number of municipalities actually lost population during the period of analysis requiring separate treatment in the analysis (Fig. 1c). Population losers fell into two camps: older urban/suburban municipalities and rural communities. Most population losers were older urban and inner-ring suburban communities experiencing out-migration of populations to the growing outer-ring suburbs. Although urban and suburban decay are intimately connected to issues surrounding suburban sprawl, these communities are for the most part already built-out and therefore do not incur major additional impacts to critical land resources. However, a number of rural municipalities not only lost population but actually developed significant tracts of new land. These municipalities exemplify shifting internal urban land use patterns and suggest problematic sprawling conditions where older urban centers in these rural towns are abandoned for new housing in the periphery. The population-losing municipalities were removed from the per capita land use change analysis due to the nonsensical nature of the resulting metric value (i.e. negative value).

Table 1 provides summary statistics for the LRI values by municipality for localities that experienced population growth. Upon examination of municipalities that increased in population in New Jersey between 1986 and 1995, we find that on average for each additional new resident: 0.23 ha of land was consumed; 0.05 ha of prime farmland, 0.10 ha of forest core habitat and 0.02 ha of natural wetlands were lost; and 0.05 ha of impervious surface were created. These summary statistics provide a baseline by which municipalities can be gauged as experiencing more impacting or less impacting patterns of growth than other New Jersey municipalities on average for each metric.

Urban growth during the period between 1986 and 1995 follows an S-shaped curve starting in the northern part of the state swinging west then east across the central neck of New Jersey and then south and west (Fig. 2a). In southern New Jersey the pattern diverges around the Pinelands National Reserve with growth lining the Atlantic coastal region and in an arc fringing the Philadelphia-Camden suburbs. Fig. 2b shows the pattern of urban growth in percent of total municipal land area demonstrating how extensive new urbanization is occurring across the state with a large number of municipalities experiencing significant growth rates (e.g., > 5.5% increase in urban area). The per capita urban growth map (Fig. 2c) highlights the urban growth that has occurred in the more exurban areas of the state. It is in these relatively rural municipalities that large lot development is rapidly consuming large land areas. Areas of negative population growth (shown as cross-hatched in Fig. 2c) are shown centered around the inner ring of New York City suburbs in northeast NJ, the older urban centers along the southern Delaware

Table 1
Summary statistics for LRI indicators for municipalities that gained population

	$Pop\Delta_{pct}$	UG_{pct}	PF_{pct}	FC_{pct}	WL_{pct}	S_{pct}
Mean:	12.2	13.0	9.4	11.7	3.1	11.2
Median:	8.1	8.8	2.4	5.8	1.0	7.9
Max:	70.7	78.6	100.0	100.0	100.0	70.4
		UG_{percap}	PF_{percap}	FC_{percap}	WL_{percap}	IS_{percap}
Mean:		0.232	0.053	0.103	0.014	0.052
Median:		0.109	0.004	0.020	0.005	0.030
Max:		3.823	1.769	3.000	0.646	1.183

