Available online at www.sciencedirect.com
ScienceDirect
ELSEVIER
Landscape and Urban Planning 79 (2007) 150–159
LANDSCAPE AND URBAN PLANNING
This article is also available online at:
www.elsevier.com/locate/landurbplan

Consequences of land use change in the New York–New Jersey Highlands, USA: Landscape indicators of forest and watershed integrity

Richard G. Lathrop*, David L. Tulloch, Colleen Hatfield

Center for Remote Sensing & Spatial Analysis, Rutgers University, New Brunswick, NJ 08901-8551, United States

Abstract

The New York–New Jersey Highlands, a 600,000 ha area of forested uplands, provide vital environmental services to the growing New York City, USA metropolitan region. Urban development and associated land use/land cover change threaten to impair the Highland's natural resource values. In response, the USDA Forest Service, in collaboration with Rutgers University, the U.S. Geological Survey, and the Regional Plan Association, undertook a regional study of the NY–NJ Highlands to characterize the resources at stake and assess the implications of continued land use change. This paper will focus on the Highlands as a case study on the application of landscape-scale indicators to assess the potential impacts of future land use change. A three-pronged approach was adopted: (1) land use/land cover change mapping to assess past changes, (2) build-out modeling to project possible future land use change, and (3) landscape-scale indicators of forest and watershed condition. The coupled build-out and landscape indicator analysis served as a planning tool to assess the potential impacts to forest and watershed integrity based on two different scenarios of future development.

Keywords: Landscape indicators; Remote sensing; Highlands

1. Introduction

The phenomenon of sprawling urban development is one of the major forces driving environmental change in the USA. Most USA metropolitan areas are adding new urbanized land at a much faster rate than they are adding population, resulting in large amounts of land consumed for urbanization while accommodating comparatively small numbers of people (Fulton et al., 2001). While most of this urbanization is occurring as one house or small subdivision at a time here and there across the landscape, taken in aggregate the implications are enormous. Urbanization and associated changes in the regional landscape composition and pattern sets off a cascade of environmental impacts that are of growing concern (Alberti, 1999; Bartlett et al., 2000; McKinney, 2002; Nilsson et al., 2003). The rapid pace and broad scope of urbanization is testing the ability of land use planners and environmental resource managers to address the cumulative degradation of regional ecosystems and the resources and services that they provide.

Examination of the implications of future change is critical to inform the local and regional land use planning process before ill-advised and irreversible land use decisions occur. Land use change scenarios and models provide an increasingly valuable tool for examining future landscapes to investigate the process of change as well as potential future landscape configurations (Lambin, 1997; Lee et al., 1998; Theobald and Hobbs, 1998). Presently, within the landscape ecology and regional planning literature, there is great interest in developing land use change models that focus on simulating the processes that drive the spatial and temporal dynamics of change. However, if the overriding concern is landscape configuration at a future endpoint and the resulting environmental implications, then a build-out model provides an alternative approach to dynamic models (Botequilha Leitao and Ahern, 2002; Conway and Lathrop, 2005). A build-out model can be used to examine the form of the fully developed landscape, while avoiding the uncertainty of predicting when the changes will occur. The build-out modeling approach is only valid where there is some concrete form of spatial planning that constrains the location and type of future development. In USA, spatial

---

* Corresponding author. Tel.: +1 732 932 15 80; fax: +1 732 932 25 87.
E-mail addresses: lathrop@crssa.rutgers.edu (R.G. Lathrop), dtulloch@crssa.rutgers.edu (D.L. Tulloch), chatfld@crssa.rutgers.edu (C. Hatfield).

0169-2046/$ – see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.landurbplan.2006.02.008

planning is usually codified through municipal zoning. Zoning regulations define acceptable types of future development but rarely take into account the environmental consequences of development, especially cumulative impacts at the watershed scale.

To make land use change models more relevant to the planning process, there needs to be greater linkage between measurable changes in land cover with the expected environmental consequences of the projected land use change. At the same time, these often-complex model outcomes need to be synthesized and simplified so as to provide information in a form that is readily understandable and relevant for land managers and policy makers. Such simple metrics for analyzing, monitoring, and communicating information about environmental change are often referred to as *environmental indicators*. With the increasing availability of broad-scale data provided by remote sensing along with the insights of landscape ecology, the indicator concept has been expanded to include "landscape" indicators for measuring and monitoring environmental condition at watershed to regional scales. In most instances, landscape indicators take the form of metrics that quantify the composition or some component of the spatial pattern of the landscape (Jones et al., 1997). Where strong relationships exist between landscape composition and pattern (i.e., as measured by a landscape indicator) and the conditions of the environmental resources of interest, then it should be feasible to employ landscape indicators to assess the environmental condition (Kepner et al., 1995). By combining knowledge on how landscape pattern influences environmental condition, landscape indicators can be used to evaluate risk or vulnerability of environmental resources in a given region (Kepner et al., 1995). For example, a number of studies have found that a decline in stream water quality (condition of a key environmental resource) is strongly related to the amount of impervious surface cover in the stream's watershed. Accordingly, impervious surface is often used as a landscape indicator of watershed integrity (Arnold and Gibbons, 1996; Schueler, 1998).

The New York–New Jersey Highlands, a 600,000 ha area of rugged uplands largely covered in forests, serve as a natural geographic boundary delimiting the northern edge of the New York City metropolitan region (Fig. 1). The distinct possibility that expanding urbanization will overwhelm the Highlands has instigated intense concern and interest in trying to conserve the region's natural values as watershed, wildlife habitat, and public open space. In response, the U.S. Forest Service in collaboration with Rutgers University, the U.S. Geological Survey, and the Regional Plan Association, undertook the NY–NJ Highlands Regional Study to characterize the resources at stake, assess the implications of continued land use change, and address a potential federal role in the region (Phelps and Hoppe, 2002). This 2002 study updates an earlier USDS Forest Service-sponsored Highlands Regional Study conducted in 1992 (Michaels et al., 1992). This paper will focus on the Highlands as a case study on the application of build-out models coupled with landscape-scale indicators as a planning tool to assess the potential impacts to forest and watershed integrity based on several different scenarios of future development.

