

A COMPARISON OF LANDSAT ETM+
AND HIGH-RESOLUTION AERIAL
ORTHOPHOTOS TO MAP URBAN/
SUBURBAN FOREST COVER IN
MASSACHUSETTS, USA

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A Comparison of Landsat ETM+ and High-Resolution Aerial Orthophotos to Map Urban/Suburban Forest Cover in Massachusetts, USA

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Abstract: This paper examines the extent to which L(ow)-spatial resolution Landsat Enhanced Thematic Mapper Plus (ETM+) imagery can be used to map urban/suburban forest cover in comparison to H(igh)-spatial resolution (less than 1 m) digital aerial orthophotos from the same study area and time period. This research has practical implications for resource managers, government agencies, and forestry researchers interested in mapping large-area urban/suburban forests because Landsat imagery is more accessible, has an extensive historical archive, has broader spatial and temporal coverage, and is more cost efficient than H-resolution aerial orthophotos. Classification tree results suggest that Landsat ETM+ imagery is adequate for mapping larger, contiguous patches of forest (i.e. small forest patches greater than 2 acres) in urban/suburban settings, but its spatial resolution is too coarse to accurately map spatially complex residential areas in urban/suburban landscapes.

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1. Introduction

Forests provide numerous environmental benefits to urban/suburban settings, including reduction of urban heat island effects (Nichol 1996), enhanced water and air quality (McPherson 2006), regulation of storm water drainage and runoff, and provision of wildlife habitat (Nichol 2009). Urban forests also provide many societal benefits, such as recreational space, improved community stability, identity, and pride (Grove *et al.* 2005), reduction of violent behavior and crime (Kuo and Sullivan 2001), and reduction of automobile noise pollution (Lohr *et al.* 2004). Consequently, urban/suburban forests have recently garnered increased attention from resource managers, local, state, and federal agencies, and forestry researchers.

This increased attention to forests is evident in both urban and suburban environments. In densely populated urban areas, existing trees and trees planted through urban greening projects are of interest because of the rapid global increase in urban populations, which is currently at its highest point in human history and is projected to continue to increase (Nowak and Walton, 2005, Seto *et al.* 2010). As a result, the number of urban forest inventories has risen in recent years in the United States, with examples in New York City (Grove *et al.* 2006), Baltimore (O’Neil-Dunne, 2007), Boston (Urban Ecology Institute, 2008), and Philadelphia (O’Neil-Dunne, 2011), to name a few. Suburban settlement—the growth and development of areas on the peripheries of cities—is growing at a faster rate than the population in urban areas, and the percentage of developed land in the United States is predicted to increase from 5.2% to 9.2% by 2025 (Grove *et al.* 2005, Troy *et al.* 2007). Increasing suburbanization is a direct threat to forests because it transforms forests and other land-use/land-covers to impervious surfaces (i.e. buildings, roads, parking lots), which can impact downstream biogeochemical and hydrological processes from water infiltration and increased storm water runoff. Based on the considerable environmental and societal benefits of forests and the rapid global population increases in both urban and suburban areas, it is vital to consistently map and monitor the spatial and temporal changes of urban/suburban forest cover (Zhou and Troy 2008, Tooke *et al.* 2009).

Remotely sensed data have been extensively used to map urban/suburban forest cover by local, regional, and federal organizations such as the United States Forest Service (USFS), Natural Resources Conservation Service (NRCS) (Iverson and Cook 2000), United States Environmental Protection Agency (EPA), United States Geological Survey (USGS), National Oceanic and Atmospheric Administration (NOAA) (Homer *et al.* 2007, Yang 2008), Research Triangle Institute (RTI) International, and the Environmental Defense Fund (Mansfield *et al.* 2005). Recent studies have focused on the use of H-resolution satellite imagery or aerial orthophotos to map urban/suburban forest cover due to its ability to characterize fine-scaled urban vegetation types such as lawns, open areas, wetlands, recreational spaces, and conifer/hardwood trees (Akbari *et al.* 2003, Thomas *et al.* 2003, Small and Lu 2006). However, most H-resolution remotely sensed datasets are costly, have a limited archive of historical imagery, have scene extents that are not sufficient for large area mapping and monitoring projects, and have inconsistent temporal coverage (Rogan and Chen, 2004).

Table 1 presents a comparison of five H-resolution datasets (IKONOS, Quickbird, Worldview-1, GeoEye-1, and aerial orthophotos) with the L-resolution Landsat dataset. The average cost per km² of H-resolution datasets is approximately \$14 U.S., while the entire Landsat archive is now freely downloadable and accessible to the public. It is important to note that the H-resolution satellite imagery addressed here has an average revisit time of two to four days, while many other H-resolution datasets (i.e. aerial orthophotos) are captured by demand

and only when cloud cover is low. Additionally, Landsat TM/ETM+ historical imagery dates back to 1982, while most H-resolution satellite imagery is only available since 1999, when the U.S. Department of Commerce first permitted the commercial acquisition and distribution of H-resolution imagery (Fritz, 1996). Furthermore, the ratio of the areal extent of a Landsat scene to the average scene size from the five H-resolution datasets is one to 160, which implies that approximately 160 H-resolution image scenes would be required to equal the spatial coverage of one Landsat scene.

The objective of this research is to determine how effectively L-resolution Landsat ETM+ imagery can be used to map urban/suburban forest cover in comparison to a classification generated from sub-metre H-resolution aerial orthophotos. Landsat TM/ETM+ is of particular interest to this study because of its extensive archive of historical imagery, broad areal coverage, 16-day revisit cycle, and free availability and access (Small 2001). Additionally, this study builds on and contributes to a series of ongoing assessments of suburban sprawl, land-use/land-cover change, and forest cover change, which are three major environmental challenges faced by the state of Massachusetts (Rogan *et al.* 2010, Fortier *et al.* 2011). This study can have practical implications for resource managers, government agencies, or other researchers who lack the financial and personnel resources to capture and process H-resolution imagery for large study areas, but want to obtain accurate areal and spatial estimates of urban/suburban forest cover.

2. Study area and data

The town of Lynnfield (42°32'20.36"N, 71°02'53.19"W) in northeastern Massachusetts, USA covers 27 km². Lynnfield is located within the Greater Boston metropolitan region, one of the most rapidly suburbanizing regions in the United States. Between 1980 and 2000, the ratio of developed land area increase to population increase in the Boston metropolitan region was over four to one (Otto *et al.* 2002). Forest abundance varies spatially throughout Lynnfield, from large contiguous patches in the northern and southern portion of the town to smaller patches interspersed within the low/medium density residential areas in the town centre. Dominant forest types include hardwood red maple (*Acer rubrum*) and red oak (*Quercus rubra*) species, and conifer white pine (*Pinus strobus*) species (Hall *et al.* 2002).

Two Landsat ETM+ images (path 12, row 30) were captured on 1 May 2004 and 4 July 2004 to represent leaf-off and leaf-on conditions, respectively. These dates were chosen because of the availability of cloud-free images with the closest temporal match to the aerial orthophotos that were used in the H-resolution classification. Both image dates were affected by the post-2003 Scan Line Corrector (SLC) error, but Lynnfield fell within an un-affected location in the scene and was therefore clipped from the image. The Landsat images were radiometrically calibrated to at-sensor reflectance and path radiance effects were removed using the Cos(t) model (Chavez 1996). The Landsat images were geometrically corrected prior to acquisition using the Level 1T Standard Terrain Correction method (Roy *et al.* 2010), and a qualitative assessment using a GIS road centerlines layer confirmed that further geometric correction was unnecessary.

