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Rescaling the Human Footprint: A tool for conservation planning at an ecoregional scale

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ABSTRACT

Measuring and mapping human influence at the global scale suffers from problems of accuracy and resolution. To evaluate the magnitude of this problem we mapped the Human Footprint (HF) for the Northern Appalachian/Acadian ecoregion at a 90-m resolution using best available data on human settlement, access, land use change, and electrical power infrastructure. Such a map measures the magnitude of human transformation of a landscape, scaled between Human Footprint scores of 0 and 100. Comparison with a 1-km resolution Global Human Footprint map revealed similar spatial patterns of human influence. The correlation between HF scores, however, declined with the size of the area compared, with the rank correlation between ecoregional and global HF scores ranging between 0.67 for 100% of the ecoregion and 0.41 for 0.1% of the ecoregion. This indicates that rescaling the map to a finer resolution leads to improvements that increase as the planning area becomes smaller. The map reveals that 46% of the ecoregion has HF $\leq$ 20 (compared to 59% in the global analysis) and 34% had HF > 40 (compared to 21% in the global analysis). These results demonstrate the benefit of performing region-scale Human Footprint mapping to support conservation-based land use planning at the ecoregional to the local scale. This exercise also provides a data framework with which to model regionally plausible Future Human Footprint scenarios. These and other benefits of producing a regional-scale Human Footprint must be carefully weighed against the costs involved, in light of the region's conservation planning needs.

1. Introduction

Transformation of the landscape to human uses underlies most global conservation problems. Evidence for human impacts on biological systems from conversion of terrestrial ecosystems has mounted for numerous parameters, including population declines of native species (Hughes et al., 1997), extinction (Dirzo and Raven, 2003), local extirpation of top predators (Ray et al., 2005), loss of ecosystems (Noss et al., 1995), degradation of ecosystem function (Millennium Ecosystem Assessment, 2005), and appropriation of net primary productivity (Vitousek et al., 1986). Given the general importance of understanding patterns of human transformation of natural ecosystems, accurate means of assessing such changes at multiple scales and of mapping levels of influence across several parameters are central to optimal land use planning.

Numerous projects mapping a variety of anthropogenic parameters at varying degrees of resolution and spatial extent have been presented over the last decade in an effort to assess human impact on wilderness quality, wildlife habitat, and biological systems (e.g., Aplet et al., 2000; Bryant et al., 1997; Hannah et al., 1995; UNEP, 2001; WWF-Canada, 2003). Sanderson et al. (2002) developed a unique methodology to calculate a single relative human impact value for discrete locations using multiple, mapped parameters at the global scale. The goal of the Global Human Footprint was to quantify a continuum of human influence (HI) on terrestrial ecosystems and identify the remaining large wild places on the

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planet—the Last of the Wild. By mapping the relative influences of human-induced land use change, settlement patterns, access, and infrastructure for energy generation and transmission, the 1 km resolution map of the Global Human Footprint provides an assessment of anthropogenic stress on biological diversity at a scale that can support global conservation planning. For ecoregional application, however, the authors of the Global Human Footprint identified two significant shortcomings:

(a) The quality of the geographic data available for a global map of human influence can be poor in terms of accuracy (e.g., incorrect placement or attribution of features), completeness (e.g., features missing due to error or data currency), and resolution (e.g., lack of detail).
(b) The ability to interpret patterns of human influence based on geographic features in a globally consistent manner given a limited understanding of the complexities of human interaction with nature.

Sanderson et al. (2002) suggested that these drawbacks can be addressed by restricting areas of subsequent study to regional, national, or local levels, which would allow the use of more relevant and accurate data mapped at finer resolutions. For example, a multi-level classification of road data that would be possible at the ecoregional level is a more evolved indicator of human presence, actions, and infrastructure than the single road category in the Global Human Footprint. Given the burgeoning availability of region-scale geospatial data that provide indicators of human impact, including road layers generated by states and provinces, it is becoming increasingly realistic for planning groups to generate Human Footprint (HF) maps at multiple scales. It is not clear, however, whether such maps provide improvement over the global map, thereby justifying their development. To determine whether adapting the Human Footprint methodology to an ecoregional scale improves spatial interpretations of landscape transformation, we used a regionalization of the Human Footprint methodology to assess the relative influence of spatial accuracy and scale in mapping human transformation of the landscape. Specifically, we tailored the methodology of Sanderson et al. (2002) to the Northern Appalachian/Acadian (NAP) ecoregion of North America and compared the results of our ecoregional assessment to their Global Human Footprint for this region.

2. Materials and methods

2.1. Study area

The transboundary Northern Appalachian/Acadian ecoregion as delineated (Fig. 1) by The Nature Conservancy (Anderson et al., 2006), encompasses 330 000 km^2 and portions of five U.S. states (New York, Massachusetts, Vermont, New Hampshire, and Maine) and all or part of four Canadian provinces (Québec, New Brunswick, Nova Scotia, and Prince Edward Island). It is dominated by spruce-balsam fir (*Picea* spp., *Abies balsamea*) and northern hardwood (primarily maple [*Acer* spp.], beech [*Fagus grandifolia*], and birch [*Betula* spp.]) forests.

Several characteristics of the NAP ecoregion make comparison of its Human Footprint mapped at different resolutions of general interest. High-quality geospatial data that are comparatively accurate, complete, and current are available for many different parameters. It exhibits a wide range of ecological diversity with respect to species, aquatic and terrestrial ecosystems, and land forms. It also has a long history of human occupancy (especially post-Columbian settlement), proximity to large urban areas (e.g., New York City, Boston, Montreal), an economy strongly dependent on both natural resource extraction (e.g., timber, fish) and nature-based recreation, and a diversity of political traditions. In combination, these result in the potential for a broad range of kinds and magnitudes of human impacts across the ecoregion.

2.2. Mapping protocol

In order to develop spatial data layers comparable to the Global Human Footprint, we followed the general methodology developed by Sanderson et al. (2002):

(a) Selection of spatial resolution of analysis based on the scale of the best available data.
(b) Selection of datasets representing the different sources of landscape transformation and assignment of human influence scores between 0 and 10.
(c) Combination of HI scores across datasets to quantify direct human influence, resulting in a map of the human influence index (HII).
(d) Normalization of the HII across ecological subregions to calculate relative transformation within each subregion, resulting in a map of the Human Footprint.

To fully capture the human influences on the periphery of the ecoregion boundary, we buffered our analytical boundary to 40 km. Ultimately, we mapped the Human Footprint to a 20 km buffer around the NAP ecoregion. Following Sanderson et al. (2002), we only assessed human influence on terrestrial ecosystems and not freshwater or coastal systems.

