Journal of Applied Ecology

British Ecological Society

Journal of Applied Ecology 2015 doi: 10.1111/1365-2664.12444

Land-use impacts on the quantity and configuration of ecosystem service provisioning in Massachusetts, USA

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Summary

1. Meeting fundamental human needs while also maintaining ecosystem function and services is the central challenge of sustainability science. In the densely populated state of Massachusetts, USA, abundant forests and other natural land cover convey a range of ecosystem services. However, after more than a century of reforestation following an agrarian past, Massachusetts is again losing forests, this time to housing and commercial development.

2. We used land-cover maps, ecosystem process models and land-use data bases to map changes (2001, 2006, 2011) in eight ecosystem service variables and to identify 'hotspots', or areas that produce a high value of five or more services, at three policy-relevant spatial scales.

3. Water-related services (clean water provisioning and flood regulation) experienced local declines in response to shifting land uses, but changed little when measured at the state level. General habitat quality for terrestrial species declined statewide during the study period as a consequence of forest loss. In contrast, climate regulation (carbon storage) and cultural services (outdoor recreation) increased, driven by continued forest biomass accrual and land protection, respectively. Timber harvest volume had high interannual variability, but no temporal trend.

4. The scale at which hotspots are delineated greatly affects their quantity and spatial configuration, with a higher density in eastern Massachusetts and 10–12% more hotspots overall when they are identified at a town scale as compared to a watershed or state scale.

5. *Synthesis and applications*. Ecosystem service hotspots cover a small percentage of land area in Massachusetts (2·5–3·5% of the state), but are becoming more abundant as urbanization concentrates ecosystem service provisioning onto a diminished natural land base. This suggests that while ecosystem service hotspots are valuable targets for conservation, more are not necessarily better since hotspot proliferation can reflect the bifurcation of the landscape into service and non-service provisioning areas and subsequent loss of diversity across the landscape.

Key-words: ecosystem management, ecosystem services, forests, hotspots, land-use change, Massachusetts, scale

Introduction

Developing knowledge that supports society's efforts to meet fundamental human needs while also maintaining ecosystem function and services is the central challenge of sustainability science (Kates *et al*. 2001). Today, over 60% of the world's temperate forest and grassland ecosystems have been converted to human-dominated uses, and the rate and intensity of land-use conversion are increasing (Foley *et al*. 2005; Millennium Ecosystem Assessment 2005; Lambin & Meyfroidt 2011). Such massive scales of land use have profound consequences for natural processes, including global carbon and hydrologic cycles, and their ability to support human populations. As human influences on the natural environment increase, setting priorities for environmental protection becomes ever more important (Daily 2001). Ecosystem services, or the benefits people receive from nature, provide a useful framework for assessing trade-offs between human needs and ecosystem functioning.

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Not all land is equal with regard to its ability to provision particular ecosystem services. Moreover, finite social and economic capacity for conservation compels land-use managers to strive for efficient approaches to sustaining services and, thus, to protect the most valuable land available. Thus, there is great potential for incorporating the geography of ecosystem services into land-use decision-making and to conserve areas that offer disproportionate benefits, termed ecosystem service hotspots. Hotspots are areas that provide a high value of multiple ecosystem services. Several studies have mapped hotspots (e.g. Anderson *et al.* 2009; Crossman & Bryan 2009), and some have found high spatial concordance between certain groups of ecosystem services, such as water-related and forest-related services (Anderson *et al.* 2009; Tallis & Polasky 2009; Raudsepp-Hearne, Peterson & Bennett 2010; Qiu & Turner 2013). These findings underscore the potential for practitioners to use hotspots for geographic prioritization in their efforts to sustain multifunctionality within landscapes or to achieve multiple land-use and conservation objectives.

Methods for defining hotspots differ, but they are typically identified in relationship to their landscape context, representing the highest ranked areas for multiple services within a given study area (e.g. Crossman & Bryan 2009; Qiu & Turner 2013). Accordingly, the spatial scale at which hotspots are delineated can exert a strong influence on their amount and distribution. Determining the proper spatial scale for delineating hotspots, therefore, represents an important component of efficient land-use planning. Overall, identifying hotspots at local scales may result in smaller and less pristine sites than hotspots identified at regional scales, but local-scale hotspots may serve more people or more relevant constituencies. Thus, the scale of analysis must be chosen based on the scale of demand for ecosystem services, the scale at which the ecosystem service provides a valuable function, and the scale of the decision-making authority to protect it (e.g. the town, county or state). While many hotspot analyses cite scale as an important consideration (e.g. Raudsepp-Hearne, Peterson & Bennett 2010), we are unaware of any that have explicitly examined the impact that scale of delineation has on hotspot quantity or configuration.

Just as landscapes are dynamic, so too are hotspots. Therefore, temporal scale is another important consideration when considering the role of hotspots for land-use planning. As natural and human processes modify the landscape, the amount and spatial configuration of hotspots can change concomitantly. Temporal dynamics of hotspots have not received much attention (but see Holland *et al.* 2011; Jiang, Bullock & Hooftman 2013). Nonetheless, an understanding of how land-use change affects ecosystem service provisioning is essential to prioritizing land management (Lambin & Meyfroidt 2011). While the identification of sites that supply high values of multiple services is often thought of as a 'win-win' for conservation prioritization, an increase in the area of hotspots may not always be a good thing. Indeed, a proliferation of hotspots may be an indicator that the landscape's ability to provision ecosystem services diffusely is being degraded as the burden is consolidated into a smaller area.

This study quantifies the impacts of land use on ecosystem services and hotspots in the state of Massachusetts. Like much of the north-eastern United States, land use has been transforming the Massachusetts landscape and affecting ecosystem processes for more than 400 years (Thompson *et al.* 2013). Following European settlement (*c.* 1600), the region's expansive forests were widely cleared for agriculture and cut over until the mid-19th century when farmland was progressively abandoned and allowed to reforest. The process of natural reforestation continued for more than a century until forest cover peaked at around 70% of the state in the mid-20th century (Foster *et al.* 2010). The return of forests brought many concomitant ecosystem services. Since then, however, the region has experienced a second wave of deforestation, this time due to increasing urban and rural development (Foster *et al.* 2010; Jeon, Olofsson & Woodcock 2014). This trend threatens the landscape's capacity to provide services to the most densely populated region of the United States.