The H-resolution aerial orthophotos are 8-bit, 0.5 m spatial resolution, 4-band (visible and near-infrared) orthorectified aerial photographs taken between 9 and 17 April 2005. The H-resolution classification was performed using object-based image analysis (OBIA) methods and a nearest neighbour classification algorithm (Burnett and Blaschke 2003). The minimum mapping unit of the classification was 6 m². An accuracy assessment showed that the H-

resolution classification agreed with a photo interpretation of the aerial orthophotos over 78% of the landscape and the forest class agreed over 95% of the landscape. The H-resolution map contains seven land-cover classes (bare soil, conifer forest, hardwood forest, grass/lawn, impervious surfaces, water, and wetlands). Ancillary data included a GIS layer of Massachusetts Department of Environmental Protection (DEP) wetlands. The aerial orthophotos and ancillary data were obtained from the Massachusetts Geographic Information Systems office (MassGIS). For a more detailed explanation of the methods used to create the H-resolution classification, see <http://hero.clarku.edu/holmes/>.

3. Methods

The methods used to generate the Landsat-based classifications and the comparison statistics to the H-resolution classification involved three steps: (i) Spectral Mixture Analysis, (ii) classification tree analysis, and (iii) map comparison and area analysis.

Spectral Mixture Analysis (SMA) extracts landscape feature proportions from within individual L-resolution pixels, where the spectral value of each pixel is a linear combination of biophysical endmember fraction values. In this study, SMA was used to derive fraction images for four image endmembers (forest, grass/lawn, urban/impervious, and water/shade) that were chosen based on the Lu-Weng urban landscape model (Lu and Weng 2004). Training sites for the four endmembers were selected via photo-interpretation of a 0.5 m resolution aerial orthophoto. SMA was performed on bands 1-5 and 7 from both the leaf-off and leaf-on Landsat ETM+ images. Outputs included fraction images for each endmember indicating the percent of that endmember within each Landsat image pixel and a residual image for each Landsat image date indicating how closely the actual pixel values match the calculated mixture of endmembers.

The Landsat classifications were created using classification tree analysis. A stratified random sample of 157 training sites were selected from the forest, grass/lawn, urban/impervious, and water classes in the H-resolution classification map for the classification tree calibration and recursive splits were performed using the Gini split rule (Zambon *et al.* 2006). Classification was performed on three subsets of input image bands. The first two subsets included the four fraction images (forest, grass/lawn, urban/impervious, and water/shade) generated by the SMA from the leaf-off and leaf-on Landsat ETM+ images, respectively. The third subset was a combination of all eight fraction images from both the leaf-off and leaf-on images. Figure 1 shows an example of the classification tree from the third subset (leaf-off/leaf-on combination).

Following classification tree analysis, the three Landsat output maps (leaf-off, leaf-on, and the leaf-off/leaf-on combination) were vectorized and the ancillary wetlands GIS layer was merged with each of the three output maps such that wetland areas were included in the Landsat-derived classifications. The final step was to calculate the forest quantity (km^2) in each of the three Landsat classifications for comparison to the forest quantity in the H-resolution classification.

4. Results

The maps of the three Landsat classifications and the H-resolution classification are presented in figure 2. In the H-resolution classification, 12.88 km^2 were classified as forest, accounting for about 48% of the study area. Of the three Landsat classifications, the combination leaf-off/leaf-on subset provided the nearest estimation of quantity of overall forest area when compared to the

H-resolution forest quantity (14.03 km², or 52% of the study area). These statistics indicate that there was a 1.15 km² (8.9%) difference in forest quantity between the Landsat leaf-off/leaf-on and H-resolution classifications.

In addition to comparing the differences in forest quantity between the Landsat and H-resolution classifications, we examined the differences in terms of spatial allocation, which occurs when a given quantity of pixels in category x is spatially allocated differently in two different maps (Pontius and Millones 2011). The results presented in table 2 show the locations of spatial agreement and disagreement between the Landsat leaf-off/leaf-on classification and the H-resolution classification. 73% of the area classified as forest in the Landsat leaf-off/leaf-on classification spatially corresponded to areas classified as forest in the H-resolution classification. The other 27% of the area classified as forest in the Landsat classification was Landsat commission error, meaning it was not classified as forest in the H-resolution classification. Additionally, 21% of the area classified as forest in the H-resolution classification was not classified as forest in the Landsat classification.

The results presented in table 2 are also shown in the binary maps in figure 3. Shaded areas in figure 3a represent locations where the Landsat leaf-off/leaf-on and H-resolution forest classifications were in spatial agreement. The shaded areas in Figure 3b show locations where the *only* the Landsat image was classified as forest (i.e. Landsat commission error), while the shaded areas in figure 3c show locations where *only* the H-resolution image was classified as forest (i.e. Landsat omission error). Finally, the relative proportions of the H-resolution land-covers contained within the area classified as Landsat commission error (figure 4) were as follows: 49% urban/impervious surface, 36% grass/lawn, 11% bare soil, 2% water, and just over 1% wetlands.

5. Conclusion

Landsat imagery is widely available, freely accessible, has broad spatio-temporal coverage, and has an extensive historical archive. Therefore, it is attractive to resource managers, local, state, and federal agencies, and researchers who are interested in mapping and monitoring large areas of urban/suburban forest cover but may lack the resources to acquire and process more costly H-resolution satellite imagery or aerial orthophotos. This paper offers an example of how urban/suburban forest cover can be mapped from Landsat imagery in comparison to an object-based image analysis classification of an H-resolution aerial orthophoto from the same study area and time period.

Results indicate that the Landsat leaf-off/leaf-on forest classification had 73% spatial agreement with the H-resolution forest classification. This 73% spatial agreement in Landsat and H-resolution forest areas is generally located in larger, contiguous forest patches in the northern and southern portions of the study area. Conversely, 27% of Landsat forest area that did not spatially agree (Landsat commission error) with the H-resolution forest classification was mainly composed of urban/impervious (49%) and grass/lawn (36%) surfaces in the central portion of the town. In other words, 85% of the area that was Landsat forest commission error was composed of roads, sidewalks, houses, driveways, and residential lawns—all characteristic features of the fragmented, spatially complex nature of the residential suburban landscape. This suggests that Landsat imagery is adequate for mapping larger, contiguous patches of forest (i.e. small urban forests greater than 2 acres) in urban/suburban settings, but its spatial resolution is too coarse to accurately map highly fragmented residential areas in urban/suburban landscapes.

In this study, the inputs to the classification tree were solely image derived and included no ancillary datasets. Recent research has shown that the inclusion of ancillary non-remote sensing data such as elevation, slope, and aspect derived from digital elevation models (DEMs) is useful in discriminating land-cover categories where spectral-radiometric data fails to discriminate the categories. The inclusion of these ancillary datasets has reportedly led to higher overall map accuracies of up to 5 to 10 percentage points (Rogan *et al.* 2003). Incorporating texture information and spatial detail by including the Landsat panchromatic band (15 m spatial resolution) has also been reported to improve classification accuracies, particularly in complex urban/suburban landscapes (Lu and Weng 2005). Future research will incorporate both ancillary DEM and finer resolution panchromatic data, as we hypothesize that a data-fused Landsat product and information regarding elevation may increase the classification tree's ability to discriminate land-cover classes, in particular spectrally similar classes such as forest and grass/lawn.