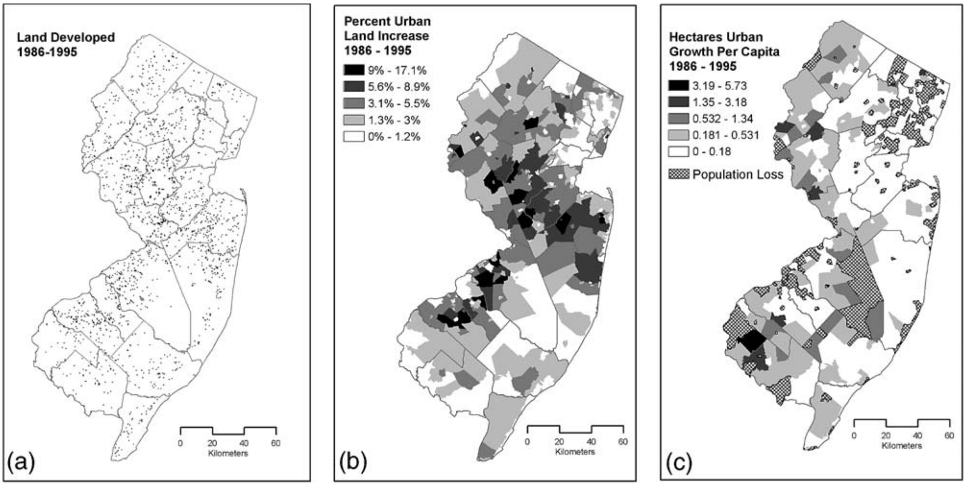

Fig. 2. Urban growth as depicted by: (a) raw land use/land cover change, (b) percentage areal growth by municipality, and (c) per capita areal growth (i.e *density*) by municipality.

River valley (e.g., Camden and Salem areas) and the south central Pinelands region which is home to Fort Dix Military Reservation and McGuire Air Force Base.

During the 1986 to 1995 study period, 23,314 ha of farmland were lost directly to new urban growth (Hasse & Lathrop, 2001). What is perhaps more significant is the loss of prime farmland (Fig. 3a). While prime farmland accounted for 53% of

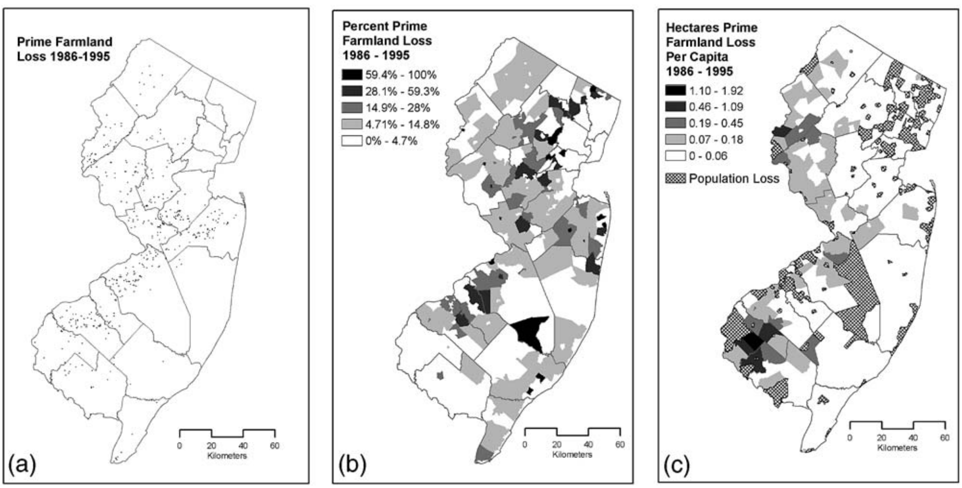

Fig. 3. Prime farmland loss as depicted by: (a) raw land use/land cover change, (b) percentage areal loss of prime farmland attributed to urban growth by municipality, and (c) per capita areal loss of prime farmland by municipality.

all farmland under the plow in 1986, it accounted for 60% of the development that occurred on farmland. This loss suggests that prime farmland is more vulnerable to urbanization than non-prime farmland. The percentage prime farmland loss indicator shows the greatest hotspots of farm loss were in those municipalities adjacent to the urban cores of northeast, central and southwest New Jersey (Fig. 3b). While the absolute magnitudes observed were not necessarily the largest, these municipalities lost high percentages of their existing available prime farmland (using the amount of prime farmland in 1986 in each municipality as the basis). In comparison, the per capita farmland loss shows a dramatically different pattern with the highest values occurring in what have been largely rural farming areas of northwestern and southwestern New Jersey (Fig. 3c). The percentage prime farm loss indicator shows where farming is most at risk by highlighting areas where the last remaining prime farmland is being lost. The per capita indicator shows prime farmland loss from a different perspective by highlighting those communities where farmland is being consumed at a comparatively high per capita rate.