The objectives of this study were as follows: (i) to quantify the impact of the current land-use regime on ecosystem service provisioning within Massachusetts and (ii) to examine how the quantity and spatial distribution of hotspots is affected by the spatial scale of delineation. Specifically, we mapped and modelled change over the past decades at three points in time (2001, 2006, 2011) in eight variables that are closely related to ecosystem services. We chose services of importance in the state for which we had sufficient data. The variables serve as proxies for provisioning, regulating and cultural ecosystem services as well as habitat quality (Millennium Ecosystem Assessment 2005; Daily *et al.* 2009). We then used the maps of ecosystem service production at each time step to identify hotspots – defined here as areas that provide high values for five or more services – at three spatial scales that are relevant to decision-making (state, watershed and town), to examine how spatial scale affects the quantity and configuration of hotspots.

Materials and methods

STUDY AREA

Massachusetts (69·9–73·5°E, 41·3–42·9°N; Fig. 1) is approximately 21 000 km^2 and is predominately forested (63%). The average annual temperature is 7·3°C (PRISM Climate Group 2004). Elevations range from 0 to 364 m, with a mean of 79 m. The state contains 27 major watersheds and a lattice of 351 towns that are political and geographical units. In 2013, the human population of Massachusetts was 6·7 million, with a strong west to east to gradient in increasing population density (U.S. Census Bureau 2014).

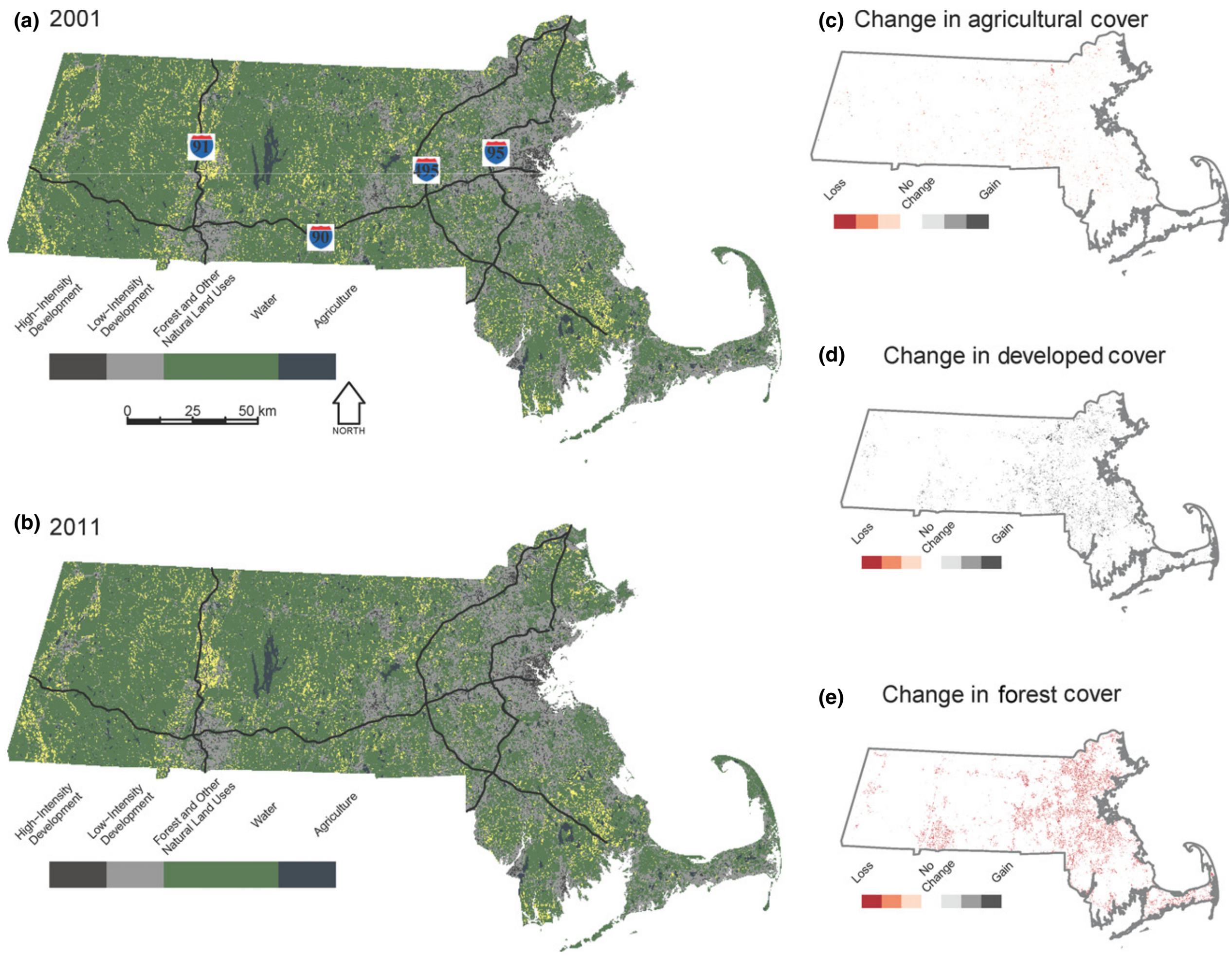

Fig. 1. Land use and land cover in (a) 2001 and (b) 2011. Maps depicting change in three major land-use classes (changed pixels smoothed using a focal window to highlight changes): (c) agriculture, (d) development and (e) forests.

LAND-COVER MAPS

We used 30-m resolution National Land-Cover Datasets (NLCD) for the years 2001, 2006 and 2011 as a component of our ecosystem service models and to infer changes in land use during the 10-year period (Homer *et al.* 2007; Fry *et al.* 2011; Jin *et al.* 2013). The NLCD is the primary source of land-cover data in the USA and has been used extensively in studies of habitat loss, forest fragmentation and ecosystem service valuation (Konarska, Sutton & Castellon 2002; Troy & Wilson 2006; Wickham *et al.* 2010; Qiu & Turner 2013). The 2001 NLCD was created using a classification of Landsat-TM data (Wickham *et al.* 2013). In contrast, NLCDs for 2006 and 2011 are land-cover change data bases that utilize the 2001 map as the baseline. An accuracy assessment of the 2001 and 2006 change maps found an overall map accuracy of 79 and 78%, respectively, for the continental USA (Wickham *et al.* 2013). The 2001 and 2006 maps have since been retrofitted for use in change detections against the 2011 map and rereleased in 2014. The NLCD 2011 map (released 8 May 2014) utilized an improved change-detection method, and while an accuracy for the whole country has not yet been completed, a preliminary analysis of two study areas found a 100% agreement between the 'no–change' class with a reference data set and an 18 and 82% disagreement for the change class of the two areas, respectively (Jin *et al.* 2013). We retained the 15 land-cover classes found in the state (Table S1 of Supporting Information). While it is likely that the NLDC data include some misclassifications, recent efforts by the developers to improve comparability through time and qualitative agreement within independent analyses (e.g. Jeon, Olofsson & Woodcock 2014, DeNormandie 2009) give us confidence that the trends observed are real and the data are appropriate for these analyses.