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References

- AKBARI, H., SHEA ROSE, L. and TAHA, H., 2003, Analyzing the land cover of an urban environment using high-resolution orthophotos. *Landscape and Urban Planning*, **63**, pp. 1-14.
- BURNETT, C. and BLASCHKE, T., 2003, A multi-scale segmentation/object relationship modeling methodology for landscape analysis. *Ecological Modelling*, **168**, pp. 233-249.
- CHAVEZ, P.S., 1996, Image-based atmospheric corrections – revisited and improved. *Photogrammetric Engineering and Remote Sensing*, **62**, pp. 1025-1036.
- FORTIER, J., ROGAN, J., WOODCOCK, C.E., and RUNFOLA, D.M., 2011, Utilizing temporally invariant calibration sites to classify multiple dates and types of satellite imagery. *Photogrammetric Engineering and Remote Sensing*, **72**, pp. 181-189.
- FRITZ, L.W., 1996, Commercial Earth observation satellites. In *The International Archives of Photogrammetry and Remote Sensing*, Vol. XXXI. Part B4. 1996, Vienna, Austria, pp. 273-282.
- GROVE, J.M., BURCH, W.R. and PICKETT, S.T.A., 2005, Social mosaics and urban forestry in Baltimore, Maryland. In *Communities and Forests: Where People Meet the Land*, R.G. Lee and D.R. Field, pp. 248-273 (Corvallis, OR: Oregon State University Press).
- GROVE, J.M., O'NEIL-DUNNE, J., PELLETIER, K., NOWAK, D., and WALTON, J., 2006, A report on New York City's present and possible urban tree canopy. United States Department of Agriculture, Forest Service, Northeastern Area, South Burlington, Vermont.
- HALL, B., MOTZKIN, G., FOSTER, D.R., SYFERT, M. and BURK, J., 2002, Three hundred years of forest and land-use change in Massachusetts, USA. *Journal of Biogeography*, **29**, pp. 1319-1335.
- HOMER, C., DEWITZ, J., FRY, J., COAN, M., HOSSAIN, N., LARSON, C., HEROLD, N., MCKERROW, A., VANDRIEL, J.N. and WICKHAM, J., 2007, Completion of the 2001 national land cover database for the conterminous United States. *Photogrammetric Engineering and Remote Sensing*, **73**, pp. 337-341.
- IVERSON, L.R. and COOK, E.A., 2000, Urban forest cover of the Chicago region and its relation to household density and income. *Urban Ecosystems*, **4**, pp. 105-124.
- KUO, F.E. AND SULLIVAN, W.C., 2001, Environment and crime in the inner city: does vegetation reduce crime? *Environment and Behavior*, **33**, pp. 347-367.
- LOHR, V.I., PEARSON-MIMS, C.H., TARNAI, J. and DILLMAN, D.A., 2004, How urban residents rate and rank the benefits and problems associated with trees in cities. *Journal of Arboriculture*, **30**, pp. 28-35.
- LU, D. and WENG, Q., 2004, Spectral mixture analysis of the urban landscape in Indianapolis with Landsat ETM+ imagery. *Photogrammetric Engineering and Remote Sensing*, **70**, pp. 1053-1062.
- LU, D. and WENG, Q., 2005, Urban classification using full spectral information of Landsat ETM+ imagery in Marion County, Indiana. *Photogrammetric Engineering and Remote Sensing*, **71**, pp. 1275-1284.
- MCPHERSON, E.G., 2006, Urban forestry in North America. *Renewable Resources Journal*, **24**, pp. 8-12.

- MANSFIELD, C., PATTANAYAK, S.K., MCDOW, W., MCDONALD, R. and HALPIN, P., 2005, Shades of green: measuring the value of urban forests in the housing market. *Journal of Forest Economics*, **11**, pp. 177-199.
- NICHOL, J., 1996, High resolution surface temperature patterns related to urban morphology in a tropical city: a satellite-based study. *Journal of Applied Meteorology*, **35**, pp. 135-146.
- NICHOL, J., 2009, Remote sensing of urban areas. In *The SAGE Handbook of Remote Sensing*, T.A. Warner, M.D. Nellis, and G.M. Foody (Eds.), pp. 423-436 (London: SAGE Publications, Ltd.).
- NOWAK D.J., and WALTON, J.T., 2005, Projected urban growth (2000-2050) and its estimated impact on the U.S. forest resource. *Journal of Forestry*, **103**, pp. 383-389.
- O'NEIL-DUNNE, J., 2007, A report on the city of Baltimore's existing and possible urban tree canopy. United States Department of Agriculture, Forest Service, Northeastern Area, South Burlington, Vermont.
- O'NEIL-DUNNE, J., 2011, A report on the city of Philadelphia's existing and possible urban tree canopy. United States Department of Agriculture, Forest Service, Northeastern Area, South Burlington, Vermont.
- OTTO, B., RANSEL, K., TODD, J., LOVAAS, D., STUTZMAN, H. and BAILEY, J., 2002, Paving our way to water shortages: how sprawl aggravates the effects of drought. Available online at: <http://www.smartgrowthamerica.org/documents/DroughtSprawlReport09.pdf>. (accessed 15 July 2011).
- PONTIUS JR., R.G., and MILLONES, M., 2011, Death to kappa: Birth of quantity disagreement and allocation disagreement for accuracy assessment. *International Journal of Remote Sensing*, **32**, pp. 4407-4429.
- ROGAN, J., MILLER, J., STOW, D., FRANKLIN, J., LEVIEN, L., and FISCHER, C., 2003, Land-cover change monitoring with classification trees using Landsat TM and ancillary data. *Photogrammetric Engineering and Remote Sensing*, **69**, pp. 793-804.
- ROGAN, J. and CHEN, D., 2004, Remote sensing technology for mapping and monitoring land-cover and land-use change. *Progress in Planning*, **61**, pp. 301-325.
- ROGAN, J., BUMBARGER, N., KULAKOWSKI, D., CHRISTMAN, Z.J., RUNFOLA, D.M., and BLANCHARD, S.D., 2010, Improving forest type discrimination with mixed lifeform classes using fuzzy classification thresholds informed by field observations. *Canadian Journal of Remote Sensing*, **36**, pp. 699-708.
- ROY, D.P., JU, J., KLINE, K., SCARAMUZZA, P.L., KOVALSKYY, V., HANSEN, M., LOVELAND, T.R., VERMOTE, E., and ZHANG, C., 2010, Web-enabled Landsat data (WELD): Landsat ETM+ composited mosaics of the coterminous United States. *Remote Sensing of Environment*, **114**, pp. 35-49.
- SETO, K.C., SANCHEZ-RODRIGUEZ, R. and FRAGKIAS, M., 2010, The new geography of contemporary urbanization and the environment. *Annual Review of Environment and Resources*, **35**, pp. 167-194.
- SMALL, C., 2001, Estimation of urban vegetation abundance by spectral mixture analysis. *International Journal of Remote Sensing*, **22**, pp. 1305-1334.
- SMALL, C. and LU, J.W.T., 2006, Estimation and vicarious validation of urban vegetation abundance by spectral mixture analysis. *Remote Sensing of Environment*, **100**, pp. 441-456.

- THOMAS, N., HENDRIX, C. and CONGALTON, R.G., 2003, A comparison of urban mapping methods using high-resolution digital imagery. *Photogrammetric Engineering and Remote Sensing*, **69**, pp. 963-972.
- TOOKE, T.R., COOPS, N.C., GOODWIN, N.R., and VOOGT, J.A., 2009, Extracting urban vegetation characteristics using spectral mixture analysis and decision tree classifications. *Remote Sensing of Environment*, **113**, pp. 398-407.
- TROY, A.R., GROVE, J.M., O'NEIL-DUNNE, J.P.M., PICKETT, S.T.A. and CADENASSO, M.L., 2007, Predicting patterns of vegetation and opportunities for greening on private urban lands. *Environmental Management*, **40**, pp. 394-412.
- URBAN ECOLOGY INSTITUTE, 2008, State of the urban forest: A summary of the extent and condition of Boston's urban forest. Urban Ecology Institute, Cambridge, Massachusetts.
- YANG, L., 2008, Development of the United States national land cover database: experience from 1992 and 2001 implementation. In *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, Vol. XXXVII. Part B4. 2008, Beijing, China (Sioux Falls: USGS), pp. 1461-1466.
- ZAMBON, M., LAWRENCE, R., BUNN, A. and POWELL, S., 2006, Effect of alternative splitting rules on image processing using classification tree analysis. *Photogrammetric Engineering and Remote Sensing*, **72**, pp. 25-30.
- ZHOU, W. and TROY, A.R., 2008, An object-oriented approach for analysing and characterizing urban landscape at the parcel level. *International Journal of Remote Sensing*, **29**, pp. 3119-3135

Table 1. Comparison of five H-resolution sensors and the Landsat sensor in terms of historical coverage, spatial resolution, areal coverage, temporal resolution, and cost.