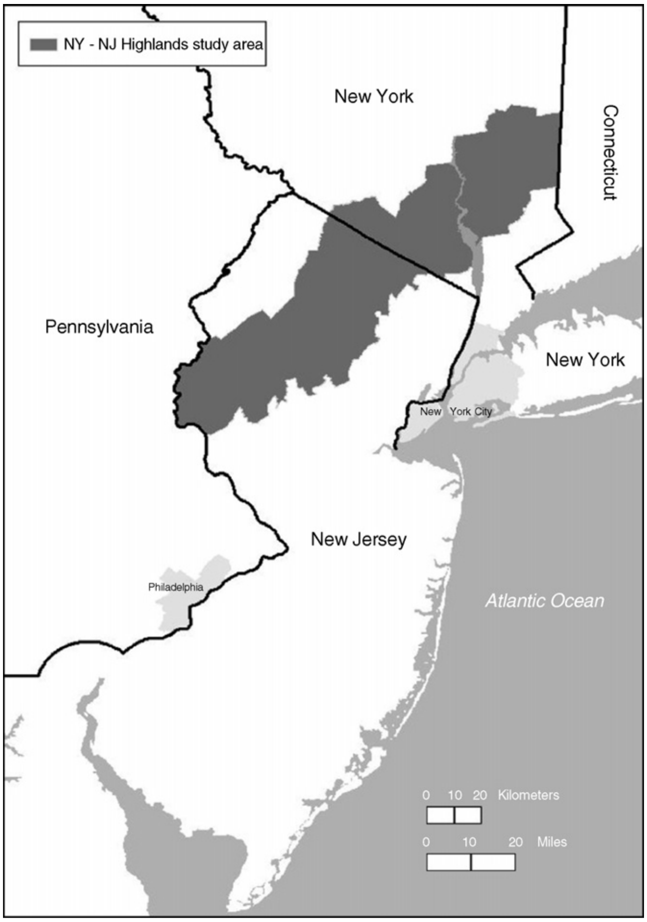

Fig. 1. Location map of New York–New Jersey Highlands study area.

2. Methods

2.1. Overall approach

The two main objectives for this portion of the NY–NJ Highlands study were: (1) to compare the relative impact of the low versus high constraint scenarios at the regional scale and (2) to identify potential hotspots of environmental change that deserve greater consideration in future land management decisions. A three-pronged approach has been adopted: (1) land use (LU)/land cover (LC) change mapping to assess past changes, (2) build-out modeling to project possible future land use (LU)/land cover (LC) change, and (3) landscape-scale indicators of forest and watershed condition. A suite of landscape-level indicators were chosen to assess the condition of the NY–NJ Highlands' forests and watersheds:

(1) percentage of altered and unaltered land cover;
(2) percentage of impervious surface cover;
(3) percentage of the riparian zones in altered land covers;
(4) percentage of interior forest.

The environmental indicators were analyzed on a watershed basis, aggregating results to the HUC 11 (U.S. Geological Survey Hydrological Unit Code 11) level. There are 51 complete or partial HUC 11 watersheds within the NY–NJ Highlands study region. The 4 indicators were calculated for each of the 51 watersheds for each of the 3 years for which LU/LC was mapped (1984, 1995, and 2000) and for the Low and High Constraint build-out scenarios. The relationships between selected landscape indicators and independently measured environmental parameters were examined to assist in identifying important thresholds that may signify high potential for environmental degradation.

2.2. *Land cover mapping methods*

The objective of the land cover change mapping was to assess past changes and present trends in land cover conversion from the 1980s through to 2000. Landsat Thematic Mapper and digital ortho-photographic imagery were used to develop standardized land cover information that was consistent across the bi-state region. Land cover was mapped over 3 time periods spanning a total time frame of 16 years: 1984, 1995, and 2000. Ortho-rectified leaf-on and leaf-off Landsat Thematic Mapper imagery were used as the basis of the land cover classification (UTM Zone 18; datum: NAD 83; spheroid: WGS84). To try to correct for various scene-to-scene differences in brightness and spectral response (including atmospheric influences), an image-to-image empirical normalization procedure that compared invariant scene targets was used to normalize the 1984 and 2000 TM imagery to the corresponding Landsat TM from 1995. A combination of digital image analysis techniques were used to classify the Landsat TM images into land cover maps. Incorporation of additional mapped data sets in the context of a geographic information system (GIS) was used to provide further classification improvement through either pre-classification stratification or post-classification modification. For example, a combination of existing land use maps and on-screen interpretation of high resolution digital ortho-photography and SPOT panchromatic imagery were used to create an urban land use area mask for each of the three time periods and these thereby restrict the classification of urban land covers to within the mask coverage. For more details on the land cover classification protocols employed, consult Lathrop (2004).

2.3. *Future land use change*

To analyze the potential impact of land use change on the Highlands environment, a spatially explicit build-out analysis was conducted to model different levels of future development. The first step of the build-out analysis for the Highlands was to map "vacant" land, i.e. privately owned land that was presently not developed. This was accomplished by removing from consideration places where future development and population change would not be expected (i.e., publicly owned land or lands already built out to zoned density). The second step was to further exclude land, based on various regulatory constraints. In order to provide multiple outcomes, two different build-out scenarios were constructed to show potential patterns of varying impacts:

- Low Constraint build-out scenario map of areas that would presumably develop if current policies (including zoning) were continued unchanged indefinitely.
- High Constraint build-out scenario map of areas that would presumably develop if a few current policies (excluding zoning) were changed to increase the constraints on future development by increasing protection of wetland/riparian buffers and steep slopes.

After removing the constrained areas (e.g., wetlands and regulated upland buffers), the remaining area was then considered "available" for residential development. The map of "available" land was cross-tabulated with land use zoning maps to estimate the density of future development and calculate the number of additional housing units that might potentially be built. The future population is expected to increase by approximately 47.6% under the Low Constraint scenario and 26.3% under the High Constraint scenario. For more details on the build-out modeling techniques employed in the NY–NJ Highlands study, consult Lathrop et al. (2003).

2.4. *Altered land cover*

The original, and still primary, land cover of the NY–NJ Highlands is forest and, to a lesser extent, wetlands. Undisturbed forest and wetlands provide the essential ecosystem services of natural water filtration, soil stabilization, and groundwater recharge. U.S. EPA has developed a number of landscape indicators for watershed to regional scale assessments to quantify environmental conditions. One of the simplest yet most powerful indicators is the human use index, which is the proportion of watershed area that is altered due to urban or agricultural land cover (Jones et al., 1997; O'Neill et al., 1988). We used a similar index that was modified slightly to include lands that have become barren due to mining/quarrying activities, in addition to cultivated land, grassland, and developed (urban) land cover, as altered land. A simple majority threshold of 50% altered land was chosen as the threshold signifying increased risk of environmental degradation.