ECOSYSTEM SERVICES AND HABITAT QUALITY VARIABLES

Land cover alone is a poor proxy for many ecosystem services (Konarska, Sutton & Castellon 2002; Seppelt *et al.* 2011); therefore, we coupled estimates of land-cover change to ecosystem and hydrologic models and to a range of publicly available land-use data bases to better estimate the impact of land-use on ecosystem and human processes (sensu Qiu & Turner 2013). We estimated changes in eight variables that are closely related to regulating (hydrologic and climatic), provisioning (clean water and timber harvest) and cultural services (outdoor recreation) as well as habitat quality (general terrestrial species habitat (Polasky *et al.* 2010)). All variables were quantified and mapped at 30-m spatial resolution throughout the state in 2001, 2006 and 2011. Below we offer summaries of our methods for estimating values for each metric; full details on data sources, models and calibration are in Appendix S2.

Regulating services

• *Climatic*. Carbon sequestered from the atmosphere and stored in the terrestrial environment through photosynthesis is a negative feedback to climate change and is a significant offset to fossil fuel-related carbon emissions (Dixon *et al.* 1994). We used: (1) LANDIS-II v 6.0 (Scheller 2007) forest landscape model and a previously published parameterization (Thompson *et al.* 2011) to estimate live above-ground forest carbon, (2) data from the US Forest Service Inventory and Analysis Program to estimate soil forest carbon, and (3) previous studies that quantified above-ground and soil carbon across urban to rural gradients in Massachusetts to estimate the carbon within all other land-cover classes (Raciti *et al.* 2011, Table S2).

• *Hydrologic*. Changes in surface water run-off associated with land use can result in increased storm run-off and elevated flooding risk (Spierre & Wake 2010). We estimated surface water run-off and amount of impervious surface as two indicators of hydrologic regulation because each gives different, and valuable, information. To calculate the amount of impervious surface, we used a 1-m impervious cover map (MassGIS 2014) and estimated the average imperviousness of each land-cover class. We used the InVEST Water-yield model (3.1.0) to estimate changes in water export to streams over our time period (Tallis *et al.* 2013). InVEST is a set of spatial models developed by the Natural Capital Project designed to predict the provision and value of ecosystem services and habitat quality given land-use and land-cover maps and related biophysical, economic and institutional data for the study region (Kareiva *et al.* 2011; For details see Appendix S2). We used PRISM Normals data for 1981–2010 (PRISM Climate Group 2004) for monthly minimum and maximum temperature and precipitation to isolate the effects of land-use change on ecosystem services. While climate has been demonstrated to have a greater influence on water-related services than land-use change in Massachusetts (Thompson *et al.* 2014), we limited this study to the effects of land-use change.

Provisioning services

• *Water purification*. Excess nitrogen and phosphorus run-off can degrade surface water quality, resulting in higher filtration costs (Carpenter *et al.* 1998). We modelled nutrient export into streams and determined the proportion of nutrients retained at each site relative to the total amount exported by each watershed. We quantified nutrient export and water filtration using the InVEST Nutrient Export Model (3.1.0) (Tallis *et al.* 2013). Loading and filtration parameters were estimated from the literature and calibrated using the Spatially Referenced Regression On Watershed model's (SPARROW) estimates of N and P export (Moore *et al.* 2004) (For details, see Appendix S2).

• Timber harvesting, while not currently a major part of Massachusetts's overall economy, is an important land-use and ecological disturbance process, particularly in the western two-thirds of the state (McDonald *et al.* 2006). To examine the amount and spatial distribution of harvest volume over the study period, we utilized a geo-data base of all cutting events for the state (McDonald *et al.* 2006) and tax-assessor parcel data. These data allowed us to map actual harvest events and their spatial extent for each year of analysis (For details, see Appendix S2).

Cultural services

• *Recreation*. About 61% of Massachusetts' residents participate in outdoor recreation each year, which generates $10 billion in consumer spending each year (The Trust for Public Land 2013). We quantified outdoor recreation as a function of land-cover type, level of protection and public accessibility, similar to Qiu & Turner (2013). We weighted protected areas within the state based on their proximity to major roads, train stops and population centres and whether or not they were deemed noteworthy by the state (Appendix S2). Higher scores were given to more accessible and noteworthy sites, with 100 being the maximum score.

Habitat quality

• *General Terrestrial Species Habitat Quality*. In Massachusetts, land conversion to developed uses is the single most important proximate cause of habitat loss (Woolsey, Finton & DeNormandie 2010). We focused on terrestrial habitat because it is strongly affected by land use in the state (Forman & Deblinger 2000) and modelled habitat quality as a function of a site's proximity to other land-cover classes (Foley *et al.* 2005). We used InVEST's habitat quality module (3.1.0) to calculate terrestrial species' habitat availability and its relative degradation given its proximity to degrading land covers (i.e. high-density development, barren land), following Polasky *et al.* (2010) (For details, see Appendix S2).

SPATIAL RELATIONSHIP AMONG ECOSYSTEM SERVICES

All analyses were conducted using the R Statistical environment (R Development Core Team 2006) and the Raster library (Hijmans, Etten & Hijmans 2010). To understand the spatial patterns of co-occurrence among variables and to ensure that each metric provided unique information, we calculated pairwise Spearman's correlations between all variables. Correlations were calculated from a random sample of 1000 points separated by >1000 m to reduce the statistical effects of spatial autocorrelation. At each point, we extracted values for all eight ecosystem service variables and calculated a cross-correlation matrix. Next, we defined ecosystem service hotspots at the full study area scale, following Qiu & Turner (2013); specifically, we identified sites (pixels) that were rated as high value – that is within the top 20th percentile of all pixels (using the bottom 20th percentile for inverse indicators, such as imperviousness, where a high service value is associated with low absolute values) – for each of the variables and coded those pixels to 1, setting the remainder to 0. We then delineated the areas of co-occurring high-value pixels by summing the eight Boolean high-value layers. This resulted in a map with a potential range of zero to eight, where a value of eight represents an area that has scores in the top 20th percentile for all eight variables. Last, we classified this map such that sites with a score of zero are classed as low-value sites, scores from one to four are 'warm-spots', and scores of five or more classed as hotspots.