Sensor mission	Organization	Operation period	Spatial resolution (m)	Swath (km)	Spectral coverage (μm)	Average revisit period	Scene extent (km^2)	Cost per km^2 (\$ U.S.)
IKONOS	GeoEye	1999-	1	11 x 11	0.45-0.90	2-3 days	121	10
Quickbird	DigitalGlobe	2001-	0.61	16.5 x 16.5	0.45-0.90	2-3 days	272.25	17
Worldview-1	DigitalGlobe	2007-	0.5	15 x 15	0.40-0.90	3-4 days	225	17
GeoEye-1	GeoEye	2008-	0.5	15 x 15	0.45-0.92	2-3 days	225	12.5
Landsat TM/ETM+	NASA/Landsat Program	1982-	15 (PAN) 30 (MS)	185 x 185	0.45-2.35	16 days	34225	0
Mass. Aerial Orthophoto Acquisition (2005)	Vexcel Corporation	By demand	0.5	4 x 4	0.40-0.90	By demand	16	Unavailable

Detailed information on most sensors can be found in Rogan and Chen (2004) and the following WebPages: www.digitalglobe.com, www.geoeye.com, and www.spatialenergy.com. ETM+, enhanced thematic mapper plus; MS, multi-spectral; NASA, National Aeronautics and Space Administration; PAN, panchromatic; TM, thematic mapper. Note: The cost of the Mass. Aerial Orthophoto Acquisition in 2005 was unavailable at this time.

Table 2. Spatial agreement and disagreement between the Landsat leaf-off/leaf-on combination classification and the H-resolution classification.

	Area (km²)	Proportion of Study Area
Landsat forest quantity	14.03	52%
H-resolution forest quantity	12.88	48%
Forest quantity in both Landsat and H-resolution classifications	10.18	38%
Forest quantity in <i>only</i> Landsat classification (Landsat commission)	3.85	14%
Forest quantity in <i>only</i> H-resolution classification (Landsat omission)	2.70	10%
	Percentage	
Percentage of Landsat forest that agreed with H-resolution forest	73%	
Percentage of Landsat forest commission error	27%	
Percentage of Landsat forest omission error	21%	

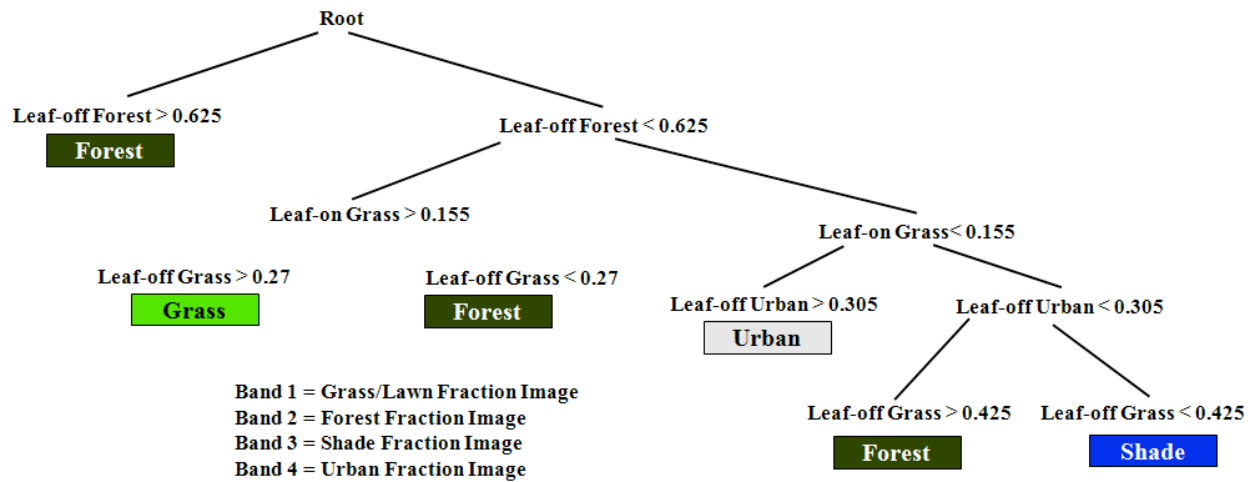


Figure 1. The classification tree model for the third image subset, containing the Landsat leaf-off/leaf-on fraction images.

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Forests provide numerous environmental benefits to urban/suburban settings, including reduction of urban heat island effects (Nichol 1996), enhanced water and air quality (McPherson 2006), regulation of storm water drainage and runoff, and provision of wildlife habitat (Nichol 2009). Urban forests also provide many societal benefits, such as recreational space, improved community stability, identity, and pride (Grove *et al.* 2005), reduction of violent behavior and crime (Kuo and Sullivan 2001), and reduction of automobile noise pollution (Lohr *et al.* 2004). Consequently, urban/suburban forests have recently garnered increased attention from resource managers, local, state, and federal agencies, and forestry researchers.

This increased attention to forests is evident in both urban and suburban environments. In densely populated urban areas, existing trees and trees planted through urban greening projects are of interest because of the rapid global increase in urban populations, which is currently at its highest point in human history and is projected to continue to increase (Nowak and Walton, 2005, Seto *et al.* 2010). As a result, the number of urban forest inventories has risen in recent years in the United States, with examples in New York City (Grove *et al.* 2006), Baltimore (O’Neil-Dunne, 2007), Boston (Urban Ecology Institute, 2008), and Philadelphia (O’Neil-Dunne, 2011), to name a few. Suburban settlement—the growth and development of areas on the peripheries of cities—is growing at a faster rate than the population in urban areas, and the percentage of developed land in the United States is predicted to increase from 5.2% to 9.2% by 2025 (Grove *et al.* 2005, Troy *et al.* 2007). Increasing suburbanization is a direct threat to forests because it transforms forests and other land-use/land-covers to impervious surfaces (i.e. buildings, roads, parking lots), which can impact downstream biogeochemical and hydrological processes from water infiltration and increased storm water runoff. Based on the considerable environmental and societal benefits of forests and the rapid global population increases in both urban and suburban areas, it is vital to consistently map and monitor the spatial and temporal changes of urban/suburban forest cover (Zhou and Troy 2008, Tooke *et al.* 2009).

Remotely sensed data have been extensively used to map urban/suburban forest cover by local, regional, and federal organizations such as the United States Forest Service (USFS), Natural Resources Conservation Service (NRCS) (Iverson and Cook 2000), United States Environmental Protection Agency (EPA), United States Geological Survey (USGS), National Oceanic and Atmospheric Administration (NOAA) (Homer *et al.* 2007, Yang 2008), Research Triangle Institute (RTI) International, and the Environmental Defense Fund (Mansfield *et al.* 2005). Recent studies have focused on the use of H-resolution satellite imagery or aerial orthophotos to map urban/suburban forest cover due to its ability to characterize fine-scaled urban vegetation types such as lawns, open areas, wetlands, recreational spaces, and conifer/hardwood trees (Akbari *et al.* 2003, Thomas *et al.* 2003, Small and Lu 2006). However, most H-resolution remotely sensed datasets are costly, have a limited archive of historical imagery, have scene extents that are not sufficient for large area mapping and monitoring projects, and have inconsistent temporal coverage (Rogan and Chen, 2004).