The proportion of altered to unaltered land was calculated for each of the 51 HUC-11 watersheds for 1984, 1995, and 2000 by use of the NY–NJ Highlands LU/LC database. It was necessary to establish a relationship between unaltered land area and housing unit density in order to estimate the amount of residual unaltered land under build-out. U.S. Census 2000 block group housing unit density data and the 2000 land cover map were used to establish the relationship for present day conditions. The census data were aggregated into housing density classes corresponding to commonly used municipal zoning densities. This housing unit density map was then cross tabulated with the land cover map to determine the percentage area of each density class that was mapped as unaltered (e.g., forest and wetlands) land cover. Fig. 2a shows that there is a smoothly asymptotic relationship of decreasing unaltered land with increasing housing unit density. Municipal zoning under the two build-out scenarios was used to estimate the housing unit density after build-out. Then, based on the observed relationship between housing unit

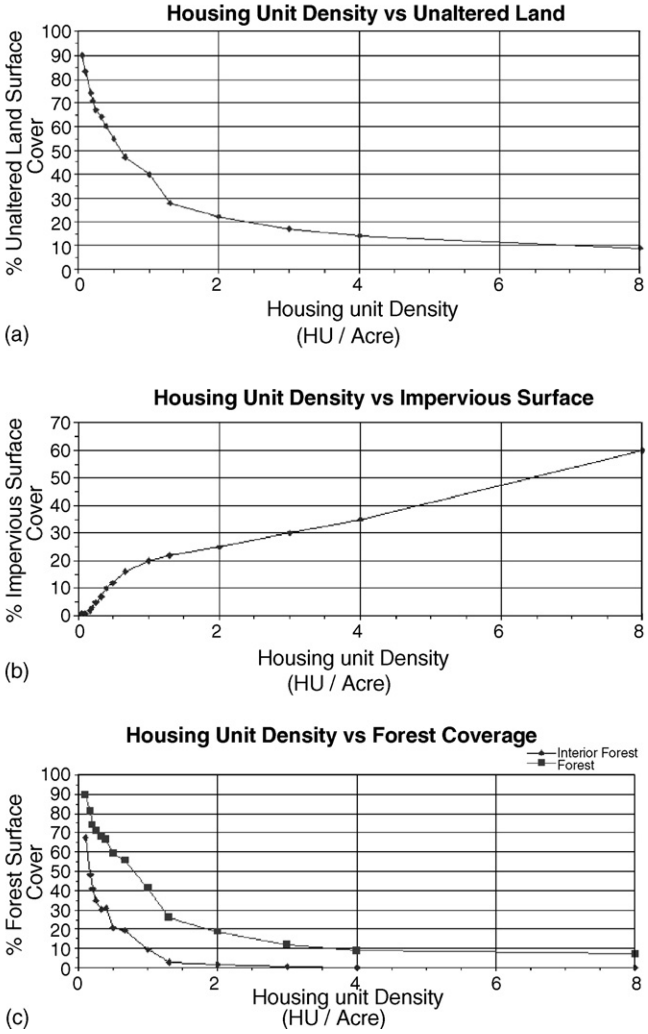

Fig. 2. Plot of selected landscape indicators vs. housing unit density (hu/acre). (a) Plot of % unaltered land cover vs. housing unit density (hu/acre). (b) Plot of % impervious surface cover vs. housing unit density (hu/acre). (c) Percentage forest and interior forest vs. housing unit density (hu/acre).

density and unaltered land, the amount of unaltered land after build-out was estimated for each zoning area. The percentage of unaltered land was then calculated on the HUC-11 watershed basis.

2.5. *Impervious surface cover*

Impervious surface (e.g., asphalt, concrete, buildings, road surfaces) is an important environmental indicator of the intensity of human land use, and closely correlates with water quality degradation and altered runoff patterns in urban and urbanizing areas (Novotny and Chesters, 1981; Arnold and Gibbons, 1996). Impervious surface cover is increasingly used as a landscape-level indicator of non-point source pollution and watershed health. Arnold and Gibbons (1996) compared data from several studies and found that at 10% impervious surface cover, water quality begins to show signs of impact. Water quality is often seriously degraded at more than 25–30% impervious surface cover. We chose an impervious surface cover threshold of 10%, based on our interest in protecting existing high quality water.

The proportion of impervious surface was calculated for each of the 51 HUC-11 watersheds for 1984, 1995, and 2000 by use of the NY–NJ Highlands LU/LC database. The 1995 NJDEP land use data included estimates of impervious surface cover for each land use polygon. These data were rasterized to match the Landsat TM grid for the NJ Highlands study area and were used to determine the mean impervious surface cover for each of the Landsat TM spectral training classes used to map developed land cover for the 1995 time period. The mean impervious surface cover for the NJDEP data set were regressed against the Landsat TM data from a large sample of polygons for each of 13 different land use classes as a validation check of the utility of this relationship. The regression showed a good fit, with a coefficient of determination (R^2) value of 0.91. The impervious surface cover was then estimated across the entire NY–NJ Highlands study area, based solely on the Landsat TM data. This same relationship was then applied to the normalized 1984 and 2000 imagery data sets.

In order to estimate the amount of impervious surface under build-out, it was necessary to establish a relationship between impervious surface cover and housing unit density. Using census data as outlined above for the altered land indicator the relationship between impervious surface cover and housing unit density was determined (Fig. 2b). The percentage of impervious surface cover increases in a nonlinear fashion to a housing density of approximately 1 unit/acre, and then continues to increase at a more linear pace. The amount of impervious surface cover after build-out was then estimated for each municipal zoning area based on the observed relationship between housing unit density and impervious surface cover. The percentage of impervious surface cover was then calculated for each HUC-11 watershed.