2.3. Selection of spatial resolution

Sanderson et al. (2002) chose the 1 km spatial resolution of the Global Human Footprint based on the scale of the best available data they used. We followed a similar process to select the optimal spatial resolution for the NAP Human Footprint. Although the vector data we used were predominantly available at 1:100 000 (e.g., census data, roads data), suggesting a 100 m resolution, raster-based data were generally available at 30 m resolution (e.g., land cover data derived from Landsat imagery). Thus, to minimize information loss associated with rescaling raster-based data, we chose an analytical resolution of 90 m, an integer multiple of 30 m, rather than 100 m. This resulted in the NAP ecoregion being represented by 41 495 812 separate 90 m data cells.

2.4. Selection of datasets and assignment of influence scores

For the NAP ecoregion, we used 10 datasets to represent the four categories of human influence used in the Global Human Footprint (sources and resolution of all datasets listed in Table 1). We compiled nine from two or more sources and combined them across political boundaries to form single, ecoregionally continuous datasets:

(a) human settlement: population density, dwelling density, and urban areas;
(b) human access: roads and rail lines;
(c) human land use change: land cover, large dams, watersheds, and mines; and
(d) energy infrastructure: utility corridors.

We chose data layers to capture those human activities and trends relevant to assessing human influence in the NAP ecoregion in the present time. Thus, we included dwelling density

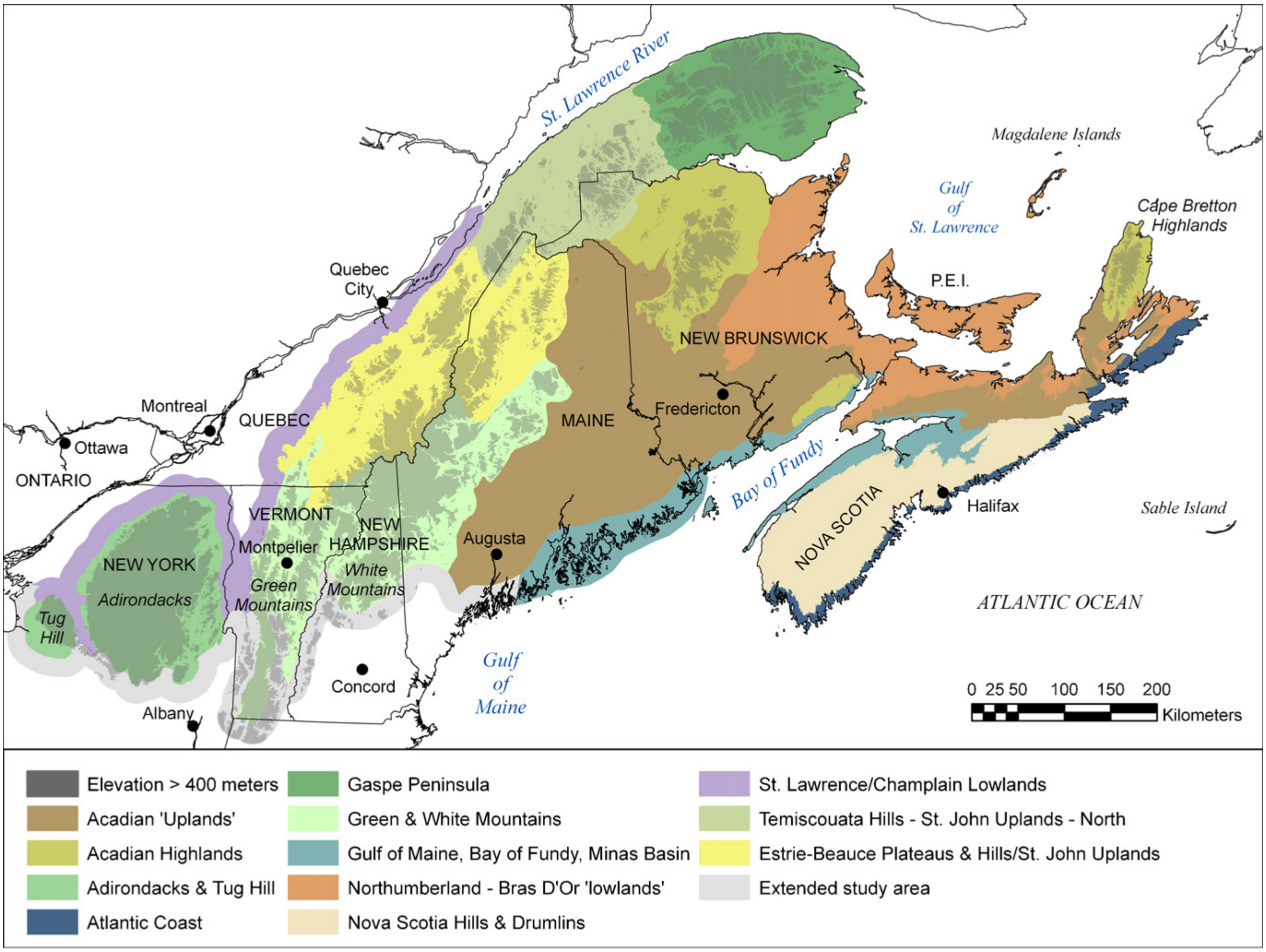

Fig. 1. The Northern Appalachian/Acadian ecoregion.

to capture the influence of second homes related to amenity developments and decreasing household size, but we did not use navigable rivers as Sanderson et al. (2002) did because rivers do not presently serve as significant transportation corridors in the NAP ecoregion.

Following the methodology of Sanderson et al. (2002) we assigned human influence scores to each dataset to reflect their relative contribution to human impact and transformation on a scale from 0 (low) to 10 (high). We based scores (described below) on published studies relevant to the NAP ecoregion and on expert opinion.

2.4.1. *Human settlement*

Both numbers of people and dwellings are implicated as causes of biological decline (Cincotta and Engelman, 2000; Liu et al., 2003). To map the influence of settlements, we used urban areas, population density, and dwelling density from the U.S. 2000 census block and Canadian 2001 dissemination area census statistics. The census block and dissemination area represent the smallest census units in each country.

We assigned human influence scores to population density in each cell using the continuum approach of Sanderson et al. (2002), where HI scores for densities between 0 and 10 persons/km^2 increase linearly from 0 to 10. Based on the assumption that the influence of population density reaches an asymptote at 10/km^2, we assigned all densities greater than that an HI score of 10.

The literature provides little information on ecological response thresholds for dwelling density other than Sabor et al. (2003), who observed that 90% of forest harvest events for aspen occurred at housing densities below 5.5 houses/km^2 in the Upper Lake States of the U.S. Thus, we assigned scores to dwelling density linearly and assumed an asymptote at 5.5 dwellings/km^2.

We used areas identified as “urban” in census statistics to recognize the relatively complete conversion of the land in these places. We assigned urban areas an HI score of 10 and gave areas not identified as “urban” a score of 0.