Table 1 presents a comparison of five H-resolution datasets (IKONOS, Quickbird, Worldview-1, GeoEye-1, and aerial orthophotos) with the L-resolution Landsat dataset. The average cost per km² of H-resolution datasets is approximately \$14 U.S., while the entire Landsat archive is now freely downloadable and accessible to the public. It is important to note that the H-resolution satellite imagery addressed here has an average revisit time of two to four days, while many other H-resolution datasets (i.e. aerial orthophotos) are captured by demand

and only when cloud cover is low. Additionally, Landsat TM/ETM+ historical imagery dates back to 1982, while most H-resolution satellite imagery is only available since 1999, when the U.S. Department of Commerce first permitted the commercial acquisition and distribution of H-resolution imagery (Fritz, 1996). Furthermore, the ratio of the areal extent of a Landsat scene to the average scene size from the five H-resolution datasets is one to 160, which implies that approximately 160 H-resolution image scenes would be required to equal the spatial coverage of one Landsat scene.

The objective of this research is to determine how effectively L-resolution Landsat ETM+ imagery can be used to map urban/suburban forest cover in comparison to a classification generated from sub-metre H-resolution aerial orthophotos. Landsat TM/ETM+ is of particular interest to this study because of its extensive archive of historical imagery, broad areal coverage, 16-day revisit cycle, and free availability and access (Small 2001). Additionally, this study builds on and contributes to a series of ongoing assessments of suburban sprawl, land-use/land-cover change, and forest cover change, which are three major environmental challenges faced by the state of Massachusetts (Rogan *et al.* 2010, Fortier *et al.* 2011). This study can have practical implications for resource managers, government agencies, or other researchers who lack the financial and personnel resources to capture and process H-resolution imagery for large study areas, but want to obtain accurate areal and spatial estimates of urban/suburban forest cover.

2. Study area and data

The town of Lynnfield (42°32'20.36"N, 71°02'53.19"W) in northeastern Massachusetts, USA covers 27 km². Lynnfield is located within the Greater Boston metropolitan region, one of the most rapidly suburbanizing regions in the United States. Between 1980 and 2000, the ratio of developed land area increase to population increase in the Boston metropolitan region was over four to one (Otto *et al.* 2002). Forest abundance varies spatially throughout Lynnfield, from large contiguous patches in the northern and southern portion of the town to smaller patches interspersed within the low/medium density residential areas in the town centre. Dominant forest types include hardwood red maple (*Acer rubrum*) and red oak (*Quercus rubra*) species, and conifer white pine (*Pinus strobus*) species (Hall *et al.* 2002).

Two Landsat ETM+ images (path 12, row 30) were captured on 1 May 2004 and 4 July 2004 to represent leaf-off and leaf-on conditions, respectively. These dates were chosen because of the availability of cloud-free images with the closest temporal match to the aerial orthophotos that were used in the H-resolution classification. Both image dates were affected by the post-2003 Scan Line Corrector (SLC) error, but Lynnfield fell within an un-affected location in the scene and was therefore clipped from the image. The Landsat images were radiometrically calibrated to at-sensor reflectance and path radiance effects were removed using the Cos(t) model (Chavez 1996). The Landsat images were geometrically corrected prior to acquisition using the Level 1T Standard Terrain Correction method (Roy *et al.* 2010), and a qualitative assessment using a GIS road centerlines layer confirmed that further geometric correction was unnecessary.

The H-resolution aerial orthophotos are 8-bit, 0.5 m spatial resolution, 4-band (visible and near-infrared) orthorectified aerial photographs taken between 9 and 17 April 2005. The H-resolution classification was performed using object-based image analysis (OBIA) methods and a nearest neighbour classification algorithm (Burnett and Blaschke 2003). The minimum mapping unit of the classification was 6 m². An accuracy assessment showed that the H-

resolution classification agreed with a photo interpretation of the aerial orthophotos over 78% of the landscape and the forest class agreed over 95% of the landscape. The H-resolution map contains seven land-cover classes (bare soil, conifer forest, hardwood forest, grass/lawn, impervious surfaces, water, and wetlands). Ancillary data included a GIS layer of Massachusetts Department of Environmental Protection (DEP) wetlands. The aerial orthophotos and ancillary data were obtained from the Massachusetts Geographic Information Systems office (MassGIS). For a more detailed explanation of the methods used to create the H-resolution classification, see <http://hero.clarku.edu/holmes/>.

3. Methods

The methods used to generate the Landsat-based classifications and the comparison statistics to the H-resolution classification involved three steps: (i) Spectral Mixture Analysis, (ii) classification tree analysis, and (iii) map comparison and area analysis.

Spectral Mixture Analysis (SMA) extracts landscape feature proportions from within individual L-resolution pixels, where the spectral value of each pixel is a linear combination of biophysical endmember fraction values. In this study, SMA was used to derive fraction images for four image endmembers (forest, grass/lawn, urban/impervious, and water/shade) that were chosen based on the Lu-Weng urban landscape model (Lu and Weng 2004). Training sites for the four endmembers were selected via photo-interpretation of a 0.5 m resolution aerial orthophoto. SMA was performed on bands 1-5 and 7 from both the leaf-off and leaf-on Landsat ETM+ images. Outputs included fraction images for each endmember indicating the percent of that endmember within each Landsat image pixel and a residual image for each Landsat image date indicating how closely the actual pixel values match the calculated mixture of endmembers.

The Landsat classifications were created using classification tree analysis. A stratified random sample of 157 training sites were selected from the forest, grass/lawn, urban/impervious, and water classes in the H-resolution classification map for the classification tree calibration and recursive splits were performed using the Gini split rule (Zambon *et al.* 2006). Classification was performed on three subsets of input image bands. The first two subsets included the four fraction images (forest, grass/lawn, urban/impervious, and water/shade) generated by the SMA from the leaf-off and leaf-on Landsat ETM+ images, respectively. The third subset was a combination of all eight fraction images from both the leaf-off and leaf-on images. Figure 1 shows an example of the classification tree from the third subset (leaf-off/leaf-on combination).

Following classification tree analysis, the three Landsat output maps (leaf-off, leaf-on, and the leaf-off/leaf-on combination) were vectorized and the ancillary wetlands GIS layer was merged with each of the three output maps such that wetland areas were included in the Landsat-derived classifications. The final step was to calculate the forest quantity (km²) in each of the three Landsat classifications for comparison to the forest quantity in the H-resolution classification.

4. Results

The maps of the three Landsat classifications and the H-resolution classification are presented in figure 2. In the H-resolution classification, 12.88 km² were classified as forest, accounting for about 48% of the study area. Of the three Landsat classifications, the combination leaf-off/leaf-on subset provided the nearest estimation of quantity of overall forest area when compared to the

H-resolution forest quantity (14.03 km², or 52% of the study area). These statistics indicate that there was a 1.15 km² (8.9%) difference in forest quantity between the Landsat leaf-off/leaf-on and H-resolution classifications.

In addition to comparing the differences in forest quantity between the Landsat and H-resolution classifications, we examined the differences in terms of spatial allocation, which occurs when a given quantity of pixels in category x is spatially allocated differently in two different maps (Pontius and Millones 2011). The results presented in table 2 show the locations of spatial agreement and disagreement between the Landsat leaf-off/leaf-on classification and the H-resolution classification. 73% of the area classified as forest in the Landsat leaf-off/leaf-on classification spatially corresponded to areas classified as forest in the H-resolution classification. The other 27% of the area classified as forest in the Landsat classification was Landsat commission error, meaning it was not classified as forest in the H-resolution classification. Additionally, 21% of the area classified as forest in the H-resolution classification was not classified as forest in the Landsat classification.