2.6. *Riparian corridors*

Riparian zones composed of natural vegetation where human development or agriculture is excluded or minimized is a “best management practice” that helps protect adjacent stream ecosystems and downstream water quality (Welsch, 1991; Muscutt et al., 1993). Protected riparian zones serve as vital habitat for both upland- and wetland-dependent species in addition to reducing non-point source pollution. Riparian areas were defined as those areas that are adjacent or hydrologically connected to the surface water network (e.g., streams, rivers, lakes, or reservoirs). Riparian areas of the Highlands were delineated as those areas that are adjacent to the stream corridor and classed as either: (1) 100 year floodplain as mapped by the Federal Emergency Management agency; (2) wetlands as mapped by the US Fish & Wildlife Service National Wetland Inventory or New Jersey Department of Environmental Protection or (3) hydric soils as mapped by the National Resources Conservation Service. Isolated wetland areas (i.e., those not adjacent to a stream corridor) were excluded from this analysis. Freshwater streams and rivers were extracted from the USGS 1:24,000 scale digital GIS data set. A 90-m buffer on both sides of all mapped streams/rivers was delineated to create a 180-m-wide riparian corridor and was included as a riparian area. The relative percentage of the riparian area that is in altered land cover (e.g., developed, cultivated/grassland or barren) was calculated. The alteration of the riparian zones was then summarized on a HUC-11 watershed basis. The proportion of the riparian zones in altered land cover was estimated, based on the amount of altered land calculated under the various build-out scenarios.

2.7. *Forest fragmentation*

The conservation of large tracts of contiguous forest habitat and the minimization of fragmentation were identified as major issues of concern in the NY–NJ Highlands study region. Human development has the direct impact of removing existing natural habitat as well as fragmenting the habitat that remains into smaller pieces (Forman and Godron, 1986). Paved roads and residential and commercial development often serve as a barrier or hazard to wildlife movement and native plant dispersal, as well as altering "natural" disturbance regimes. Human development also has "indirect" impact by creating a number of different kinds of intrusions with varying depth of impact from the edge into the interior (Zipperer, 1993). Depending on the phenomena of interest or species of concern, what distance constitutes an "edge" versus "interior forest" will vary. For the purposes of this study, the edge zone was defined as 90 m in depth, with interior forest defined as areas more than 90 m from the forest outer boundary. This 90 m edge distance was selected because: (1) it has been applied elsewhere to reflect habitat quality for forest-interior-dependent neotropical migrant songbirds (Temple and Cary, 1988; Niles et al., 1999), which are a key suite of species of concern in the Highlands region and (2) was straightforward to implement, as it represented an even number of Landsat TM pixels (i.e., three 30 m pixels). Several nationwide studies of the effect of forest fragmentation on the conterminous USA have also used a 90 m edge distance, allowing for a useful comparison across regions (Heilman et al., 2002; Riitters et al., 2002).

All upland and wetland forest types were combined to create a simple binary forest/non-forest map. Major roads (i.e., county level highways and larger) were included in the analysis as a fragmenting influence or barrier, such that a tract of forest that might otherwise be considered contiguous, if it were subdivided by a major road, would be mapped as two separate parcels separated by a non-forest edge. Using a GIS spatial analysis procedure called buffering, a 90-m buffer was delineated inside the boundary of every forest habitat patch in order to exclude this edge zone and leave only interior forest habitat. Contiguous forest tracts smaller than 25 acres in size (10 ha) were further excluded. This interior forest analysis was conducted for the 2000, 1995, and 1984 time periods. In order to estimate the amount of interior forest habitat under build-out, it was necessary to establish a relationship between interior forest area and housing unit density. Using census data as outlined above for the altered land indicator, the relationship between interior forest cover and housing unit density was determined (Fig. 2c). A threshold of 40% of the watershed as interior forest was selected, based on our assessment of the present day distribution of interior forest in the contiguous forest core of the Highlands region.

3. Results

The land cover change analysis shows a general trend towards increasing altered land cover during the 1980s and 1990s to the year 2000. The number of watersheds with greater than 50% altered land went from 12 in 1984, to 13 in 1995 to 17 in 2000 (i.e., from 24 to 25 to 33% of the watersheds) (Table 1). Depending on the build-out scenario, the number of watersheds expected to have greater than 50% altered land cover could more than double. Under the High Constraint scenario, the number of watersheds with greater than 50% altered area would be 24, and under the Low Constraint scenario, would increase to 36 (Fig. 3a and b). Under the High Constraint scenario, most of the predicted increase would be less than 10% change as compared to 2000 (Fig. 3c). Under the Low Constraint scenario, a significant number of watersheds (i.e. 10 out of 51 or nearly 20%) are expected to show a greater than 20% change over 2000 conditions.

The land cover change analysis shows a general trend towards increasing impervious surface cover. The number of watersheds with greater than 10% impervious surface cover went from 6 in 1984, to 9 in 1995 and 2000 (Table 1). While the number of watersheds with greater than 10% impervious cover remained stable between 1995 and 2000, the number of watersheds with between 5 and 10% impervious surface cover increased from 20 in 1995 to 24 in 2000. Depending on the build-out scenario, the number of watersheds expected to have greater than 10% impervious surface cover could more than triple to quadruple. Under the High Constraint scenario, the number of watersheds with greater than 10% impervious surface cover would be 33 (i.e., 33 out of 51, or 65%) and under the Low Constraint scenario would increase to 41 (i.e., 41 out of 51, or 80%) (Fig. 4a and b). Under both scenarios, most of the predicted increase would be less than a 10% change as compared to 2000 (Fig. 4c and d). Under the Low Constraint scenario, a significant number of watersheds (i.e. 23 out of 51, or 45%) are expected to show a 5–10% change over 2000 conditions. Of special concern is the increase in impervious surface cover and the potential for degradation of water quality conditions in the watersheds of several major drinking water supply reservoirs.

The analysis shows that alteration of riparian zones has not dramatically increased between 1984 and 2000. The number of

Table 1
Number of watersheds that exceed landscape indicator threshold for three past time periods (1984, 1995, and 2000) and for two future build-out scenarios

Landscape Indicator	Number of HUC 11 watersheds				
	1984	1995	2000	Build-out: high constraint	Build-out: low constraint
>50% altered	12	13	17	24	36
>10% impervious surface	6	9	9	33	41
>50% altered riparian zone	5	6	7	10	24
>40% interior forest	15	12	9	6	5