We also delineated hotspots at the watershed scale (n = 27, average area = 77 637 ha, SD = 46 983 ha) and the town scale (n = 351, average area = 5970 ha, SD 3381 ha). The process was similar to what is described above, except that the identification of high-value pixels was determined as those in the top 20th percentile within the subunit. Consequently, each of the eight resulting high-value maps contains 20% of the pixels in the state, just like the state-scale analysis. The aggregation of high-value maps for watershed and municipal hotspots was conducted just as described above, by summing all high-value layers.

Results

OVERALL PATTERNS OF LAND-COVER CHANGE

The greatest single land-cover transition observed between 2001 and 2011 was from forest to development (Fig. 1). Residential and commercial development increased along the western edge of the Boston metropolitan region (Fig. 1d), replacing agricultural and forestlands, which experienced the greatest losses (Fig. 1c, e). Over the study period, forest land-cover categories declined by 24 928 ha or 1·9% of total forest cover (all changes reported represent a net loss, Fig. 2). Developed categories had the greatest amount of change, increasing by 31 190 ha during the study period, or 6·3% (Fig. 2). Agricultural land uses declined by 5·3% over the study period, representing a loss of 6860 ha of agricultural land (Fig. 2). Notably, there were more changed pixels from 2001 to 2006 than from 2006 to 2011 (Fig. 2).

REGULATORY: CLIMATIC

Forest growth was the primary driver of carbon dynamics in Massachusetts from 2001 to 2011, bringing the statewide ecosystem carbon stores from 297 Tg C in 2001 to 325 Tg C in 2011, a 9% increase (Fig. 3a, b; Table 1). This increase is particularly notable given the loss of forest cover and gain of developed classes. The distribution of carbon stores varied spatially across the state, with the largest absolute gains occurring in the heavily forested western portion of the state, particularly in the western third of the state (Fig. 3a, b).

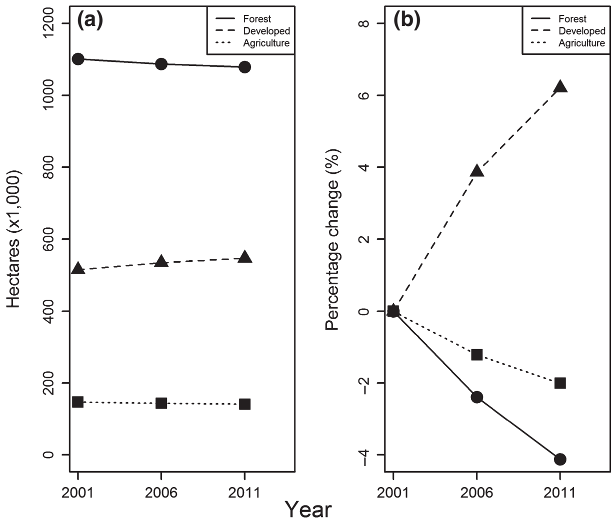

Fig. 2. Change in the major land-use classes during the study period (2001–2011) in (a) hectares and (b) percentage change from 2001.

REGULATORY: HYDROLOGIC

The amount of impervious surface across the state increased steadily through time coincident with the spread of development, from 201 240 ha of the state in 2001 to 213 820 ha of the state by 2011, a 6·3% increase overall (Table 1). These increases occurred predominantly in the central and south-eastern areas of the state, radiating west and south from major urban areas (Fig. 4a). The most intensely developed areas, for example Boston, Lowell, Worcester and Springfield, experienced the least amount of change during this time period because they were largely built out before 2001 (Fig. 4a).

Run-off remained relatively constant throughout the period, ranging between a statewide average of 853 mm yr^{-1} and 858 mm yr^{-1} (Table 1). This low variability reflects the use of the 30-year Normals for precipitation data, attributing all changes to land cover. The greatest change in run-off occurred in the eastern watersheds east of the Interstate 495 (a beltway around the city of Boston and its suburbs) (Fig. 1), reflecting the expansion of low-intensity development in these areas (Fig. 4b). These watersheds experienced up to a 1·5% increase in run-off due to spreading and intensifying development (Fig. 4b).

PROVISIONING: CLEAN WATER

The annual load of nitrogen and phosphorous into streams remained relatively constant at 1·13–1·16 and 0·14–0·15 kg ha^{-1} year, respectively (Table 1). Nitrogen loading was highest in more urbanized watersheds as well as in the Connecticut River Valley where there is a large amount of both development and agriculture (Fig. 4c), but the greatest changes to nitrogen again occurred along the I-495-corridor reflecting increased development and loss of filtering forest classes (Fig. 4c). Some of these watersheds experienced as much as a 5·4% increase in total nitrogen export. Even still, the towns with the greatest amount of increase still had export values that were much lower than the already densely urbanized areas. Phosphorus loading also predominately occurred in more urbanized regions, with the areas of greatest change paralleling the patterns in nitrogen, with up to 10·2% gains in some watersheds in the south-eastern portion of the state (Fig. 4d). In contrast to nitrogen, however, phosphorus showed little change in western and southern Massachusetts, despite modest increases in development, due to a loss of agriculture in these watersheds.