The results presented in table 2 are also shown in the binary maps in figure 3. Shaded areas in figure 3a represent locations where the Landsat leaf-off/leaf-on and H-resolution forest classifications were in spatial agreement. The shaded areas in Figure 3b show locations where the *only* the Landsat image was classified as forest (i.e. Landsat commission error), while the shaded areas in figure 3c show locations where *only* the H-resolution image was classified as forest (i.e. Landsat omission error). Finally, the relative proportions of the H-resolution land-covers contained within the area classified as Landsat commission error (figure 4) were as follows: 49% urban/impervious surface, 36% grass/lawn, 11% bare soil, 2% water, and just over 1% wetlands.

5. Conclusion

Landsat imagery is widely available, freely accessible, has broad spatio-temporal coverage, and has an extensive historical archive. Therefore, it is attractive to resource managers, local, state, and federal agencies, and researchers who are interested in mapping and monitoring large areas of urban/suburban forest cover but may lack the resources to acquire and process more costly H-resolution satellite imagery or aerial orthophotos. This paper offers an example of how urban/suburban forest cover can be mapped from Landsat imagery in comparison to an object-based image analysis classification of an H-resolution aerial orthophoto from the same study area and time period.

Results indicate that the Landsat leaf-off/leaf-on forest classification had 73% spatial agreement with the H-resolution forest classification. This 73% spatial agreement in Landsat and H-resolution forest areas is generally located in larger, contiguous forest patches in the northern and southern portions of the study area. Conversely, 27% of Landsat forest area that did not spatially agree (Landsat commission error) with the H-resolution forest classification was mainly composed of urban/impervious (49%) and grass/lawn (36%) surfaces in the central portion of the town. In other words, 85% of the area that was Landsat forest commission error was composed of roads, sidewalks, houses, driveways, and residential lawns—all characteristic features of the fragmented, spatially complex nature of the residential suburban landscape. This suggests that Landsat imagery is adequate for mapping larger, contiguous patches of forest (i.e. small urban forests greater than 2 acres) in urban/suburban settings, but its spatial resolution is too coarse to accurately map highly fragmented residential areas in urban/suburban landscapes.

In this study, the inputs to the classification tree were solely image derived and included no ancillary datasets. Recent research has shown that the inclusion of ancillary non-remote sensing data such as elevation, slope, and aspect derived from digital elevation models (DEMs) is useful in discriminating land-cover categories where spectral-radiometric data fails to discriminate the categories. The inclusion of these ancillary datasets has reportedly led to higher overall map accuracies of up to 5 to 10 percentage points (Rogan *et al.* 2003). Incorporating texture information and spatial detail by including the Landsat panchromatic band (15 m spatial resolution) has also been reported to improve classification accuracies, particularly in complex urban/suburban landscapes (Lu and Weng 2005). Future research will incorporate both ancillary DEM and finer resolution panchromatic data, as we hypothesize that a data-fused Landsat product and information regarding elevation may increase the classification tree's ability to discriminate land-cover classes, in particular spectrally similar classes such as forest and grass/lawn.

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References

- AKBARI, H., SHEA ROSE, L. and TAHA, H., 2003, Analyzing the land cover of an urban environment using high-resolution orthophotos. *Landscape and Urban Planning*, **63**, pp. 1-14.
- BURNETT, C. and BLASCHKE, T., 2003, A multi-scale segmentation/object relationship modeling methodology for landscape analysis. *Ecological Modelling*, **168**, pp. 233-249.
- CHAVEZ, P.S., 1996, Image-based atmospheric corrections – revisited and improved. *Photogrammetric Engineering and Remote Sensing*, **62**, pp. 1025-1036.
- FORTIER, J., ROGAN, J., WOODCOCK, C.E., and RUNFOLA, D.M., 2011, Utilizing temporally invariant calibration sites to classify multiple dates and types of satellite imagery. *Photogrammetric Engineering and Remote Sensing*, **72**, pp. 181-189.
- FRITZ, L.W., 1996, Commercial Earth observation satellites. In *The International Archives of Photogrammetry and Remote Sensing*, Vol. XXXI. Part B4. 1996, Vienna, Austria, pp. 273-282.
- GROVE, J.M., BURCH, W.R. and PICKETT, S.T.A., 2005, Social mosaics and urban forestry in Baltimore, Maryland. In *Communities and Forests: Where People Meet the Land*, R.G. Lee and D.R. Field, pp. 248-273 (Corvallis, OR: Oregon State University Press).
- GROVE, J.M., O'NEIL-DUNNE, J., PELLETIER, K., NOWAK, D., and WALTON, J., 2006, A report on New York City's present and possible urban tree canopy. United States Department of Agriculture, Forest Service, Northeastern Area, South Burlington, Vermont.
- HALL, B., MOTZKIN, G., FOSTER, D.R., SYFERT, M. and BURK, J., 2002, Three hundred years of forest and land-use change in Massachusetts, USA. *Journal of Biogeography*, **29**, pp. 1319-1335.
- HOMER, C., DEWITZ, J., FRY, J., COAN, M., HOSSAIN, N., LARSON, C., HEROLD, N., MCKERROW, A., VANDRIEL, J.N. and WICKHAM, J., 2007, Completion of the 2001 national land cover database for the conterminous United States. *Photogrammetric Engineering and Remote Sensing*, **73**, pp. 337-341.
- IVERSON, L.R. and COOK, E.A., 2000, Urban forest cover of the Chicago region and its relation to household density and income. *Urban Ecosystems*, **4**, pp. 105-124.
- KUO, F.E. AND SULLIVAN, W.C., 2001, Environment and crime in the inner city: does vegetation reduce crime? *Environment and Behavior*, **33**, pp. 347-367.
- LOHR, V.I., PEARSON-MIMS, C.H., TARNAI, J. and DILLMAN, D.A., 2004, How urban residents rate and rank the benefits and problems associated with trees in cities. *Journal of Arboriculture*, **30**, pp. 28-35.
- LU, D. and WENG, Q., 2004, Spectral mixture analysis of the urban landscape in Indianapolis with Landsat ETM+ imagery. *Photogrammetric Engineering and Remote Sensing*, **70**, pp. 1053-1062.
- LU, D. and WENG, Q., 2005, Urban classification using full spectral information of Landsat ETM+ imagery in Marion County, Indiana. *Photogrammetric Engineering and Remote Sensing*, **71**, pp. 1275-1284.
- MCPHERSON, E.G., 2006, Urban forestry in North America. *Renewable Resources Journal*, **24**, pp. 8-12.