We calculated an overall human settlement HI score for each cell as the maximum of the HI scores for population density, dwelling density, and urban area for that cell. The maximum possible HI score for this category was 10.

2.4.2. *Human access*

Roads and other transportation corridors are well-known to affect and transform the landscape with respect to numerous parameters – ranging from wildlife demography to water quality – that have significant influences on biological systems (Trombulak and Frissell, 2000). An extensive network of 390 000 km of roads and 13 000 km of rail criss-cross the NAP ecoregion and its 20-km buffer.

We divided roads into four classes that differ in relative ecological impact: expressways and interstates; primary and secondary highways; local roads; and vehicular trails that can be accessed by

Table 1
Source and resolution for the ten datasets used to map the Human Footprint

Feature	Source
Human settlement	
Population density; dwelling density	USA: Census 2000 Tiger/Line Files – census blocks. 1:100,000
	Canada: Cartographic Boundary Files 2001 Census, Statistics Canada—dissemination areas. 1:50 000
Urban areas	USA: Census 2000 Tiger/Line Files—urbanized areas. 1:100 000
	Canada: Cartographic Boundary Files 2001 Census, Statistics Canada—urban areas. 1:50 000
Human access	
Roads	USA: Census 2000 Tiger/Line Files. 1:100 000
	Canada: CanMap Route Logistics V8.2, DMTI Spatial 1:50 000
Rail	USA: Bureau of Transportation Statistics (BTS), National Rail Network 1:100 000
	Canada: CanMap Rail V8.2, DMTI Spatial, 1:50 000
Human land use change	
Land cover	New York, Vermont, New Hampshire, Massachusetts: USGS, National Land Cover Dataset (NLDC). 1992. 30 m resolution
	Maine: USGS GAP Analysis Program. 1993. 30 m resolution
	Quebec: Canadian Wildlife Service, Environment Canada. 30 m resolution
	New Brunswick: Department of Natural Resources & Environment. 1:10 000
	Nova Scotia: Department of Natural Resources, Ecosystem Management Group. 1:10 000
	PEI: Department of Agriculture, Fisheries, Aquaculture and Forestry. 1:10 000
Large dams	USA: U.S. Army Corps of Engineers National inventory of dams (NID), 2005 (scale unknown)
	Canada: Canadian Dam Association, 2003. Locations digitized using 1:50 000 topographic maps (www.etopo.ca)
Watersheds	USA: USGS, 1:250 000 scale Hydrologic Units of the United States (HUC8), 1994
	Canada: Atlas of Canada National Frameworks—drainage areas (2003). National Resources Canada 1:1 000 000
Mine sites	USA: USGS Mineral and Metal Operations, 1998 (scale unknown)
	Canada: Principal Mineral Areas of Canada—Map 900A, Natural Resources Canada. 2003. 1:6 000 000
Electrical power infrastructure	
Utility corridors	USA and Canada: NIMA Vector Map Level 0 Edition 5 2000. 1:1 000 000

Land use/land cover data were compiled by The Eastern Resource Office of The Nature Conservancy (TNC). NIMA is the National Imagery and Mapping Agency; USGS is the United States Geological Survey; WWF is the World Wildlife Fund

four-wheel drive vehicles, including logging roads. We applied HI scores separately to each road class and to varying distances from the road to a maximum distance of 3 km (Table 2), based on work by Boer (1990), Forman and Deblinger (2000), and UNEP (2001). This approach contrasts with the Global Human Footprint, which assumed the influence of all roads were equal regardless of road class up to a distance of 15 km. We calculated the final roads HI score for each cell as the maximum influence of the four road classes.

We divided rail lines into three classes: operational, seasonal, and abandoned. At the rail bed, the influence from operational and seasonal rail lines is greater than from those that are abandoned; however, seasonal and abandoned rail lines, which are used as trails for recreational vehicles (e.g., ATV's, snowmobiles) in many parts of the NAP ecoregion, can have greater influences over longer distances. We assigned HI scores to each rail class to reflect this phenomenon, using the same distance intervals as for roads (Table 2) out to a maximum distance of 1 km. We calculated the final rail HI score for each cell as the maximum of the influences of the three rail classes.

To achieve an overall human access HI score for each cell, we summed HI scores of roads and rail lines for that cell. The maximum possible HI score for this category was 20.

2.4.3. Human land use change

To capture the overall influence of human land use change, we considered the effects of residential and industrial development, agriculture, resource extraction (forestry and mining), and major alteration of hydrology (dams). We mapped these using four datasets: land use/land cover (LULC), mines, large dams, and watersheds. In contrast, global data limitations restricted Sanderson et al. (2002) to considering only complete conversion resulting from roads, rails, and built areas, as well as the influence of agricultural and mixed-use lands.

We used the LULC dataset for the NAP ecoregion compiled by The Nature Conservancy (Anderson et al., 2006) from six separate data sources, with the exception of Maine, which we replaced with the LULC dataset from the Maine GAP Analysis Project (Hepinstal et al., 1999) to better reflect forestry related land cover types in that state.

We assigned HI scores to each of 13 land uses based on relative degree and permanence of transformation. We assigned an HI score of 10 to both low–high intensity residential and commercial/industrial/transportation, and successively lower scores to other LULC classes, such as Quarries/Strip Mines and Gravel Pits (HI = 8), Agricultural (HI = 6), and Regenerating Forest (HI = 4).

Table 2
Human influence (HI) scores for roads, rail lines, and utility corridors

	0–90 m	90–500 m	500–1000 m	1000–3000 m
Roads				
Expressways and interstates	10	8	6	4
Primary and secondary highways	8	6	4	2
Primary and secondary local roads	6	4	2	0
Vehicular trails including four-wheel drive	4	2	1	0
Rail				
Operational	6	4	0	0
Seasonal	6	4	1	0
Abandoned	4	2	1	0
Utility corridors	3	1	0	0

Because the NAP ecoregion has a long history of forestry and only an extremely small percentage of the forests in the ecoregion have not been harvested at least once, we assigned all forestland not identified as regenerating (i.e., not in the early stages of regrowth following clearing: deciduous forest, conifer forest, mixed forest) an HI score of 2. While this approach overestimates the HI score for cells that contain old growth forest, the total area affected is likely much less than 1% of the entire ecoregion (Davis, 1993). We gave all other terrestrial classes – Bare Rock/Sand/Clay, Peat Bogs, Shrubland, and Forested or Shrub Wetland – an HI score of 0.