The largest single type of landscape change that occurred to development growth in New Jersey over the last decade was the urbanization of forested lands. A total of 27,158 ha of forested land were converted to urban land uses during the nine-year period of analysis (Hasse & Lathrop, 2001). Core forest loss totaled 26,931 ha during the same time period (Fig. 4a). The percentage forest core indicator map (Fig. 4b) shows a pattern similar to that of the percentage prime farmland loss with the hotspots of loss centered around the outer ring of northeast, central and southwest suburbs but also additional hotspots along the Atlantic coastal plain.

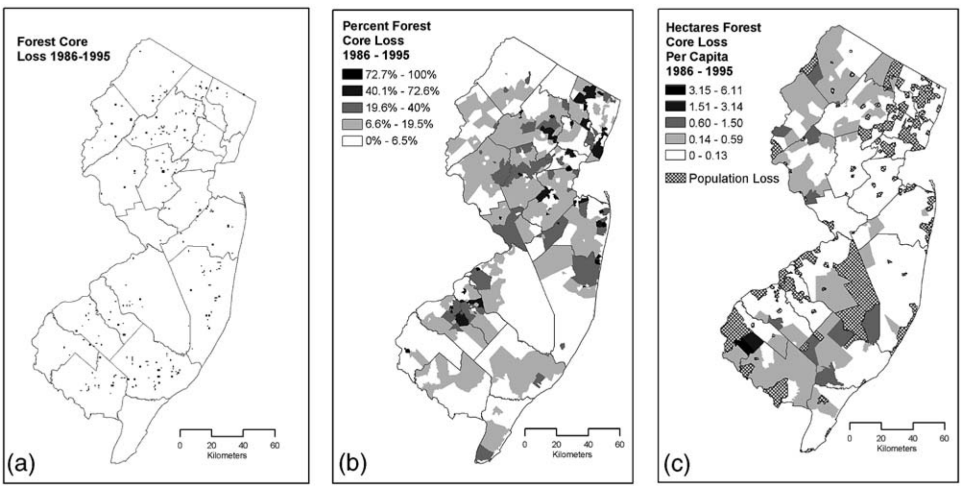

Fig. 4. Forest core loss as depicted by: (a) raw land use/land cover change, (b) percentage areal loss of forest core attributed to urban growth by municipality, and (c) per capita areal loss of forest core by municipality.

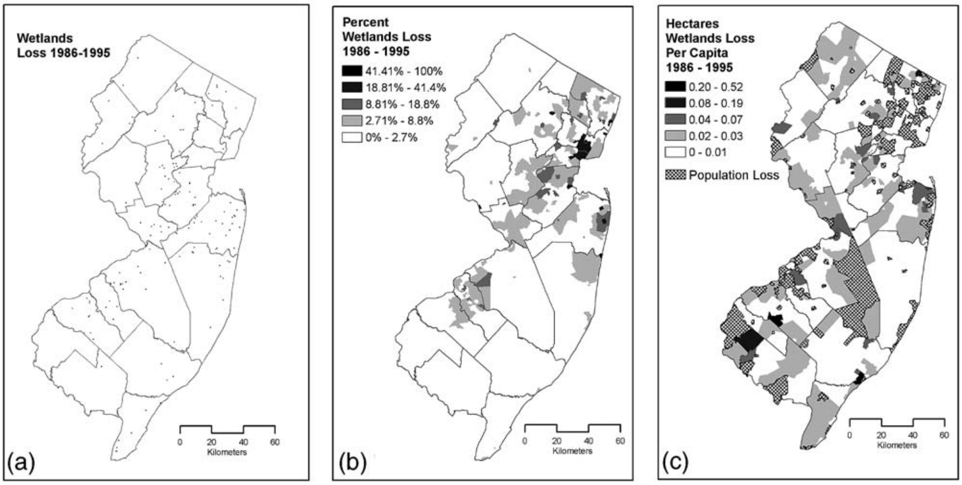

Fig. 5. Wetlands loss as depicted by: (a) raw land use/land cover change, (b) percentage areal loss of natural wetlands attributed to urban growth by municipality, and (c) per capita areal loss of natural wetlands by municipality.