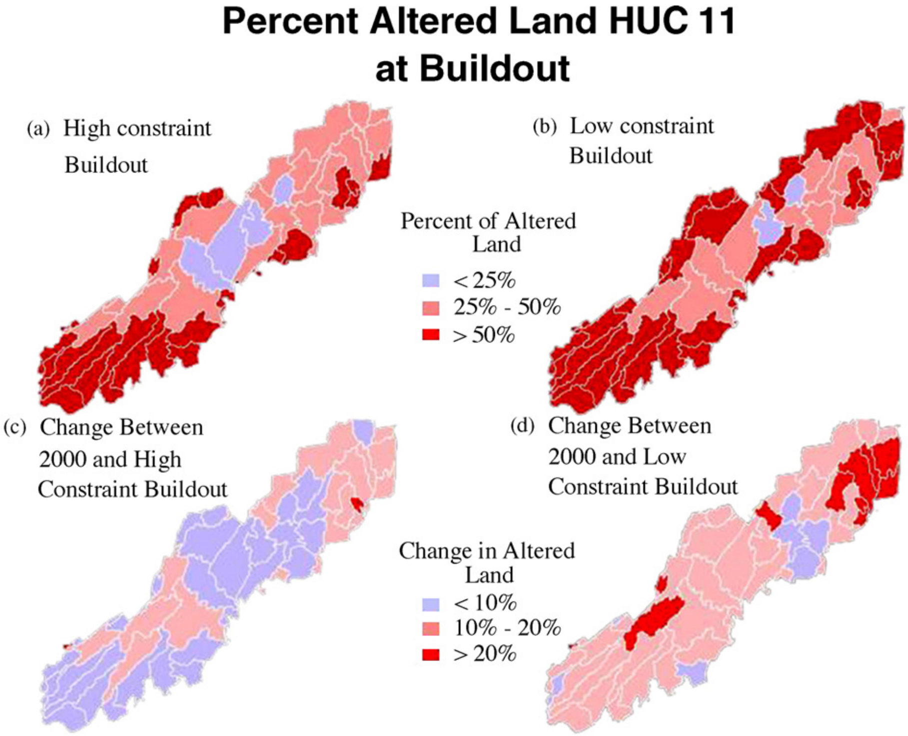

Fig. 3. Estimated changes in percent altered land at build-out.

watersheds with greater than 50% altered riparian zone area has remained stable at 5–7 (Table 1). The two build-out scenarios show a marked difference in relation to riparian zone protection. The High Constraint scenario (which incorporates wide wetland buffer distances) predicts a result largely unchanged from the present situation, with 10 watersheds with greater than 50% altered area (Table 1; Figs. 5a and 6c). The Low Constraint scenario predicts a large increase in riparian zone development

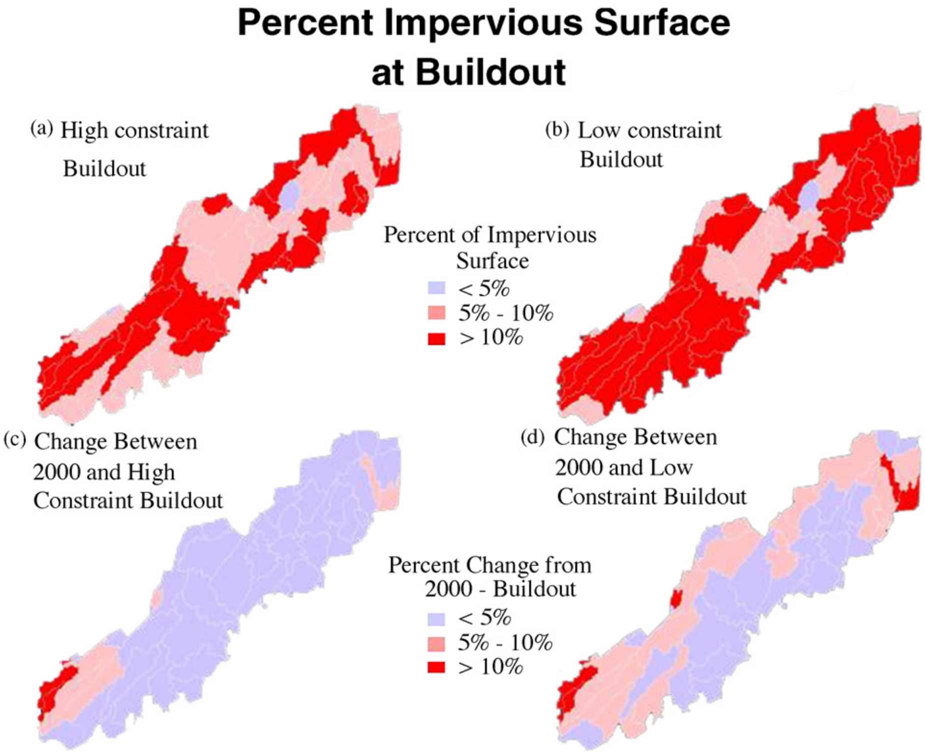

Fig. 4. Estimate changes in percent impervious surface at build-out.

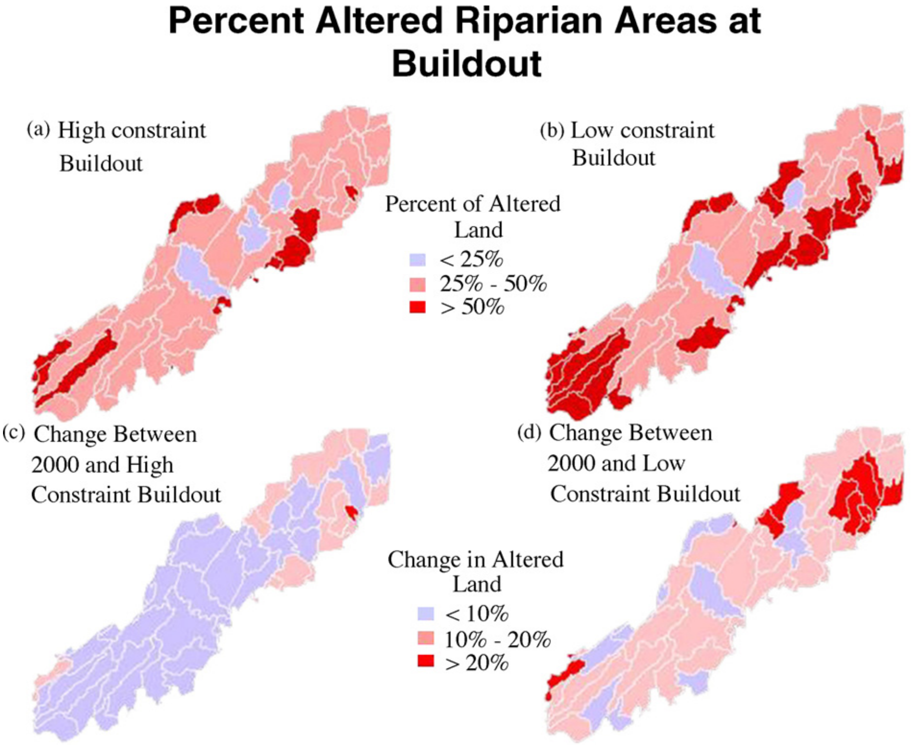

Fig. 5. Estimated changes in percent altered riparian zones at build-out.

and alteration, with the number of watersheds with greater than 50% altered land rising to 24 (i.e. 24 out of 51, or 44%) (Table 1; Fig. 5b). Of special note are the hotspots for increased riparian zone alteration in the watersheds that feed the Croton Reservoir system, an important component of New York City's drinking water supply (Fig. 5d).