Alterations to hydrology resulting from dams represent modification of natural systems at the dam sites themselves, in addition to more pervasive modification both upstream and downstream. To capture these two forms of influence we first mapped the location of large dams, defined as either ≥15 m high, 10–15 m high with a crest length >500 m, spillway discharge >2000 m^3/s, or reservoir volume >1 000 000 m^3 (Clarke, 2000). We mapped the direct influence of dam structures by buffering each dam point location by a diameter equal to crest length plus 100 m to reflect the nominal spatial accuracy of ±100 m for the dam locations. We then assigned dam footprints an HI score of 10. Finally, to assess the more pervasive influence of large dams on watersheds, we calculated the reservoir volume density for each watershed, following the approach developed by WWF-Canada (2003). We assigned HI scores to each of three watershed classes: no dams (HI score = 0), watersheds with a volume density < 40 m^3/km^2 (HI = 1), and watersheds with a volume density ≥ 40 m^3/km^2 (HI = 2). The final hydrological alteration HI score was the maximum HI score for dam footprint and watershed.

Mining (which in the NAP ecoregion is primarily for peat, gravel, and stone) is a form of land conversion that leads to changes in topography, altered watercourses, removal of topsoil, and may serve as a point source for water and air pollution. We compiled information on active mines from the U.S. Geological Survey dataset of active mines and mineral processing plants (1998) and a Canadian dataset prepared by WWF-Canada (2003), which subdivided mines into four categories based on type and size of excavation (inferred from the type of commodity extracted): large open pit, small open pit, large underground, and small underground. We assigned HI scores to mines based on the WWF-Canada (2003) scoring system (Table 3).

We calculated an overall human land use change HI score for each cell as the sum of the HI scores of LULC, hydrological alteration, and mines for that cell. The maximum possible HI score for this category was 20.

2.4.4. *Electrical power infrastructure*

We mapped major utility corridors at a scale of 1:1 000 000. These corridors represent a form of land conversion because they are kept open, fragment habitat, facilitate the spread of invasive exotics, and provide access for recreation. We applied HI scores to represent the influence of the corridor itself and the influence of access at distance from these features in the same manner as roads (Table 2). The maximum possible HI for this category was 3.

2.5. *Summation of influence scores across datasets*

Within each cell, we summed the HI scores for human settlement, access, land use change, and electrical power infrastructure, giving the human influence index for the ecoregion. The maximum possible HII score was 53, compared to a maximum of 72 for the Global Human Footprint that used the additional datasets of navigable rivers and coastlines to map influence from human access and lights at night from space dataset (Elvidge et al., 1997) to map influence from electrical infrastructure.

2.6. *Normalization of summation across subregions*

Ecological subregions reflect the primary spatial variation in dominant plant communities within an ecoregion and may serve as a proxy for regional variation in biological capacity or response to landscape transformation. To account for this regional variation, and in keeping with the Sanderson et al. (2002) methodology, we normalized the HII scores within each ecological subregion (Anderson et al., 2006; Fig. 1) to scale their range from 0 to 100, using the equation

$$\mathrm{HF}_i = \frac{(\mathrm{HII}_i - \mathrm{HII}_{\mathrm{min},j}) \times 100}{\mathrm{HII}_{\mathrm{max},j} - \mathrm{HII}_{\mathrm{min},j}}$$

where i represents the cell and j represents the subregion of which the cell is a member.

In the NAP ecoregion, HII scores varied across subregions, including for minima (0–1), maxima (34–47), and means (7.4–18.3).

The normalized scores yielded the final Human Footprint. Normalization between 0 and 100 allows for a more intuitive interpretation of the scores and comparison with the Global Human Footprint. For example, HF = 10 indicates that the score is 10% of the maximum score in that subregion, and HF = 0 indicates that it is the minimum score in that subregion. It should be noted, however, that the minimum HII scores across all subregions were between 0 and 1; thus, HF = 0 is also functionally equivalent to having no human transformation with respect to the 10 parameters that were evaluated.

2.7. *Assessing the influence inputs*

To understand the most influential forces shaping the Human Footprint, we analyzed the relationship between HF scores and the HI values of the input layers. With seven explanatory variables, we were interested in the number and identity of parameters that comprised the most parsimonious model. Thus, we used the R^2 values from applied multiple least squares regression analysis of 41 497 randomly located cells (0.001% of the data) to assess optimal number of parameters and derive best approximating models for each.

2.8. *Assessing the importance of mapping scale*

To evaluate the importance of mapping scale, we undertook both qualitative (visual) and quantitative comparisons of the global and ecoregional Human Footprint maps for the NAP ecoregion. For the latter, we assessed the value of mapping the Human Footprint at finer scales and smaller geographic areas by contrasting the calculated HF scores for matched cells at both scales. The first comparison was of the entire ecoregion (330 000 km^2). In the global analysis, the ecoregion was represented by 328 300 complete 1-km^2 cells. We sampled 1% of them by generating 3283 random points a minimum of 1.4 km apart; due to some points falling on water, there were fewer useable points. We then compared the HF scores at these points calculated in both the global and ecoregional analyses using a Spearman's rank correlation coefficient.

We then assessed correlations between the global and ecoregional analyses for a set of smaller areas (called subareas). These analyses only considered the effect of changing the spatial extent of the analysis, not the spatial resolution. Our rationale was that the resolution we used in the ecoregional analysis (90 m) is the finest resolution achievable even for smaller spatial extents and, therefore, subdividing the ecoregional analysis into subareas is equivalent to creating the best possible Human Footprint maps for subareas (e.g., local, subregional).

Table 3
Mine types and the human influence scores assigned to each type and at distance (adapted from WWF-Canada, 2003)

Mine category	0–500 m	500–1500 m	1500–2500 m	2500–5000 m	5000–10000 m
Open pit mines (large)	8	8	4	2	1
Open pit mines (small)	8	4	2	2	0
Underground mines (large)	6	6	4	2	1
Underground mines (small)	6	4	2	2	0

To create random subareas, we generated a grid of 330-km^2 hexagons, with each hexagon covering 0.1% of the total ecoregion. Target subarea sizes ranged from 0.1% to 80% of the entire ecoregion. For each target subarea size, we performed five random sampling iterations. Each such iteration involved the follow steps:

(a) A random hexagon was selected from the grid.
(b) Adjacent hexagons were selected until the target subarea size was reached.
(c) Random points at least 1.4 km apart were generated in the target subarea, and the HF scores for those points from both the global and ecoregional maps were compared. We based the number of random points generated on the number of 1-km^2 cells present in the target subarea of the global analysis. For example, for a target subarea of 80%, the number of random points selected was 1% of the number of 1-km^2 cells in 80% of the entire ecoregion.

Thus, sampling intensity remained approximately constant (1% of area before excluding points that overlapped water) for all subareas generated. The one exception was for the 0.1% target subarea. Generating only 1% of 0.1% of the cells would have resulted in only three points; therefore we arbitrarily increased the sampling intensity to 20% for this target subarea size.