The per capita indicator highlights the greatest losses in the still largely forested regions of northern and southern New Jersey (Fig. 4c).

A total of 10,433 ha of unaltered natural wetlands were converted to developed uses from 1986 to 1995, generally in small patches (Fig. 5a). The percentage wetland loss map (Fig. 5b) shows the greatest percentage losses of the remaining stock of undisturbed wetlands occurred in the urban and more densely settled suburban municipalities where wetlands often represent the last remaining areas of undeveloped land. The per capita wetlands loss map (Fig. 5c) shows a more scattered pattern with the highest values found in some of the more established but still expanding suburban areas in central NJ as well as more rural areas that are on the outer fringes of expanding suburban development in both southern and northern NJ.

Approximately 15,460 ha of impervious surface were added between 1986 and 1995, which equates to a 9.2% increase statewide. As expected, the impervious surface increase map (Fig. 6a) closely matches the spatial pattern of the urban growth map (Fig. 2a). Impervious surface has increased in a comparatively consistent basis in municipalities across the state with the exception of the already ‘built-out’ urban core and a handful of rural municipalities (Fig. 6b). Per capita impervious surface increase shows a more localized pattern highlighting a comparatively small number of municipalities as being hotspots of large per capita impervious surface gains (Fig. 6c).

The combined-LRI indicator measures provide a composite view to examine the coincidence of the individual land resource impacts. Fig. 7a,b respectively depict the percent cumulative and the per capita cumulative sum for all five individual metrics. The municipalities with the greatest combined percent change—LRI’s were

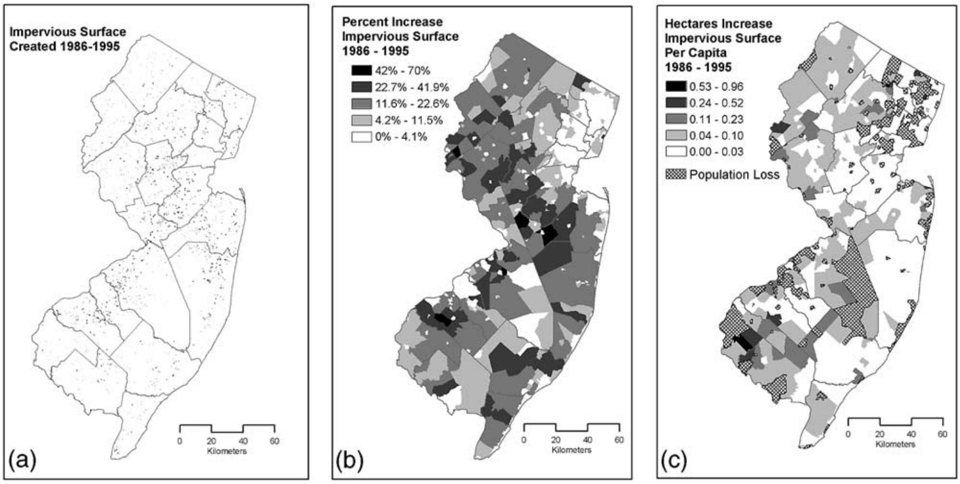

Fig. 6. Impervious surface increase as depicted by: (a) raw land use/land cover change, (b) percentage areal increase of impervious surface by municipality, and (c) per capita areal loss of natural wetlands by municipality.

generally those in or directly adjacent to the more established ‘outer ring’ suburbs. In contrast, the municipalities with the greatest cumulative per capita LRI’s were generally those in the more rural exurban areas. The most overall sprawling muni-