PROVISIONING: TIMBER HARVEST

Timber harvest for the period 2001–2011 averaged 291 658 m^3 yr^{-1} for the state, but was variable over the

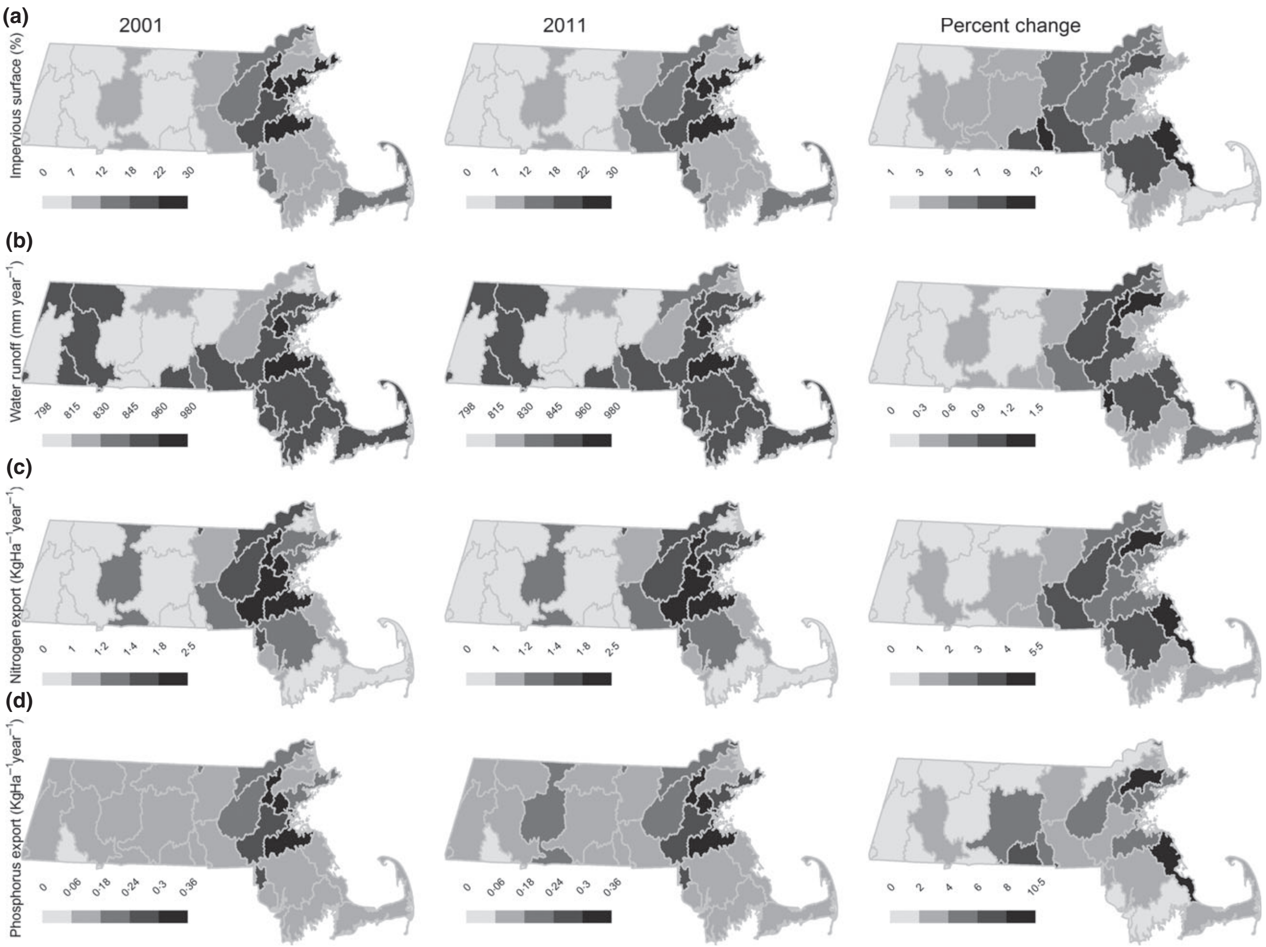

Fig. 3. Water-related services depicted by watershed for 2001, 2011, and percent change from 2001 to 2011; (a) Impervious Surface (% of watershed), (b) Runoff (mm year^{-1}), (c) Nitrogen Export (kg ha^{-1}), and (d) Phosphorus export (kg ha^{-1}). Services were quantified using 30-year Normals data (1981−2010) and mapped at the 30m scale.

Table 1. Ecosystem services mapped at the 30-m pixel level and summarized to statewide values. Pixel level standard deviations and ranges given for the services that are determined at the state scale; not reported for statewide totals. N = 23 277 523 pixels

	2001			2006			2011		
	Statewide value	SD	Range	Statewide value	SD	Range	Statewide value	SD	Range
Carbon storage (total Tg)	297	–	–	312	–	–	325	–	–
Harvest (Total m^3)	289 702	–	–	347 228	–	–	261 837	–	–
Habitat quality (unitless)	70	40	0–100	69	40	0–100	68	40	0–100
Nitrogen export (kg ha^{-1})	1·13	0·41	0–5·75	1·15	0·42	0–5·75	1·16	0·42	0–5·75
Phosphorus export (kg ha^{-1})	0·14	0·08	0–1·57	0·15	0·08	0–1·57	0·15	0·08	0–1·57
Impervious surface (ha (total)/% of state)	201 240/9·6	–	–	207 528/9·9	–	–	213 817/10·2	–	–
Run-off (mm year^{-1})	853	186	161–1464	855	188	161–1464	858	194	161–1464
Recreation	8·2	19·3	0–100	8·8	19·9	0–100	9·3	20	0–100

decade with no trend over time. These figures are consistent with the long-term averages within the data base, which spans 1984–2014. Reported harvest yields per event ranged from 0 to 7334 m^3 during the study period (Fig. 3). Harvesting frequency increased along an east to west gradient.

CULTURAL: RECREATION

The average recreation score for the state increased by about 13·5% during the study period, from a statewide average recreation index of 8·2 to 9·3 (Table 1). Small patches of high-scoring recreational areas were clustered