3. Results

3.1. The ecoregional Human Footprint

The ecoregion-scale map of the Human Footprint suggests a large-scale pattern of landscape fragmentation whereby sizeable areas with a relatively low degree of transformation are separated from each other by areas with much greater transformation (Fig. 2). Numerous large areas with relatively low HF scores exist within the Northern Appalachian/Acadian ecoregion, including (a) the Adirondack Mountains and Tug Hill Plateau in New York, (b) the area extending from the White Mountains in northern New Hampshire northeastward to northern Maine, (c) central New Brunswick, (d) the Gaspé Peninsula of Québec, and (e) both southern and northern Nova Scotia. Even these places, however, are not homogenous with respect to their relative low degree of transformation; each contains several embedded areas with much higher HF scores than the surrounding matrix landscape.

These large areas of low human influence are more or less bounded and separated from one another by regions of greater human influence. Those with the greatest human influence in the NAP ecoregion were generally low-lying areas in between mountain ranges, river valleys, and other arable areas: for example, (a) the valley between and the peripheries of the Tug Hill Plateau and Adirondack Mountains, (b) the Champlain Valley in eastern New York and western Vermont, and the interior valleys in eastern Vermont, (c) southern Québec along the international boundary, (d) the St. John River valley between Maine and New Brunswick, (e) the Chignecto Isthmus between New Brunswick and Nova Scotia, (f) central Nova Scotia, and (g) Prince Edward Island.

The distribution of HF scores (Fig. 3) demonstrates that on average the region is still only moderately transformed relative to the maximum amount present anywhere in the NAP ecoregion, even while the vast majority of the area experiences some human influence. While only 0.2% of the ecoregion has HF = 0, indicating the lowest measured level of human transformation of the landscape given the measures we incorporated in our analysis, the average HF score is only 11.62. The distribution of HF scores peaks in the HF 11–20 range and declines steadily with greater HF scores. Greater than 90% of the ecoregion has an HF ≤ 50.

The NAP ecoregion includes 53 790 km^2 with HF ≤ 10, a category we refer to as "wild" following Sanderson et al. (2002). These wild areas are distributed in 17 813 blocks (blocks defined as a minimum of six grid cells or 0.049 km^2), ranging in size from <1 to 1930 km^2. Most of these remaining wild areas are small; 14 368 (80.7%) are ≤1 km^2 in size, and only 79 (0.004%) are >1000 km^2. Thus, despite the appearance of large areas of land with low HF scores (Fig. 2), wild areas in the region are overwhelmingly small and fragmented.

The analysis of the relationship between HF scores and the seven HI input layers using the R^2 values from an applied multiple least square regression revealed that the greatest gain in R^2 was between 1 and 3 parameters (0.72–0.95, or Δ23%), whereas adding more parameters to the model resulted in a change to only 0.96–0.98, indicating little new information (Δ2%). Among the three-parameter models, the best approximating model (ΔAIC = 35 663; evidence ratio 1.0) contained human settlement, roads, and land use/land cover. As a measure of its influence, human settlement was included in every best approximating model, regardless of number of parameters.

3.2. Comparison to the Global Human Footprint

At a broad scale, a visual comparison of the Human Footprint in the NAP ecoregion derived from the global analysis (Sanderson et al., 2002) and ecoregional analysis (this study) shows spatial patterns of human influence that are quite similar. Close examination, however, reveals numerous instances of variance in the details of these broad patterns (Fig. 4). For example:

(a) In the Tug Hill Plateau and Adirondack Mountains of northern New York (Fig. 4a and b), the general patterns of both Human Footprints are similar, showing large central core areas with low levels of human-induced change. The ecoregional map, however, depicts a greater prevalence of pockets of transformation embedded within the wildest areas, and greater conversion of the landscape surrounding the core areas.
(b) Northern New Brunswick and the Gaspé Peninsula of Québec (Fig. 4c and d) are generally more transformed and fragmented when assessed with the ecoregional analysis.
(c) The relative wildness of southern Nova Scotia (Fig. 4e and f) appears significantly increased when assessed with the ecoregional analysis.
(d) On the Chignecto Isthmus (Fig. 4g and h), which links Nova Scotia and mainland Canada both geographically and biologically, the ecoregional analysis reveals small patches of low influence and a level of detail are not apparent from the global view.