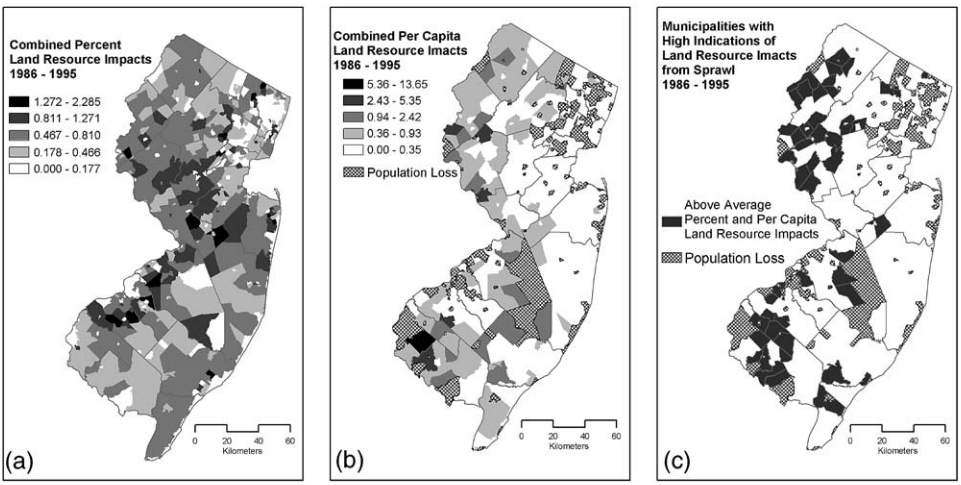

Fig. 7. Summation of the individual LRI components provides a means of characterizing overall land resource impacts. Cumulative percent impact (a) demonstrates patterns of significant magnitudes of overall impact on critical land resources. Cumulative per capita impact (b) demonstrates patterns of inefficient resource impact in relation to the number of residents accommodated with new housing. Municipalities with both above average percent *and* per capita impacts (c) characterize the most inefficient patterns of urban growth (i.e. sprawl) in relation to land resource impacts.

cipalities in terms of land resource impacts were identified by selecting municipalities that exhibited both above average percentage and above average per capita LRI's (Fig. 7c). These municipalities stand out as experiencing the most significant magnitudes of impacts to land resources while doing so in a relatively inefficient manner in terms of the number of new residents accommodated by the growth.

Discussion

The NJDEP LU/LCC data set provides a rich data set with which to examine the subtleties of New Jersey's dynamic landscape and the impact of sprawling urban growth. However, one can easily get lost in the complex dynamics and multiple transitions between numerous LU/LC categories; thus the need to clarify the picture through the use of comparatively simple indicators. The suite of additional LU/LCC-based indicators, what we term Land Resource Impact (LRI) indicators, provide an alternative and more sophisticated means of quantifying the impact of spatial patterns of urban growth on these important land resources. Recognizing that not all urban growth has equivalent impact, our LRI indicators attempt to further restrict the possible set of land use/land cover changes and focus only on those aspects of urban growth that we consider especially significant in terms of their stresses on critical land and natural resources. For example, the Prime Farm LRI measures only the loss of farmland on the prime farm soils, the soils that are most critical to the long-term sustainability of agriculture in the state. Likewise, the Forest Core LRI attempts to focus efforts on the core or interior forest habitat, the habitat that is most critical to the long-term preservation of forest-dependent wildlife that are threatened or endangered within the state. While derived from the NJDEP LU/LCC data set, they require either additional GIS data sets (e.g., the prime farm soils coverage) or additional spatial analysis (e.g., edge-buffering to determine interior forests). This additional data or processing is not prohibitive and easily accomplished at a statewide scale, as we've demonstrated.