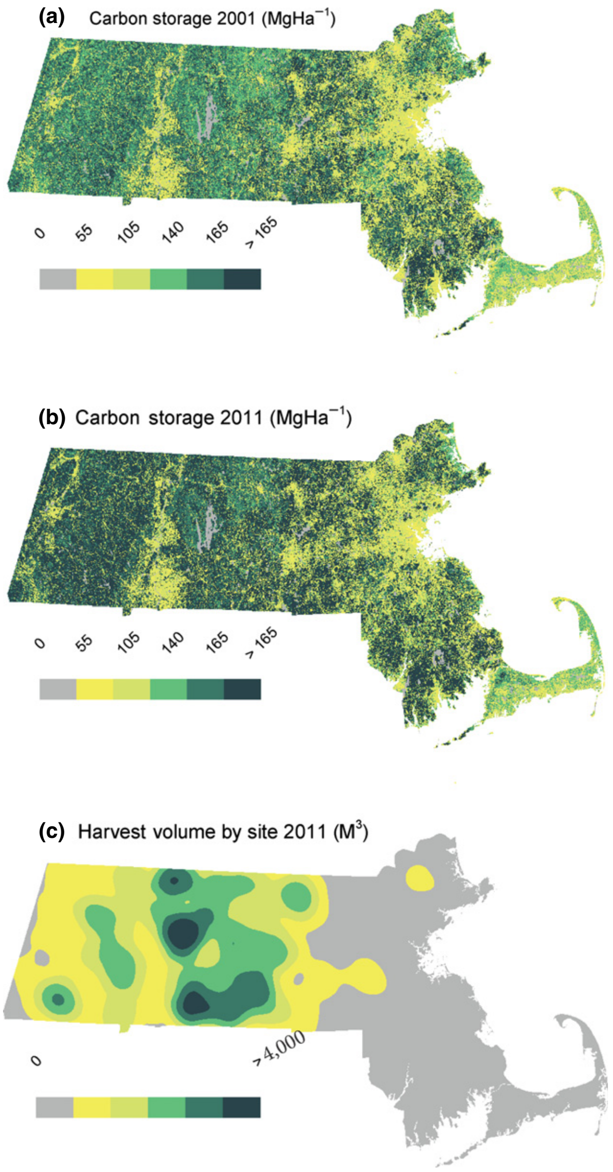

Fig. 4. Carbon stored above-ground and in soil in (a) 2001 and (b) 2011. (c) Forest harvested in 2011, categorized by size of harvests (m^3).

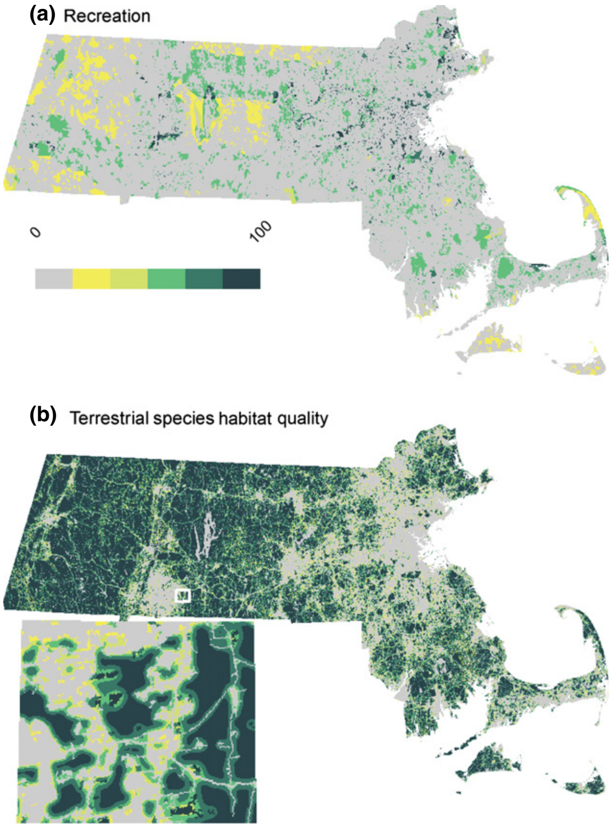

Fig. 5. (a) Recreation results (unitless), where grey are non-recreational areas and dark green are highest rated recreational locations. (b) General terrestrial species habitat quality (unitless), where grey represents non-habitat and dark green is intact, interior habitat.

near cities while larger tracts of lower-scoring areas were concentrated in the western half of the state.

HABITAT CONSERVATION: TERRESTRIAL SPECIES HABITAT

The quality of terrestrial habitat, or the quality of intact natural areas, fell steadily throughout the study period, declining by 2·8% overall in the state (Table 1). Habitat declined as forest, grasslands, wetlands and agricultural lands were converted to developed land uses and became more degraded by the radiating influence of development (Fig. 5b). The greatest declines occurred in the east and south in areas with the greatest rise in conversion of forests to developed uses (Fig. 5b).

SPATIAL RELATIONSHIP AMONG ECOSYSTEM SERVICES

Several of the ecosystem service variables are intercorrelated. The water services are most correlated, with nitrogen and phosphorus retention being the highest ($r = 0{\cdot}93$, $P < 0{\cdot}05$ in 2011), followed by pervious surface and inverse run-off ($r = 0{\cdot}48$, $P < 0{\cdot}05$) (Table 2). Forest-based resources were less correlated with the exception of habitat quality and pervious surface (0·65, $P < 0{\cdot}05$). To ensure that our results were not affected by the collinearity among services and that each contained enough unique information to be retained in the hotspot analysis, we conducted a separate hotspot analysis using only those services with correlations <0·5. Our results were robust to the number of services included; thus, we retained all services within the following results and discussion (Table 2, Tables S8–S14).

Regardless of the scale of delineation, roughly 25% of the state is a 'coldspot' or does not produce a high value of any ecosystem services. Another 72% of the state is a 'warmspot' or produces 1–4 high-valued (top 20th percentile) ecosystem services (Fig. 6). Only a small percentage (<3%) of the total area of Massachusetts is ever classified as hotspots or producing >5 high-valued ecosystem services. However, the relative area in hotspots increased

Table 2. Pairwise Spearman correlations between ecosystem services in 2011, based on a random sample of 1000 30-m pixels with a minimum spacing of 1000 m. Only 2011 data are shown because significant correlations remained consistent from year to year. Nitrogen and phosphorus is a measure of the amount of nutrient retained per pixel as a fraction of the amount exported by the watersheds in the state

	Carbon storage	Harvest	Habitat quality	Pervious surface	Nitrogen retention/export	Phosphorus retention/export	Recreation	Inverse run-off
Carbon storage	1							
Harvest	0·07	1						
Habitat quality	0·29	0·07	1					
Pervious surface	0·41	0·09	0·65	1				
Nitrogen Retention/export	0·07	NS	0·06	0·10	1			
Phosphorus Retention/export	NS	NS	0·09	NS	0·93	1		
Recreation	0·17	NS	0·29	0·18	NS	0·10	1	
Inverse run-off	0·18	NS	0·30	0·48	0·13	0·08	NS	1