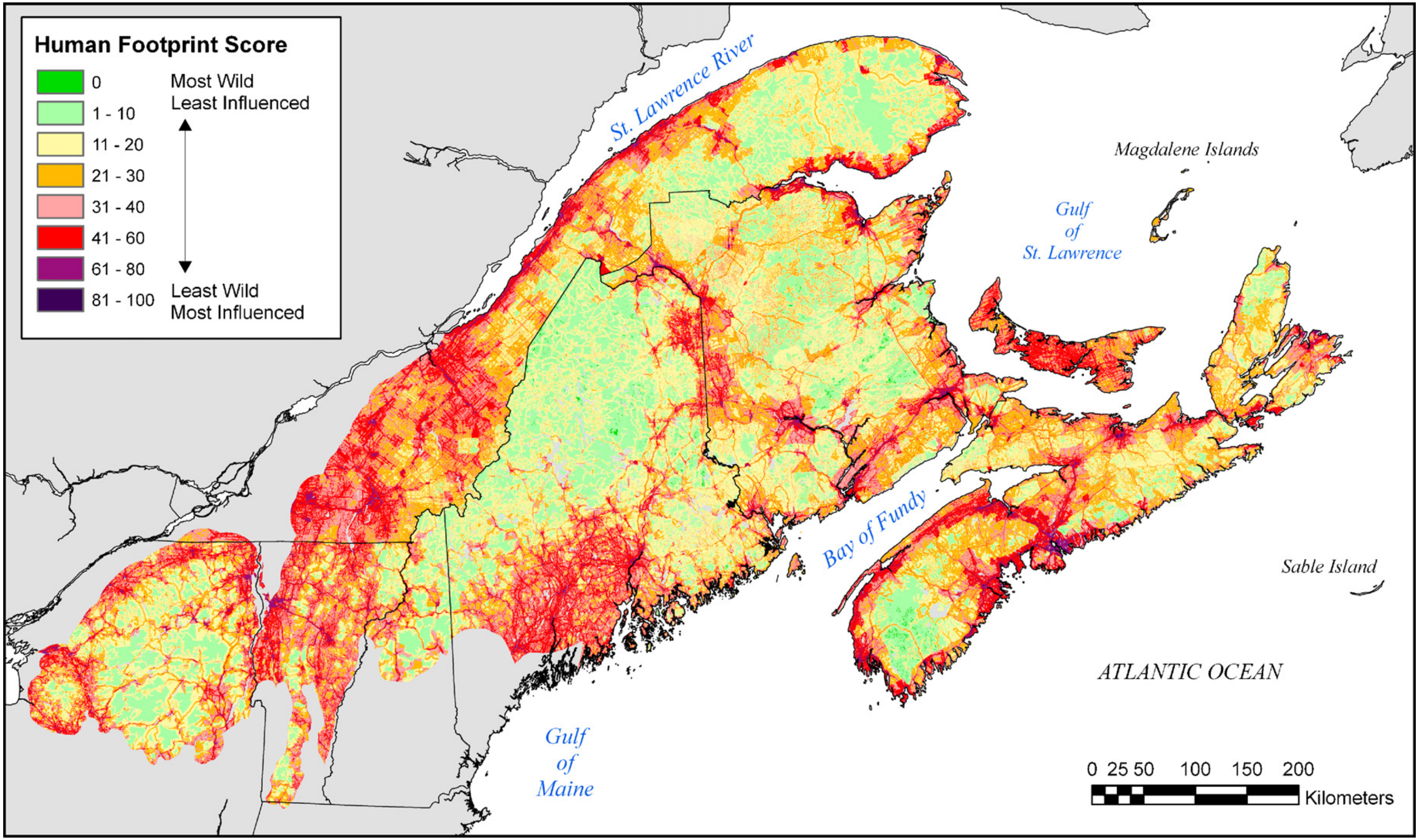

Fig. 2. The Human Footprint of the Northern Appalachian/Acadian ecoregion.

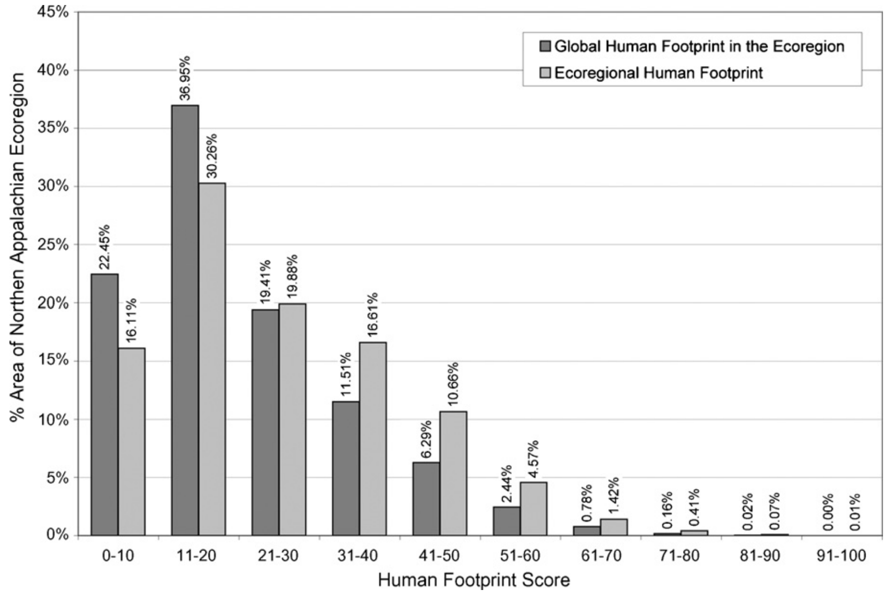

Fig. 3. The frequency distribution of HF scores across the Northern Appalachian/Acadian ecoregion compared with the distribution of HF scores for the Northern Appalachian/Acadian ecoregion derived from the global analysis (Sanderson et al., 2002).

Compared to the assessment of the NAP ecoregion derived from the global analysis, the Human Footprint mapped at the ecoregional scale reported here reveals a lower percentage of the region with low levels of transformation (HF $\leq$ 20; 46% ecoregion vs. 59% global) and a much greater percentage with moderate and high levels of transformation (HF > 40; 34% ecoregion vs. 21% global) (Fig. 3). This suggests that the Global Human Footprint underestimates human transformation and overestimates "wildness" in this ecoregion.

Spearman's rank correlation coefficient for the HF scores derived from the global and ecoregional analyses averaged 0.68 (n = 5, p < 0.0001 for all five iterations; Table 4), indicating that when considering the scale of the entire ecoregion (330 000 km^2), the HF score for a location derived from the global analysis was strongly correlated with that from the ecoregional analysis. However, this correspondence steadily declined as the spatial scale assessed became smaller. At the scale of only 0.1% of the ecoregion (330 km^2), the average correlation

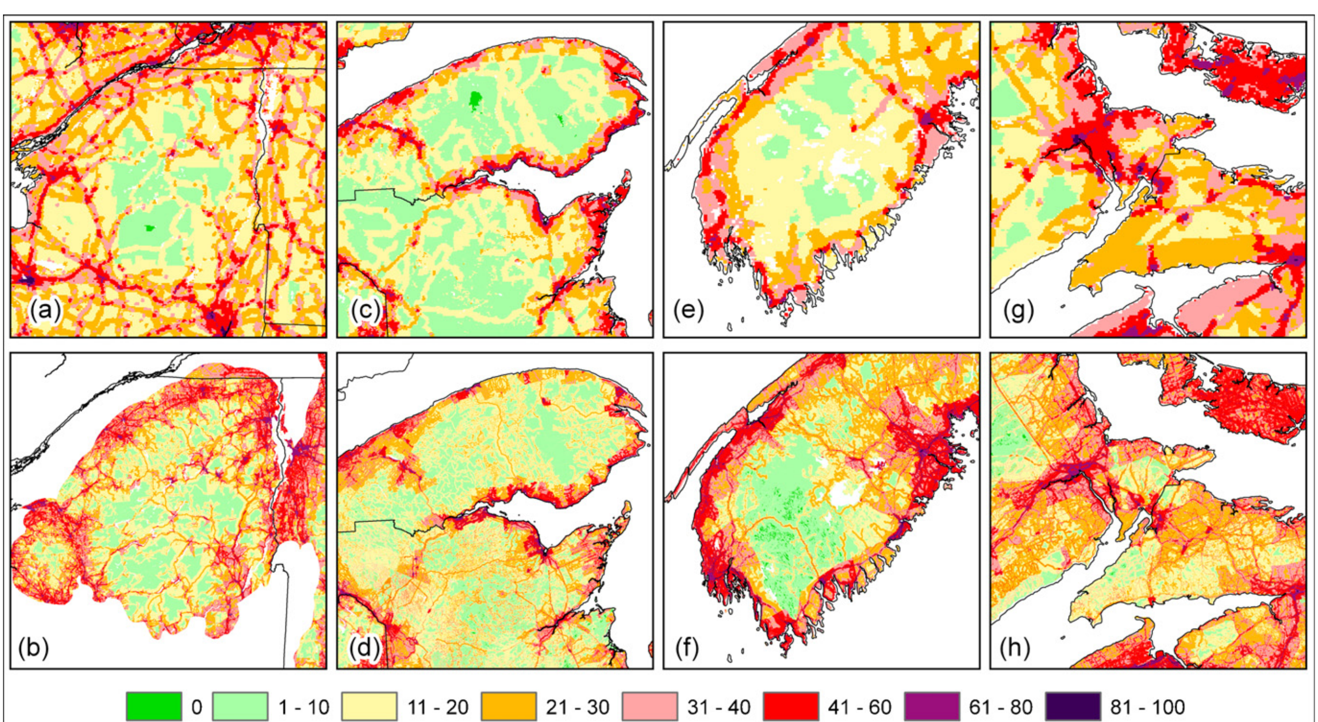

Fig. 4. Visual comparison of Global Human Footprint (Sanderson et al., 2002) and ecoregional Human Footprint (this study) for (a and b) northern New York, (c and d) New Brunswick and the Gaspé Peninsula, (e and f) southern Nova Scotia, and (g and h) the Chignecto Isthmus. In each pair, the image on top is from the global analysis.