While overall magnitude of low-density new growth is itself an indicator of sprawl, we propose that it is necessary to de-couple the amount of growth from the problematic or dysfunctional characteristics imparted by sprawling growth. In considering long-term sustainability of development, it is important to consider the efficiency of new development (i.e., hectares of new development in relation to number of people supported). Under this reasoning, sprawl is considered inefficient new urban growth. In an attempt to quantify this aspect of urban sprawl, we calculated our five *LRI indicators* on both a percentage and per capita basis. It is our contention that the straight percentage and the per capita measures provide complementary information with which to examine the spatial patterns of land use/land cover change associated to sprawl. The percent change indicators measure the impact on the selected geographic unit's remaining land resources; while the per capita indicator provides a measure of land use efficiency of the new urban growth. In combination, the LRI indicators provide a means of identifying localities (e.g., municipalities) where the least efficient and most highly impacting forms of urban growth were occurring.

A number of important issues must be adequately handled in the LRI approach to characterizing sprawl. Whereas the absolute and percent measures of LU/LC change are comparatively straight forward to calculate and interpret, the per capita measures can be more problematic. One confounding factor is that the per capita measures rely on population census data that may not be concurrent in time or correspond to the same geographic units as the LU/LCC data. Certain assumptions are then necessary in order to bring the two data sets to a comparable framework. In our analysis, we used linear interpolation to derive the municipal population estimates and are thus assuming a constant rate of growth between the decennial census endpoints. A second limitation is that negative population growth becomes difficult to handle. We did not attempt to further correct for negative population numbers but instead flagged those municipalities as population losers and did not calculate a per capita indicator value. A third complication is that the per capita measures (as we have calculated them) do not explicitly account for commercial/industrial development separate from residential development. This distinction might be useful in examining the relative balance between these two types of development.

Issues of scale are also central to geospatial analysis of urbanization. The areal unit of analysis chosen for this study was strictly the local municipality. Due to the sometimes arbitrary nature of municipal boundaries, somewhat different results would most likely be obtained had a different geographic unit been chosen (i.e. the modifiable area unit problem, Openshaw, 1984a). Other spatial units such as census tracts, zoning regions, counties, watersheds or even parcels could be reasonably utilized for analysis of land resource impacts at alternate scales so long as concurrent population data were available at the same unit of measurement. However, as there is a close correspondence between municipal units and New Jersey's locally-controlled land use decision-making system, a strong argument can be made for the appropriateness of municipalities as the geographic unit of choice in the case of New Jersey. Regardless of the scale of analysis utilized, care must be exercised not to assume that all sub units of urban growth within the unit of analysis have the same value as the overall unit of analysis (Openshaw, 1984b). Substantial variation is likely to occur within the unit of analysis as is suggested by the rural municipalities that lost population but still developed significant areas of land. A parcel level analysis would be required to calculate a truly per capita ecological footprint rather than the municipal average as presented here (Hasse & Lathrop, 2003). Nonetheless, municipal summaries provide a powerful means of identifying localities with inefficient patterns of land development. Analysis of these data at the municipal level enables local decision-makers and citizens a window into what has been occurring in their communities over time.

Conclusion

Sprawling urban growth as it is exhibited in New Jersey and elsewhere in the United States as well as around the globe, has significant associated social and environmental costs and represents a major challenge to land use planning and management in the coming century. Appropriate land use change data sets and analytical tools are needed to understand and monitor the patterns and processes involved in the phenomenon of urbanization. While sprawling patterns of development may exhibit many social and environmental impacts unable to be captured by a geospatial approach, the LRI indicators developed in this research present one suite of measures for analyzing significant specific landscape impacts to critical natural resources attributable to sprawling urban growth.

The LRI indicators provide an empirical approach for identifying, comparing and contrasting development patterns in a markedly more detailed manner for further investigation of the underlying processes at play. By identifying the municipalities experiencing the most highly impacting (and conversely least impacting) patterns of development growth on important land resources, policy makers and researchers can gain better insight into the contributing factors that have resulted in the most problematic (or least problematic) development patterns now and into the future.

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