The LU/LC analysis shows that the overall amount of forest and the amount of interior forest is decreasing. The interior forest

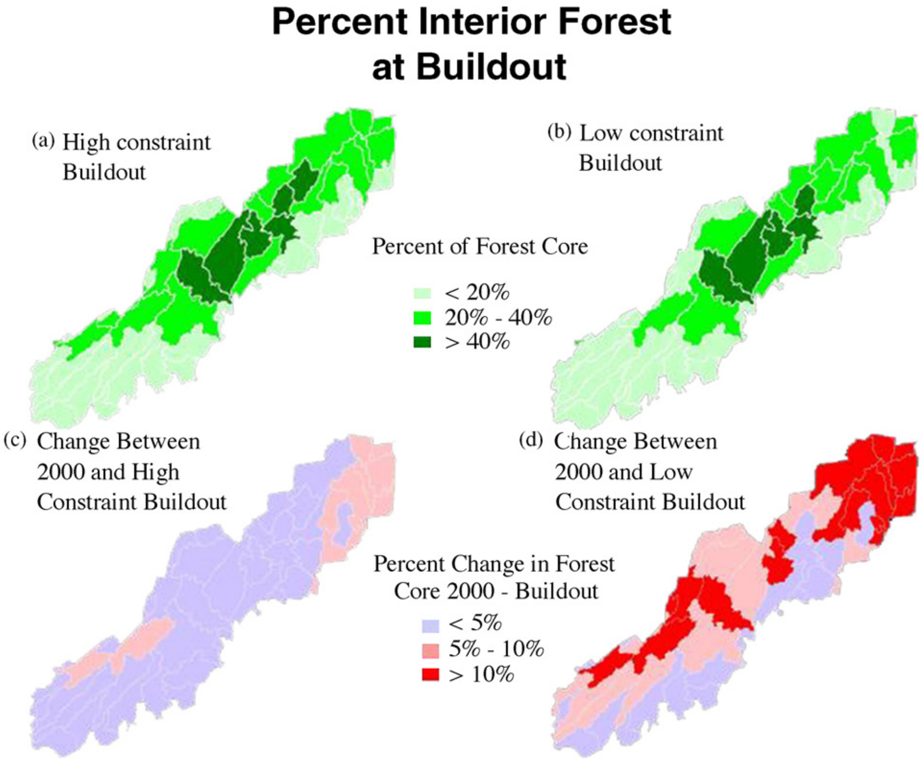

Fig. 6. Estimated changes in percent interior forest at build-out.

indicator shows a steady decline from 15 (i.e., 15 of 51, or 29%) of the watersheds having greater than 40% interior forest cover in 1984 to only 9 (i.e., 9 out of 51, or 18%) of the watersheds in 2000 (Table 1). The number of watersheds with greater than 40% interior forest is expected to decrease to 6 and 5 under the High and Low Constraints respectively (Table 1; Fig. 6a and b). The Low Constraint build-out scenario shows over a third of the watersheds (i.e. 19 out of 51 watersheds, or 37%) with a greater than 10% decline in interior forest area (Fig. 6d). The northeastern corner of the NY Highlands region and the central Highlands of New Jersey show up as hotspots for interior forest loss.

4. Discussion

The landscape indicator analysis reveals that there has been a steady increase in the number of watersheds that exceed critical thresholds for watershed integrity. As shown in Table 1, the number of watersheds with >50% cover of human altered land, >10% impervious surface cover, and >50% altered riparian zone area have increased between 1984 and 2000. As might be expected, there has been a concomitant decrease in watersheds with >40% of interior forest cover. While the four indicators show generally consistent trends, there are some differences. The % altered land index includes lands modified for agriculture as well as urban land uses and therefore begins with a higher number of impacted watersheds. The increase in number of altered watersheds over the 1984–2000 time period is largely due to increasing urban development, rather than expanding agriculture. Changes occurring to the Highlands landscape are largely the result of urban growth, namely residential, and to a lesser extent, commercial development. This is reflected in the increasing numbers of watersheds that are considered to be impacted due to >10% impervious surface cover. However, because much of the recent residential development has been at comparatively low densities, the number of watersheds above the impervious surface threshold has not risen as fast as the overall amount of altered land.

The results of our coupled build-out and landscape indicator analysis indicate that there will be significant landscape changes by build-out in the New York–New Jersey Highlands region, which will substantially impact watershed and forest integrity. The Low Constraint scenario simulates the status quo in terms of zoning and environmental regulations, while the High Constraint scenario incorporates greater wetland and riparian zone buffers, limited development on steep slopes, and no development of watershed management lands. The increase in altered land and impervious surface under both build-out scenarios, and especially under the Low Constraint scenario, indicates that the Highlands' water quality is expected to be negatively impacted by future urban growth. The results of the High Constraint build-out scenario suggests that increasing the wetland buffer distance will help to protect sensitive riparian zones (and thereby surface water quality) even in the face of increasing development. The High Constraint scenario also suggests that increasing protection of wetland/riparian buffers and steep slopes will help reduce the loss of interior forest habitat. Overall, the Low Constraint scenario shows large land cover and landscape indicator change, signaling significant environmental degradation. The High Constraint scenario shows a more limited change in landscape indicators and a lower degree of associated environmental degradation.

Visualization of the landscape indicator analysis indicates that the location of future hotspots of landscape change will be towards the periphery of the NY–NJ Highlands region. Higher urban growth and associated landscape impacts are especially evident in the northeastern corner as well as in the southwestern corner of the region in areas where the land is primarily in private ownership and there is presently a mix of forest and agricultural land uses. These landscape change hotspots generally span several adjacent sub-watersheds and cross multiple municipal boundaries and include the receiving basins for several major drinking water supply watersheds. Over 11 million New York and New Jersey residents rely on the NY–NJ Highlands for at least some portion of their drinking water supply (Phelps and Hoppe, 2002) and any compromise of the water supply watersheds is of special concern. Our spatially explicit GIS-based build-out model showed great utility in geographically highlighting these potential trouble spots that may not have been identified if a strictly aspatial approach had been employed.