Table 4
Correlation between the HF scores derived from the global and ecoregional analyses

Target subarea (%)	No. hexagons (±1 S.E.)	No. points (±1 S.E.)	Actual %area sampled (±1 S.E.)	Correlation (±1 S.E.)	Range of *p* values
100	NA	3270.8 (3.4)	100.0 (0.0)	0.679 (0.007)	<0.0001
80	804.8 (1.7)	2642.1 (5.4)	75.2 (0.3)	0.679 (0.005)	<0.0001
60	604.6 (7.4)	1984.9 (24.1)	56.5 (0.6)	0.673 (0.017)	<0.0001
40	396.6 (4.2)	1302.0 (13.7)	37.1 (0.6)	0.637 (0.024)	<0.0001
20	206.4 (2.5)	677.6 (8.3)	19.2 (0.2)	0.648 (0.037)	<0.0001
10	108.0 (3.6)	354.6 (11.7)	10.2 (0.04)	0.549 (0.024)	<0.0001
5	56.0 (3.3)	183.8 (10.8)	5.2 (0.3)	0.518 (0.046)	<0.0001
1	11.0 (1.7)	49.7 (9.1)	1.0 (0.1)	0.530 (0.065)	<0.0001–0.395
0.1	1.0 (0.0)	70.0 (0.0)	0.1 (0.0)	0.412 (0.094)	<0.0001–0.752

Values for each target subarea equals the average of five iterations. Range of *p* values indicates the high and low *p* values for the five iterations; when only one value is given, all *p* values are <0.0001.

dropped to 0.41 ($n = 5$, p ranging from 0.752 to <0.001; Table 4).

4. Discussion and conclusions

4.1. The ecoregional Human Footprint

Our analysis shows that the extent and pattern of human transformation in the Northern Appalachian/Acadian ecoregion is profound and spatially complex. In spite of having undergone centuries of human settlement and intensive use, a large percentage of the ecoregion exhibits a relatively low amount of conversion. To illustrate, 46% of the ecoregion is in the bottom 20% ($HF \leq 20$) of the scale of transformation, and 16% is in the bottom 10% ($HF \leq 10$) of the scale. This indicates that the NAP ecoregion still retains a large amount of land that represents conditions that, at least with respect to the 10 parameters assessed in this study, are relatively unmodified by humans, demonstrating that significant opportunities for large-scale conservation still exist in the region.

This does not imply, however, that the NAP ecoregion is unmodified. With only 0.2% of the ecoregion having a score of $HF = 0$, the vast majority of the landscape experiences some level of relative human influence from some combination of settlement, access, land transformation, and electrical power infrastructure. It does illustrate, however, that significant opportunities remain to conserve relatively untransformed landscapes throughout the ecoregion.

Such landscapes, although present to some extent across the full length and breadth of the ecoregion, are not homogeneously distributed. Some of the largest areas are associated with sizeable protected areas, such as the Adirondack Park (northern New York) and Kejimkujik National Park (southern Nova Scotia), suggesting the importance of public lands in protecting wild nature. On the other hand, northern Maine also shows a low level of transformation but is, for the most part, not protected as public land, but instead is largely in private ownership with low population density (Anderson et al., 2006).

These broad-scale patterns illustrated by an ecoregion-scale Human Footprint highlight that conservation planning in the NAP ecoregion must be adaptive to the reality that future opportunities will require involvement of numerous stakeholders. Timely awareness of the importance of specific areas within the ecoregion is critical because opportunities for conservation planning can dramatically change when patterns of land ownership shift. Northern Maine, for example, is currently experiencing a sea change in type of ownership (Hagan et al., 2005), shifting from timber companies to land development companies. In addition, the prospects for maintaining ecological connectivity between areas of relatively low human influence are dwindling. For example, the narrow Chignecto Isthmus between Nova Scotia and New Brunswick is mostly privately owned. If a biological corridor is to be maintained, close cooperation will be needed among provinces, municipalities, and First Nations.

Patterns of future risk for transformation can be modeled using threat forecasting techniques such as those pioneered by Theobald (e.g., 2003) and others. Baldwin et al. (2007) forecast a doubling of the area in the ecoregion susceptible to new, public roads in the next 20 years. Multiple land use change processes (e.g., growth of road networks, changes in housing and population density, and amenity development) incorporate different assumptions and result in different forecasts than any one process alone. By integrating these processes and outputs into a Future Human Footprint (FHF), future land use scenarios can be compared to each other and to the current (Trombulak et al., 2008). While it is beyond the scope of this paper to describe the FHF methodology, it is a powerful conservation planning tool that relies on the ecoregional Human Footprint as a foundation (http://www.2c1forest.org/atlas).

The detail provided by the ecoregional map of the Human Footprint for areas with relatively high levels of transformation provides important information for landscape-level planning. To the extent that areas of high human transformation become less suitable for native species and ecosystems in terms of either their persistence or movement, areas largely characterized by high HF scores become both priorities and challenges for conservation planning. For example, successful establishment of wolves (*Canis lupus*) in the northeastern U.S., either though natural recolonization from populations in Canada or purposeful reintroduction, will likely depend on opportunities for gene flow between northern New York and northern Maine, as well as between the U.S. and Canada (Carroll, 2003; Harrison and Chapin, 1998). Analysis of the Human Footprint, however, reveals that Vermont and southern Québec are among the most transformed lands in the entire ecoregion. Although this does not preclude gene flow or that strategies to promote it cannot be implemented, it does reveal the magnitude of the challenge.

Areas with high levels of transformation also indicate locations where site-based conservation planning is likely to be the most important. For example, protection of threatened or endangered species in southern Québec, Prince Edward Island, and southern Maine will require conservation efforts that can be implemented in small areas that maximize protection for populations that are likely to remain small and do not require large-scale habitat restoration.