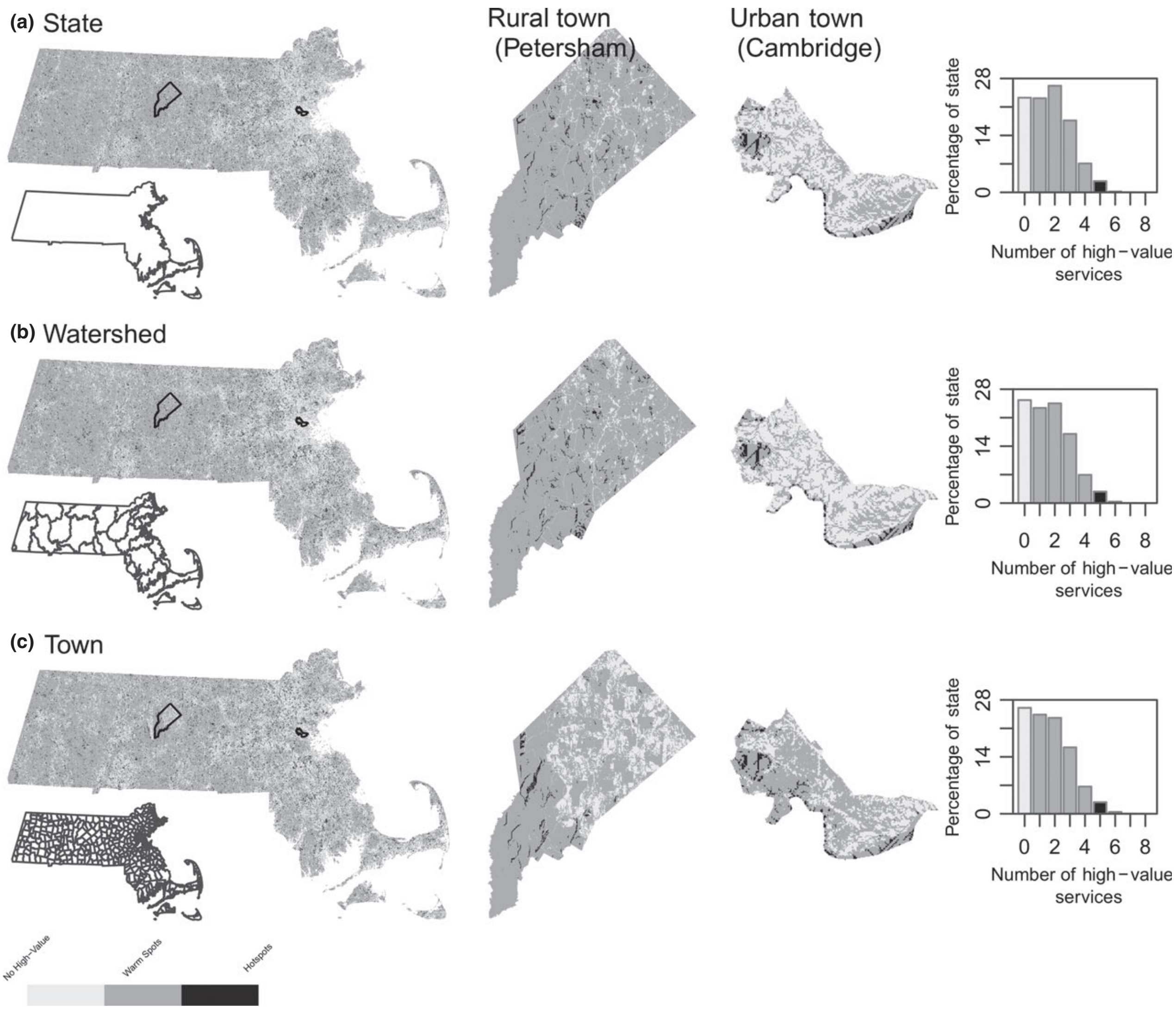

Fig. 6. Results of the hotspot analysis at multiple scales, represented by statewide and with town insets: (a) state, (b) watershed and (c) town. The lightest grey are areas where no services are produced at the top 20th percentile, medium grey are areas that produce less than five high-value services, and the darkest colour are hotspot areas, where five or more services are produced in the top 20th percentile.

Table 3. Area (ha) of hotspots by year and spatial scale of delineation. Hotspots are defined as areas where >5 high-value (top 20th percentile) ecosystem services overlap, mapped at a 30-m resolution

	2001	2006	2011
State	59 898	60 280	61 442
Watershed	63 336	64 486	66 011
Town	66 090	67 367	68 739

through time and when delineating at smaller spatial scales, for example at the town scale (Table 3, Fig. 6). At the state scale, the area of land in hotspots increases over time by about 3%, from around 59 898 ha in 2001 to 61 442 ha in 2011, or 2·8 to 2·9% of the state, while the area of land in hotspots at both the town and watershed scales increases by about 4% over the 10-year period. Analysing the value of services at the scale of individual towns resulted in the greatest amount of land categorized as hotspots, with a range from 66 090 ha in 2001 to 68 739 ha in 2011, or from 3·2 to 3·3% of the state, which is 10 to 12% greater than the area of land in hotspots when categorized at the state level (Table 3, Fig. 6).

Discussion

While forest remains the dominant cover class in Massachusetts, forested area is declining as it is converted for urban and suburban uses. This was seen most dramatically at the western fringe of the Boston metropolitan area along the so-called sprawl frontier, where high rates of forest conversion are linked to a decline in most of the ecosystem services we evaluated (five of eight variables) (sensu DeNormandie 2009) (Fig. 1). The rate of forest loss was lower in the second half of the decade, coinciding with a national economic recession that began in 2008. Such shifts in the land-use regime are a reminder that the rate of land-use change, particularly in the densely populated regions, can change quickly and that our analysis may not capture longer term trends. Nonetheless, our findings suggest that the reversal of the forest transition in the north-east, (e.g. Jeon, Olofsson & Woodcock 2014), is reconfiguring the quantity and spatial distribution of ecosystem service provisioning. Whereas once large blocks of forest area provided multiple services that benefited people across the state, increasingly, if land-use trends continue, smaller patches of remaining forest in urbanizing watersheds will be necessary to supporting place-based services for increasing numbers of people.

Ecosystem service hotspots cover a small area of Massachusetts (<3% of the state regardless of the scale of delineation). This finding is consistent with other analyses conducted in other regions, some of which used very different methods for designating hotspots including absolute as opposed to relative thresholds, for example, in Wisconsin (Qiu & Turner 2013) and Australia (Crossman & Bryan 2009). The rarity of hotspots reflects the inherent limitations to obtaining a high supply of multiple disparate services from a single area. While no combination of the services we examined is mutually exclusive, they all have unique spatial distributions that reflect their unique relationship to a complex social and biogeographical landscape. For example, outdoor recreation benefits from proximity to population centres while habitat benefits from large blocks of unfragmented natural land. Consequently, about a quarter of the state provides a high value for a single ecosystem service and another quarter provides a high value for two services. Nevertheless, while hotspots may constitute a small percentage of the state, it is still a nontrivial area – between 60 000 and 70 000 ha in 2001 – depending on the scale of delineation. These sites have a disproportionately high conservation value since any degradation of these sites would result in the loss of multiple high-value services.