While the build-out model employed in this study provided a useful means to project future land use patterns, it does have limitations. First, secondary effects of the regulations were not considered. For example, in the High Constraint scenario any effects that the more stringent regulations may have on surrounding areas were not considered. There is the strong possibility that limiting urban development in one area (e.g., on steep slopes) will increase the growth pressures in other areas, resulting in a change in zoning, allowing even higher intensity development. A second potential limitation of the model is that the timing of urban development was not considered. As mentioned earlier, a build-out model can be only used to examine the form of the fully developed landscape at some indeterminate future point in time. In the Highlands region, build-out is a reasonable scenario to plan for, as present trends indicate build-out will likely occur within a few decades.

There are many potential landscape indicators that we could have employed. For example, the USEPA employed over 30 different landscape indicators in its ecological assessment of the USA Mid-Atlantic region (Jones et al., 1997). In the NY–NJ Highlands study, we opted to employ a few key indicators that, (1) were readily accepted measures of forest and watershed integrity in the research literature, (2) captured key aspects of environmental condition, and (3) easily communicated to policy makers and the public. One difficulty was in determining general thresholds and what constituted significant changes for a given indicator. Alternatively we could have dispensed with choosing thresholds altogether and mapped the full distribution of the indicator values instead (e.g., as quintiles as was done in Jones et al., 1997). However, our charge in the study was to provide policy makers with our best judgment as to the impacts expected under future land use conditions. The use of indicator thresholds, along with an explicit acknowledgement of the uncertainties involved, was deemed the most straightforward way of communicating the information to policy makers.

For impervious surface area, we used generally accepted thresholds from literature (Arnold and Gibbons, 1996; Schueler, 1998). Where possible we examined data on the relationship between landscape pattern and watershed condition that were specifically relevant to the Highlands region. For example, a study of over 800 sites in New Jersey found that the primary factors related to degradation of stream benthic communities are the percentage of urban land use within the associated drainage basin as well as the amount of upstream wastewater discharge (Kennen, 1998). Conversely, the total amount of forested land within a drainage basin was the best predictor of an unimpaired community. Analysis of the USGS National Water Quality Assessment (NAWQA) data for other central and northern New Jersey watersheds shows that those basins with greater than 40–50% urban land cover had either medium or high stream degradation scores (Zapecza et al., 2003.). Based on these data, we selected the more conservative 50% threshold for the altered land (human use) index, though an argument could easily be made for a 40% cut-off. In the case of thresholds for riparian zone alteration and interior forest, we made reasoned judgments based on the existing conditions in the region. In a larger context, there are numerous measures of forest fragmentation, and no consensus exists over how much change is too much or where significant thresholds exist for a given metric (Turner et al., 2001). Further work needs to be undertaken to identify general thresholds and to better understand the relationships between changes in landscape indicators and the changing condition of the Highlands forests and watersheds.

5. Conclusions

The cumulative ecological impacts of land use change at broader watershed or landscape scales are not regularly included in local and even regional land use planning decisions. Part of this omission may be due to the restricted geographic view of most land use planning decisions and the limited means of assessing future impacts. The coupled build-out and landscape indicator analysis was designed to serve as a planning tool to provide a way to assess the potential impacts to forest and watershed integrity based on "what if" scenarios. The application of spatially explicit build-out models provide a useful approach to examine the consequences of local level land use planning policies at a broader regional scale. This analysis is not an "absolute" prediction of future conditions at any particular point in time. Rather it suggests what might be expected to happen based on existing patterns and trends, and under the various assumptions codified in each build-out scenario. The NY–NJ Highlands study was largely successful in achieving its two main objectives: (1) to compare the relative impact of the low versus high constraint scenarios at the regional scale and (2) to identify potential hotspots of environmental change that deserve greater consideration in future land management decisions.

Continued development of the Highlands is inevitable and in some locations welcomed. However, greater attention must be paid to protecting the integrity of the Highlands' forests and watersheds. As pointed out by Conway and Lathrop (2005), without acknowledging the full scope of future urbanization, there is little incentive or political will to adopt the necessary measures to control or mitigate the negative cumulative impacts. The results of this study highlight the disparities between the level of development allowed under existing municipal land use plans and the amount of additional development this region can support without negatively impacting resources. If urban development continues on present trajectories (as represented in the Low Constraint build-out model) then we expect the integrity of NY–NJ Highlands' watersheds to be increasingly compromised by future development. Increasing protection of steep slopes and riparian zones (as represented by the High Constraint scenario), while only a limited solution, does provide some tangible increase in watershed protection. Interest in protecting the NY–NJ Highlands as a natural resource of regional, if not national, significance has been intensifying over the last 15 years and has been the focus of a number of local, state and federal efforts in this regard. By providing solid science-based information, the Highlands Regional Study Update (Phelps and Hoppe, 2002) has helped to push the debate forward and has empowered local, state and federal government and non-governmental entities to seek greater legislative protection of the NY–NJ Highlands. The most recent culmination of this effort was the passage of the New Jersey Highlands Water Protection and Planning Act (New Jersey Assembly, 2004), which will institute regional planning along with more stringent growth controls in the core watersheds of the New Jersey portion of the Highlands.

Acknowledgements

We gratefully acknowledge the assistance of John Bognar, Scott Haag, Caroline Phillipuk, Jim Trimble, Nan Shao, and Jim Myers, on many aspects of this project. Many thanks to Martina Hoppe and Marcus Phelps for their role in organizing the 2002 Highlands Study. This project was funded by the USDA Forest Service Northeastern Area State and Private Forestry.

References

Alberti, M., 1999. Urban patterns and environmental performance: what do we know? J. Plann. Educ. Res. 19, 151–163.

Arnold Jr., C.L., Gibbons, C.J., 1996. Impervious surface coverage: the emergence of a key environmental indicator. J. Am. Plann. Assoc. 62 (2), 243–258.

Bartlett, J.G., Mageean, D.M., O'Connor, R.J., 2000. Residential expansion as a continental threat to U.S. coastal ecosystems. Popul. Environ. 21 (5), 429–469.

Botequilha Leitao, A., Ahern, J., 2002. Applying landscape ecological concepts and metrics in sustainable landscape planning. Landscape Urban Plann. 59 (2), 65–73.