- MANSFIELD, C., PATTANAYAK, S.K., MCDOW, W., MCDONALD, R. and HALPIN, P., 2005, Shades of green: measuring the value of urban forests in the housing market. *Journal of Forest Economics*, **11**, pp. 177-199.
- NICHOL, J., 1996, High resolution surface temperature patterns related to urban morphology in a tropical city: a satellite-based study. *Journal of Applied Meteorology*, **35**, pp. 135-146.
- NICHOL, J., 2009, Remote sensing of urban areas. In *The SAGE Handbook of Remote Sensing*, T.A. Warner, M.D. Nellis, and G.M. Foody (Eds.), pp. 423-436 (London: SAGE Publications, Ltd.).
- NOWAK D.J., and WALTON, J.T., 2005, Projected urban growth (2000-2050) and its estimated impact on the U.S. forest resource. *Journal of Forestry*, **103**, pp. 383-389.
- O'NEIL-DUNNE, J., 2007, A report on the city of Baltimore's existing and possible urban tree canopy. United States Department of Agriculture, Forest Service, Northeastern Area, South Burlington, Vermont.
- O'NEIL-DUNNE, J., 2011, A report on the city of Philadelphia's existing and possible urban tree canopy. United States Department of Agriculture, Forest Service, Northeastern Area, South Burlington, Vermont.
- OTTO, B., RANSEL, K., TODD, J., LOVAAS, D., STUTZMAN, H. and BAILEY, J., 2002, Paving our way to water shortages: how sprawl aggravates the effects of drought. Available online at: <http://www.smartgrowthamerica.org/documents/DroughtSprawlReport09.pdf>. (accessed 15 July 2011).
- PONTIUS JR., R.G., and MILLONES, M., 2011, Death to kappa: Birth of quantity disagreement and allocation disagreement for accuracy assessment. *International Journal of Remote Sensing*, **32**, pp. 4407-4429.
- ROGAN, J., MILLER, J., STOW, D., FRANKLIN, J., LEVIEN, L., and FISCHER, C., 2003, Land-cover change monitoring with classification trees using Landsat TM and ancillary data. *Photogrammetric Engineering and Remote Sensing*, **69**, pp. 793-804.
- ROGAN, J. and CHEN, D., 2004, Remote sensing technology for mapping and monitoring land-cover and land-use change. *Progress in Planning*, **61**, pp. 301-325.
- ROGAN, J., BUMBARGER, N., KULAKOWSKI, D., CHRISTMAN, Z.J., RUNFOLA, D.M., and BLANCHARD, S.D., 2010, Improving forest type discrimination with mixed lifeform classes using fuzzy classification thresholds informed by field observations. *Canadian Journal of Remote Sensing*, **36**, pp. 699-708.
- ROY, D.P., JU, J., KLINE, K., SCARAMUZZA, P.L., KOVALSKYY, V., HANSEN, M., LOVELAND, T.R., VERMOTE, E., and ZHANG, C., 2010, Web-enabled Landsat data (WELD): Landsat ETM+ composited mosaics of the coterminous United States. *Remote Sensing of Environment*, **114**, pp. 35-49.
- SETO, K.C., SANCHEZ-RODRIGUEZ, R. and FRAGKIAS, M., 2010, The new geography of contemporary urbanization and the environment. *Annual Review of Environment and Resources*, **35**, pp. 167-194.
- SMALL, C., 2001, Estimation of urban vegetation abundance by spectral mixture analysis. *International Journal of Remote Sensing*, **22**, pp. 1305-1334.
- SMALL, C. and LU, J.W.T., 2006, Estimation and vicarious validation of urban vegetation abundance by spectral mixture analysis. *Remote Sensing of Environment*, **100**, pp. 441-456.

- THOMAS, N., HENDRIX, C. and CONGALTON, R.G., 2003, A comparison of urban mapping methods using high-resolution digital imagery. *Photogrammetric Engineering and Remote Sensing*, **69**, pp. 963-972.
- TOOKE, T.R., COOPS, N.C., GOODWIN, N.R., and VOOGT, J.A., 2009, Extracting urban vegetation characteristics using spectral mixture analysis and decision tree classifications. *Remote Sensing of Environment*, **113**, pp. 398-407.
- TROY, A.R., GROVE, J.M., O'NEIL-DUNNE, J.P.M., PICKETT, S.T.A. and CADENASSO, M.L., 2007, Predicting patterns of vegetation and opportunities for greening on private urban lands. *Environmental Management*, **40**, pp. 394-412.
- URBAN ECOLOGY INSTITUTE, 2008, State of the urban forest: A summary of the extent and condition of Boston's urban forest. Urban Ecology Institute, Cambridge, Massachusetts.
- YANG, L., 2008, Development of the United States national land cover database: experience from 1992 and 2001 implementation. In *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, Vol. XXXVII. Part B4. 2008, Beijing, China (Sioux Falls: USGS), pp. 1461-1466.
- ZAMBON, M., LAWRENCE, R., BUNN, A. and POWELL, S., 2006, Effect of alternative splitting rules on image processing using classification tree analysis. *Photogrammetric Engineering and Remote Sensing*, **72**, pp. 25-30.
- ZHOU, W. and TROY, A.R., 2008, An object-oriented approach for analysing and characterizing urban landscape at the parcel level. *International Journal of Remote Sensing*, **29**, pp. 3119-3135

Table 1. Comparison of five H-resolution sensors and the Landsat sensor in terms of historical coverage, spatial resolution, areal coverage, temporal resolution, and cost.

Sensor mission	Organization	Operation period	Spatial resolution (m)	Swath (km)	Spectral coverage (μm)	Average revisit period	Scene extent (km^2)	Cost per km^2 (\$ U.S.)
IKONOS	GeoEye	1999-	1	11 x 11	0.45-0.90	2-3 days	121	10
Quickbird	DigitalGlobe	2001-	0.61	16.5 x 16.5	0.45-0.90	2-3 days	272.25	17
Worldview-1	DigitalGlobe	2007-	0.5	15 x 15	0.40-0.90	3-4 days	225	17
GeoEye-1	GeoEye	2008-	0.5	15 x 15	0.45-0.92	2-3 days	225	12.5
Landsat TM/ETM+	NASA/Landsat Program	1982-	15 (PAN) 30 (MS)	185 x 185	0.45-2.35	16 days	34225	0
Mass. Aerial Orthophoto Acquisition (2005)	Vexcel Corporation	By demand	0.5	4 x 4	0.40-0.90	By demand	16	Unavailable

Detailed information on most sensors can be found in Rogan and Chen (2004) and the following WebPages: www.digitalglobe.com, www.geoeye.com, and www.spatialenergy.com. ETM+, enhanced thematic mapper plus; MS, multi-spectral; NASA, National Aeronautics and Space Administration; PAN, panchromatic; TM, thematic mapper. Note: The cost of the Mass. Aerial Orthophoto Acquisition in 2005 was unavailable at this time.

Table 2. Spatial agreement and disagreement between the Landsat leaf-off/leaf-on combination classification and the H-resolution classification.

	Area (km²)	Proportion of Study Area
Landsat forest quantity	14.03	52%
H-resolution forest quantity	12.88	48%
Forest quantity in both Landsat and H-resolution classifications	10.18	38%
Forest quantity in <i>only</i> Landsat classification (Landsat commission)	3.85	14%
Forest quantity in <i>only</i> H-resolution classification (Landsat omission)	2.70	10%
	Percentage	
Percentage of Landsat forest that agreed with H-resolution forest	73%	
Percentage of Landsat forest commission error	27%	
Percentage of Landsat forest omission error	21%	

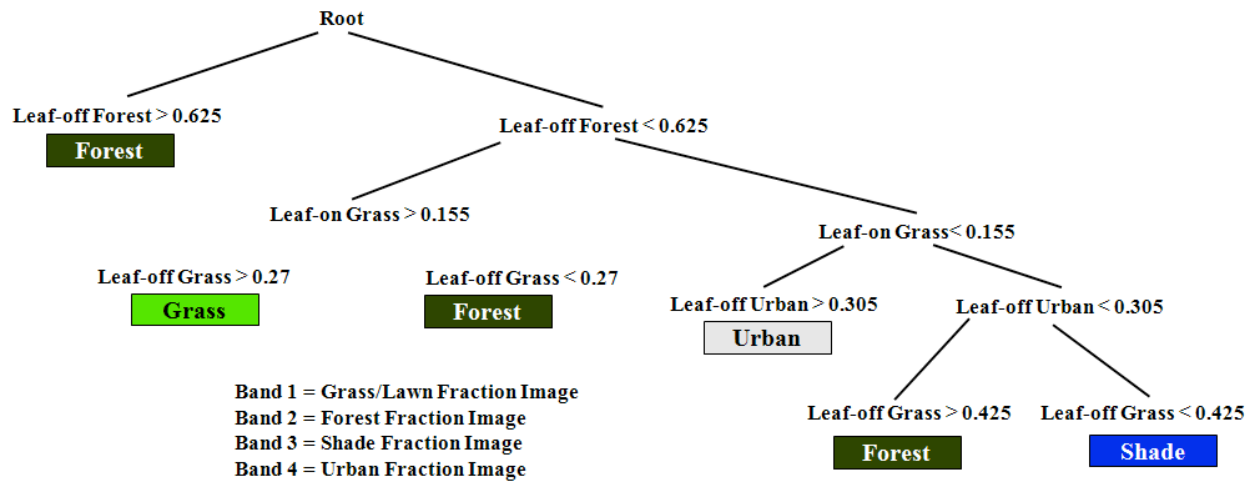


Figure 1. The classification tree model for the third image subset, containing the Landsat leaf-off/leaf-on fraction images.