While still small in percentage terms, the absolute area of hotspots increased over time, by 3–4%, depending on the scale of delineation. The increase in hotspots is a consequence of forest loss and loss of other natural land cover, which has concentrated ecosystem service provisioning onto smaller areas. As a result, the remaining natural areas are more likely to provide high values for multiple services. The Massachusetts landscape is currently spatially diversified with regard to the services it provides; however, continued loss of natural land cover will drive a bifurcation of the landscape into sites that have little or no ecosystem service value and sites that are relied upon to provide a broader suite of services. Similar patterns were documented by Jiang, Bullock & Hooftman (2013) who found that as land was converted to agriculture and intensified in Dorset, UK, services were lost and the remaining services became more unequally distributed on the landscape. Such trends are reminders that while hotspots have high conservation value, more are not necessarily better. Indeed, a proliferation of hotspots may be an indicator that the landscape is being forced to do more with less (provide a higher concentration of services in a smaller area).

The spatial scale of delineation also affected the quantity and configuration of hotspots. Again, this reflects the connection between hotspots and the ratio of built areas to natural ecosystems. The area of hotspots increased as the spatial scale of delineation got smaller, with 11% more of the state in hotspots when they were identified at the town scale as compared to the state scale. In addition, there was an eastward shift in hotspot abundance when measured at the town scale, coincident with decreasing relative abundance of forests in towns closer to Boston and the coast. The town maps shown in Fig. 6 offer a clear example of the reduction of hotspots in the rural town of Petersham and, conversely, the increase in hotspots in the city of Cambridge. The effect of spatial scale on the identification of hotspots indicates that land use designed to ensure the sustainable production of ecosystem services must consider critical place-based services that cannot be substituted by production of that service elsewhere. Indeed, a determination of the scale at which a service analysis should be undertaken must take into account the scale of service provisioning, the scale of decision-making and also the scale of demand for that service. In this analysis, our scope was limited to the former two points, and while we did not explicitly include an analysis of demand, we recognize this as an important consideration for our future efforts.

CONCLUSION

Similar to previous studies from other regions, our findings show that service provisioning in Massachusetts is spatially heterogeneous and few areas provide high values for multiple services (e.g. Jiang, Bullock & Hooftman 2013; Qiu & Turner 2013). Their rarity notwithstanding, the area of hotspots is increasing rapidly as services are concentrated onto a diminished natural land base. Further, we found that the scale at which hotspots are assessed strongly affects their abundance and spatial distribution; when hotspots are delineated at the town scale, they are more abundant overall and particularly within more urbanized parts of the state where natural land is rarer and, thus, more relied upon for service provisioning. Overall, the study indicates that while some ecosystem services co-occur, high spatial heterogeneity of service provisioning makes managing for 'bundles of ecosystem services' (sensu Raudsepp-Hearne, Peterson & Bennett 2010) have limited applicability in this region. This is in contrast to landscapes where agriculture is a dominant land use and trade-offs between provisioning and other types of services are more pronounced. Finally, this study underscores the importance of considering spatial scale when delineating hotspots for conservation prioritization and argues that local-scale hotspots may identify small but important sites that would be overlooked by regional-scale analyses (sensu, Cumming, Cumming & Redman 2006).

Conservationists have long argued about the relative value of a single large or several small reserves for biodiversity conservation (i.e. the SLOSS debate (Simberloff & Abele 1976)); the strong effects of spatial scale on the identification of high-value sites for ecosystem services suggest that these concepts may need to be revisited in the context of more contemporary conservation settings and rubric. Indeed, there is a strong push for large landscape conservation in Massachusetts and more broadly (e.g. Mckinney, Scarlett & Kemmis 2010), and these efforts may underestimate the concentration of important services emanating from small, urban and suburban forests, fields and wetlands. Therefore, the results of this hotspot analysis suggest that achieving the sustained delivery of ecosystem services from nature requires a whole-landscape approach that considers the scales at which key services operate and combines conservation priorities identified through a large landscape lens with those delineated through a finer-scale approach. In practice, this could represent bringing together the thinking and priorities of the large landscape conservation practitioners with the green infrastructure conservation leaders in areas where loss of forest to development is changing the distribution of critical services.

Acknowledgements

Funding was provided by an NSF Long Term Ecological Research grant to Harvard Forest (DEB-1237491). We thank Matthew Duveneck, David Foster and Kathy Fallon Lambert for helpful comments on an earlier draft of this manuscript and Jennifer Fish at the MA Department of Conservation and Recreation for facilitating access to the timber harvest data base.

Data accessibility

R and Python scripts and Initial Data Files have been uploaded on to Harvard Forest's Data Archive, http://harvardforest.fas.harvard.edu/harvard-forest-data-archiveas HF245; http://doi.org/10.6073/pasta/8914b507d3385c15ee9fe353557e1950.

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Received 8 September 2014; accepted 15 April 2015
Handling Editor: Ralph Mac Nally

Supporting Information

Additional Supporting Information may be found in the online version of this article.

Appendix S1. Land-cover maps from NLCD.

Appendix S2. Detailed methods for quantifying ecosystem service and habitat quality variables.

Appendix S3. Hotspot sensitivity analysis.

Table S1. NLCD land-cover classifications used.

Table S2. Carbon values assigned to each LULC.

Table S3. Proportions of impervious surface by LULC.

Table S4. InVEST biophysical table input.

Table S5. Measure and weights used to create recreation layers.

Table S6. InVEST sensitivity table input.

Table S7. InVEST threat table input.

Table S8. Results of the hotspot Analysis.

Table S9. Results of the hotspot analysis if criteria switched to the top 30th percentile.

Table S10. Results of the hotspot analysis if criteria switched to the top 10th percentile.

Table S11. Results of the hotspot analysis if nitrogen retention removed.

Table S12. Results of the hotspot analysis if water runoff removed.

Table S13. A comparison of the percentile criteria change results.

Table S14. A comparison of the dropped services results.