While the Human Footprint can itself serve as a useful tool for conservation planning, it is by no means the only tool available and in fact will be most powerful when combined with output from other analyses, including those used for identifying areas important for ecological representation (Anderson et al., 1999, 2006; Reining et al., 2006) and core areas for wide-ranging wildlife (Carroll, 2003; Harrison and Chapin, 1998). Spatial quantification of current levels of threat afforded by the Human Footprint map is an important step forward from those that are generally more qualitative in nature and can be an important building block for comprehensive conservation-based planning.

4.2. Comparison to the Global Human Footprint

In general, the global and ecoregional maps of the Human Footprint in the NAP ecoregion are strongly and positively correlated. Areas identified as having low levels of human transformation on one map were similarly identified on the other (e.g., Adirondack Mountains, Gaspé Peninsula). The ecoregional map, however, revealed a level of spatial heterogeneity in human transformation that was masked in the global analysis. Since most conservation plans must ultimately be implemented at the regional or local level, they require an understanding of such heterogeneity. On the other hand, as a means of simply identifying qualitatively the least modified areas in the region and of communicating broad patterns, both maps are equally useful.

The range of correlation coefficients observed between global and ecoregional footprints (0.41–0.68) is probably bounded on the lower end because it represents the inherent correlation between the global datasets used to map the Global Human Footprint and the regional datasets used in our study. Similarly, it is probably bounded at the upper end by our use of new datasets with increased levels of detail.

Increased detail in the ecoregional dataset (90 m) makes it particularly applicable to local-scale conservation planning compared to the Global Human Footprint (1 km). A resolution of 1 km is practically useless for conservation planning at the municipal or watershed scale, a level at which many land trusts operate (Merenlender et al., 2003). Land trusts and other local conservation groups are frequently primary users of mapped threat data (Theobald et al., 2000) such as the Human Footprint.

The global–ecoregional comparison reveals both that Sanderson et al.'s (2002) call for more regionally specific mapping is merited but that in the absence of such mapping, valid conclusions about the spatial distribution of human transformation can still be drawn from the global map. The strength of those conclusions and the extent to which they will be useful for land use planning, however, depends on the spatial extent being considered, with the correlation declining dramatically as planning areas shift from the ecoregional to the local level. However, our analysis suggests that the Global Human Footprint underestimates human transformation and overestimates "wildness." Similar analyses would need to be conducted in other regions to test if this applies elsewhere.

4.3. Limitations of the ecoregional Human Footprint

Compared to the Global Human Footprint, the picture of the Human Footprint in the NAP ecoregion is based on data that are more accurate and complete, have greater resolution, and span a wider range of human influences. Still, the map has limitations that should be kept in mind not only by those who would use it in landscape planning (Anderson et al., 2006; Bateson, 2005), but by those who seek to improve projections of future human influence. First, attribute classes and mapping scale for similar datasets (e.g., LULC, roads) were selected quite differently by different political units that generate digital spatial data. For example, in the U.S., up to 22 classes of LULC are used, while in Canada 62 classes are used just in Nova Scotia. This required us to reduce the number of classes recognized in the Canadian dataset, with a subsequent loss of potentially usable information. Further, cross-walking geographic datasets across jurisdictional boundaries presented the challenge of semantic interoperability between datasets, thus the time and logistical constraints to resolve these challenges must be weighed against the goals of the planning exercise.

Second, not all human influences on the landscape could be included in our analysis, either because of the spatial resolution of the ecoregionally available data (e.g., actual measurements of airborne pollutants) or the spatial extent of high-resolution data within the ecoregion (e.g., distribution of exotic species). Although it is more accurate than the Global Human Footprint with respect to relative levels of landscape transformation within the ecoregion, it is certainly an underestimate of the absolute amount of transformation because all locations in the ecoregion experience additional stresses beyond those considered here. Therefore, an HF score of 0 on our map should not be interpreted as "no human influence."

Third, the map has inherent temporal limitations. Not only does it simply represent conditions at the time the data were collected (generally mid-1990s–2001) and not "today," but it also cannot take into account influences that result from historic conditions ("the ghost of transformation past") not revealed by current data, such as higher past population densities or agricultural land that has reverted to forest.

Fourth, the map itself does not directly measure biological response. Such responses will certainly be species-specific with respect to the Human Footprint, with some species responding negatively to HF scores above very low values (e.g., American marten), some responding positively and preferentially to high values (e.g., European Starlings), and all other possible patterns of threshold response. Thus, although measuring the Human Footprint, as we have done here, is the first step in developing a landscape-scale view of the patterns of human transformation, translating the map into species-specific assessments of threats to biological diversity will require knowledge of how a given species responds to landscape transformation.

4.4. Streamlining the Human Footprint

Of the seven HI input variables, three (human settlement, roads, and land use/land cover) provide the greatest explanatory power of the Human Footprint. While datasets on rail lines, mining, hydrological alterations and utility lines improved the subtlety of the Human Footprint by highlighting features in areas of low human settlement, their contribution is minor because roads and some kind of land use usually co-occur with such features. Ecoregional Human Footprint assessments carried out elsewhere could achieve much of the benefit of the increased precision that comes from a focus on greater spatial resolution without all of the cost incurred in the full sweep of data acquisition and analysis done in this study.

4.5. Conclusions and next steps

Despite these limitations, our analysis reveals the most detailed and comprehensive picture possible at the present time of the relative magnitude and spatial distribution of human-induced transformation in an ecoregion, and provides the only scaled comparison with the Global Human Footprint. It shows the spatial patterns of anthropogenic landscape change in the NAP ecoregion to be highly heterogeneous compared to the Global Human Footprint, with a larger percentage of the ecoregion experiencing greater levels of transformation. Further, it shows that areas with low levels of human transformation are to some degree separated from one another by highly modified regions, a landscape-scale pattern that reflects a historical transition up to the present day and calls for timely land use planning at a variety of scales. The details of these patterns are dramatically improved over those shown in the global analysis (Sanderson et al., 2002) by the use of regionally relevant datasets and of finer data resolution.

Landscape planning to achieve conservation in this ecoregion at a variety of spatial scales will be improved by attention to these patterns. They reveal priorities for protecting wild nature as well as the realities that must be addressed in planning for landscape-scale connectivity for biological phenomena that operate over time frames both short (e.g., carnivore dispersal, range shifts of birds sensitive to fragmentation) and long (e.g., vegetation response to climate change). Coupled with species-specific information on biological response to human modifications of the landscape, this map also provides the basis for developing predictive models of habitat suitability that incorporate information on human influences.

In addition, the methodology shown here provides the basis for developing forecasting models of how the Human Footprint within an ecoregion might change in the future. While tools for build-out analyses of development are relatively well-developed for small areas (e.g., townships), there are as yet no tools to permit such analyses at the landscape-scale. In that all of the datasets included in this analysis involve features whose patterns of future development can be modeled (cf., Baldwin et al., 2007), potential Future Human Footprints can be generated to facilitate proactive approaches to landscape planning.

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