Conway, T., Lathrop, R.G., 2005. Alternative land use regulation and environmental impacts: assessing future land use in an urbanizing watershed. Landscape Urban Plann. 71, 1–15.

Forman, R., Godron, M., 1986. Landscape Ecology. Wiley & Sons, New York, NY.

Fulton, W., Pendall, R., Nguyen, M., Harrison, A., 2001. Who sprawls most? How growth patterns differ across the U.S. The Brookings Institution Survey Series, July 2001. Center on Urban & Metropolitan Policy, The Brookings Institution, Washington, DC.

Heilman Jr., G.E., Strittholt, J.R., Slosser, N.C., Dellasala, D.A., 2002. Forest fragmentation of the conterminous United States: assessing forest intactness through road density and spatial characteristics. Bioscience 52, 411–422.

Jones, K.B., Ritters, K.H., Wickham, J.D., Tankersley, R.D., O'Neill, R.V., Chaloud, D.J., Smith, E.R., Neale, A.C., 1997. An Ecological Assessment of the United States Mid-Atlantic Region: A Landscape Atlas. EPA/600/R-97/130, Washington, DC.

Kennen, J.G., 1998. Relation of benthic macroinvertebrate community impairment to basin characteristics in New Jersey streams: U.S. Geological Survey Fact Sheet. FS-057-98, West Trenton, NJ.

Kepner, W.G., Jones, K.B., Chaloud, D.J., Wickham, J.D., Riitters, K.H., O'Neill, R.V., 1995. Mid-Atlantic Landscape Indicators Project Plan. EPA/620/R-95/003, Environmental Monitoring and Assessment Program. National Exposure Research Laboratory, U.S. Environmental Protection Agency, Research Triangle Park, NC.

Lambin, E.F., 1997. Modelling and monitoring land-cover change processes in tropical regions. Prog. Phys. Geog. 21 (3), 375–393.

Lathrop, R.G., Hatfield, C., Tulloch, D., Parks, P., Butler, B., Miller-Weeks, M., 2003. In: Hoppe, M. (Ed.), Section 2. Land Resources. New York–New Jersey Highlands Technical Report. NA-TP-04-03, USDA Forest Service, Northeastern Area State and Private Forestry, Newtown, PA, pp. 45–220.

Lathrop, R.G., 2004. Land Use/Land Cover Update to Year 2000/2001. New Jersey Department of Environmental Protection, Trenton, NJ (Last accessed June 2005) http://crssa.rutgers.edu/projects/lc/download/reportsdata00_01/landuselandcov_web.pdf.

Lee, J., Tian, L., Erickson, L.J., Kulikowski, T.D., 1998. Analyzing growth-management policies with geographical information systems. Environ. Plann. B 25, 865–879.

McKinney, M.L., 2002. Urbanization, biodiversity and conservation. Bioscience 52 (10), 883–890.

Michaels, J.A., Neville, L.R., Edelman, D., Sullivan, T., DiCola, L.A., 1992. New York–New Jersey Highlands Regional Study. USDA Forest Service. Northeastern Area State and Private Forestry, Radnor, PA.

Muscutt, A.D., Harris, G.L., Bailey, S.W., Davies, D.B., 1993. Buffer zones to improve water quality: a review of their potential uses in UK agriculture. Agric. Ecosyst. Environ. 45, 59–77.

New Jersey Assembly, 2004. Highlands Water Protection and Planning Act. New Jersey Legislature Assembly, No. 2635. Trenton, NJ (http://www.state.nj.us/dep/highlands/docs/highlands_bill.pdf).

Niles, L.J., Myers, J.,Valent, M., 1999. The Landscape Project. NJ Endangered and Nongame Species Program. NJ Department of Environmental Protection, Trenton, New Jersey.

Nilsson, C., Pizzuto, J.E., Moglen, G.E., Palmer, M.A., Stanley, E.H., Bockstael, N.E., Thompson, L.C., 2003. Ecological forecasting and the urbanization of stream ecosystems: challenges for economists, hydrologists, geomorphologists and ecologists. Ecosystems 6, 659–674.

Novotny, V., Chesters, G., 1981. Handbook of Nonpoint Pollution. Van Rostrand Reinhold, New York, NY.

O'Neill, R.V., Krummel, J.R., Gardner, R.H., Sugihara, G., Jackson, B., DeAngelis, D.L., Milne, B.T., Turner, M.G., Zygmut, B., Christensen, S.W., Dale, V.H., Graham, R.K., 1988. Indices of landscape pattern. Landscape Ecol. 1, 153–162.

Phelps, M., Hoppe, M., 2002. New York–New Jersey Highlands Regional Study: 2002 Update. NA-TP-02-03, USDA Forest Service, Northeastern Area State and Private Forestry, Newtown, PA.

Riitters, K.H., Wickham, J.D., O'Neill, R.V., Jones, K.B., Smith, E.R., Coulston, J.W., Wade, T.G., Smith, J.H., 2002. Fragmentation of continental United States Forest. Ecosystems 5, 815–822.

Schueler, T., 1998. Rapid Watershed Planning Handbook—A Comprehensive Guide for Managing Urbanizing Watersheds. Center for Watershed Protection, Ellicott City, MD.

Temple, S.A., Cary, J.R., 1988. Modeling dynamics of habitat-interior bird populations in fragmented landscapes. Conserv. Biol. 2, 340–347.

Theobald, D.M., Hobbs, N.T., 1998. Forecasting rural land-use change: a comparison of regression- and spatial transition-based models. Geogr. Environ. Model. 2 (1), 65–82.

Turner, M.G., Gardner, R., O'Neill, R.V., 2001. Landscape Ecology in Theory and Practice: Pattern and Process. Springer–Verlag, New York City, NY.

Welsch, D., 1991. Riparian forest buffers. Function and design for protection and enhancement of water resources. Forest Resources Management. Northeastern Area State and Private Forestry, USDA Forest Service, Radnor, PA.

Zapecza, O., Rice, D., DePaul, V., 2003. In: Hoppe, M. (Ed.), Section 1. Water Resources. New York–New Jersey Highlands Technical Report. NA-TP-04-03, USDA Forest Service, Northeastern Area State and Private Forestry, Newtown, PA, pp. 1–44.

Zipperer, W.C., 1993. Deforestation patterns and their effects on forest patches. Landscape Ecol. 8, 177–184.