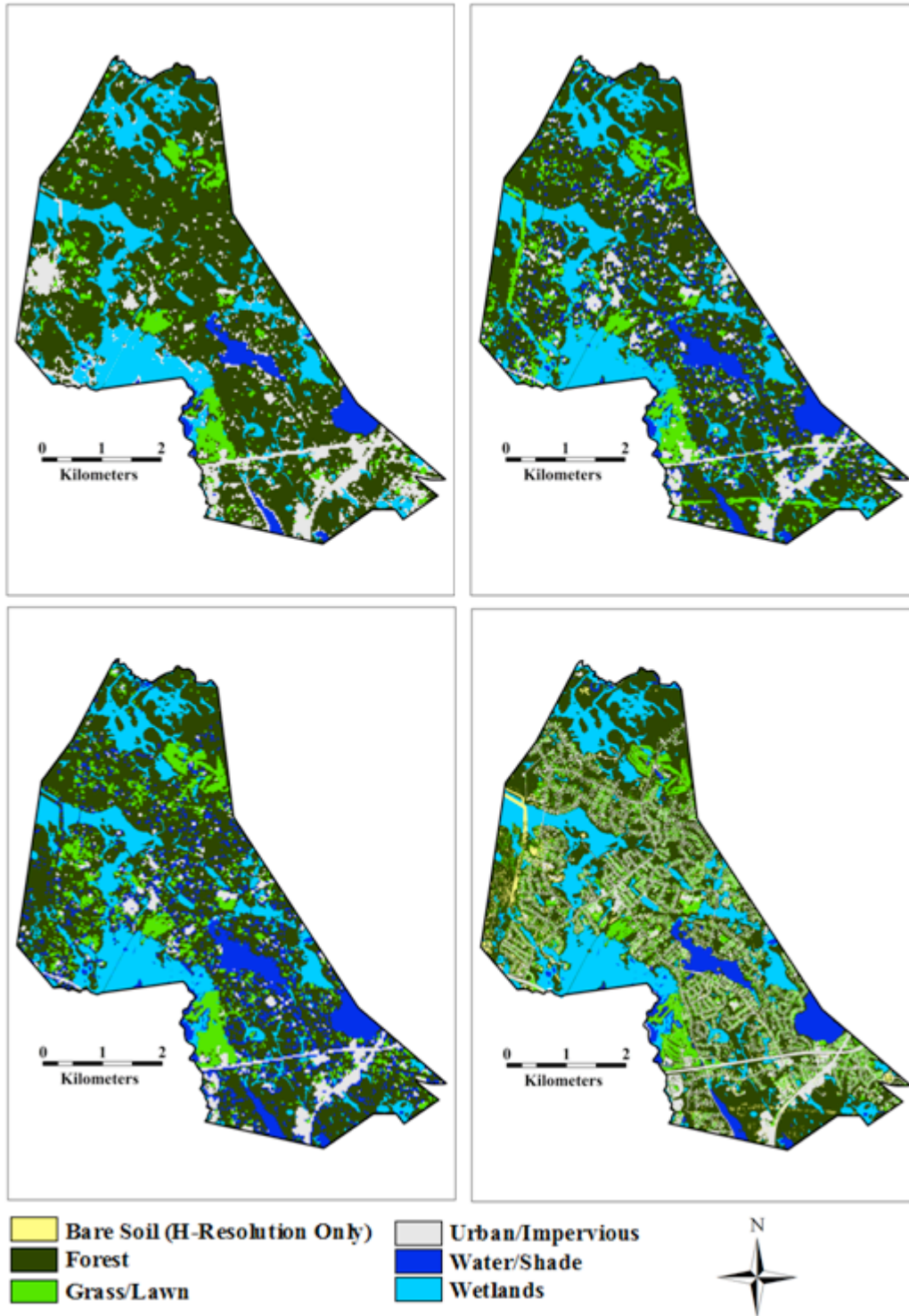


Figure 2. Classification outputs of a) Landsat leaf-off (top left), b) Landsat leaf-on (top right), c) Landsat leaf-off/leaf-on combination (bottom left), and d) H-resolution classification (bottom right).



Figure 3. Comparison maps of a) forest areas in both the Landsat leaf-off/leaf-on combination and H-resolution classifications (top left), b) forest areas in *only* the Landsat classification (Landsat commission) (top right), and c) forest areas in *only* the H-resolution classification (bottom left).

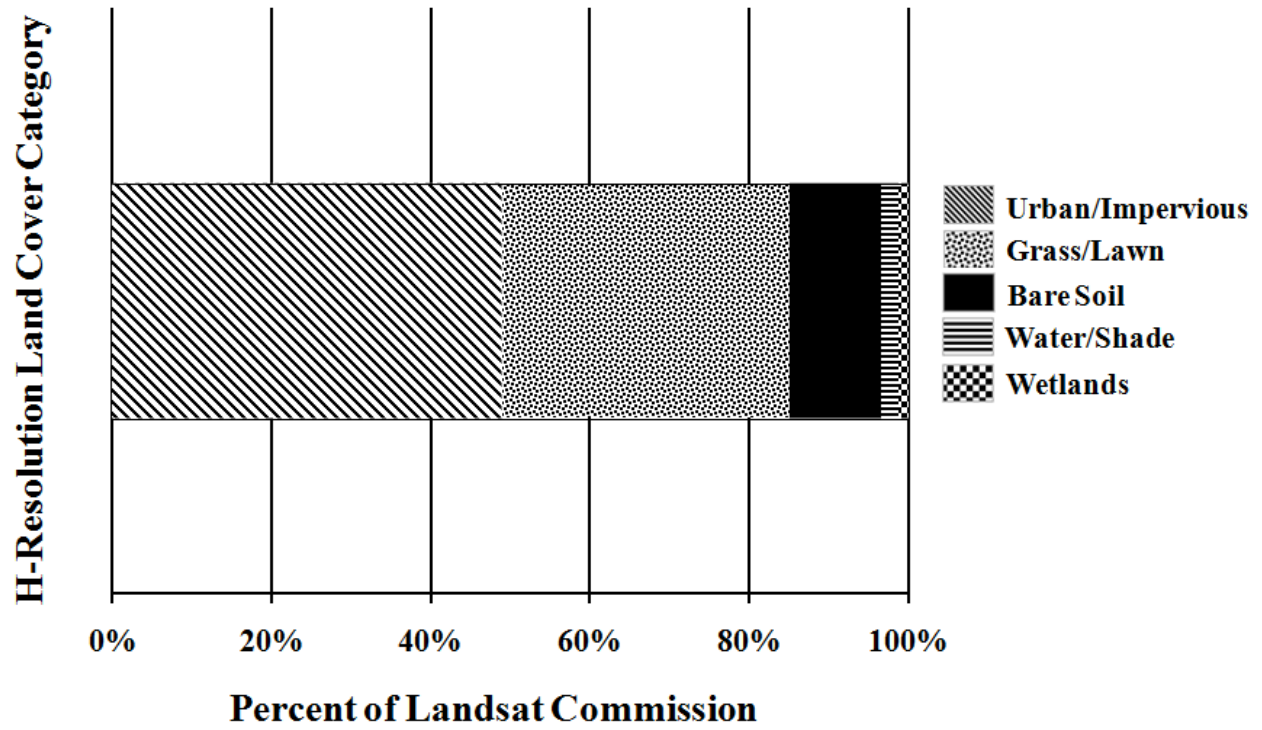


Figure 4. H-resolution land-covers included in the 27% commission error of the Landsat leaf-off/leaf-on classification.

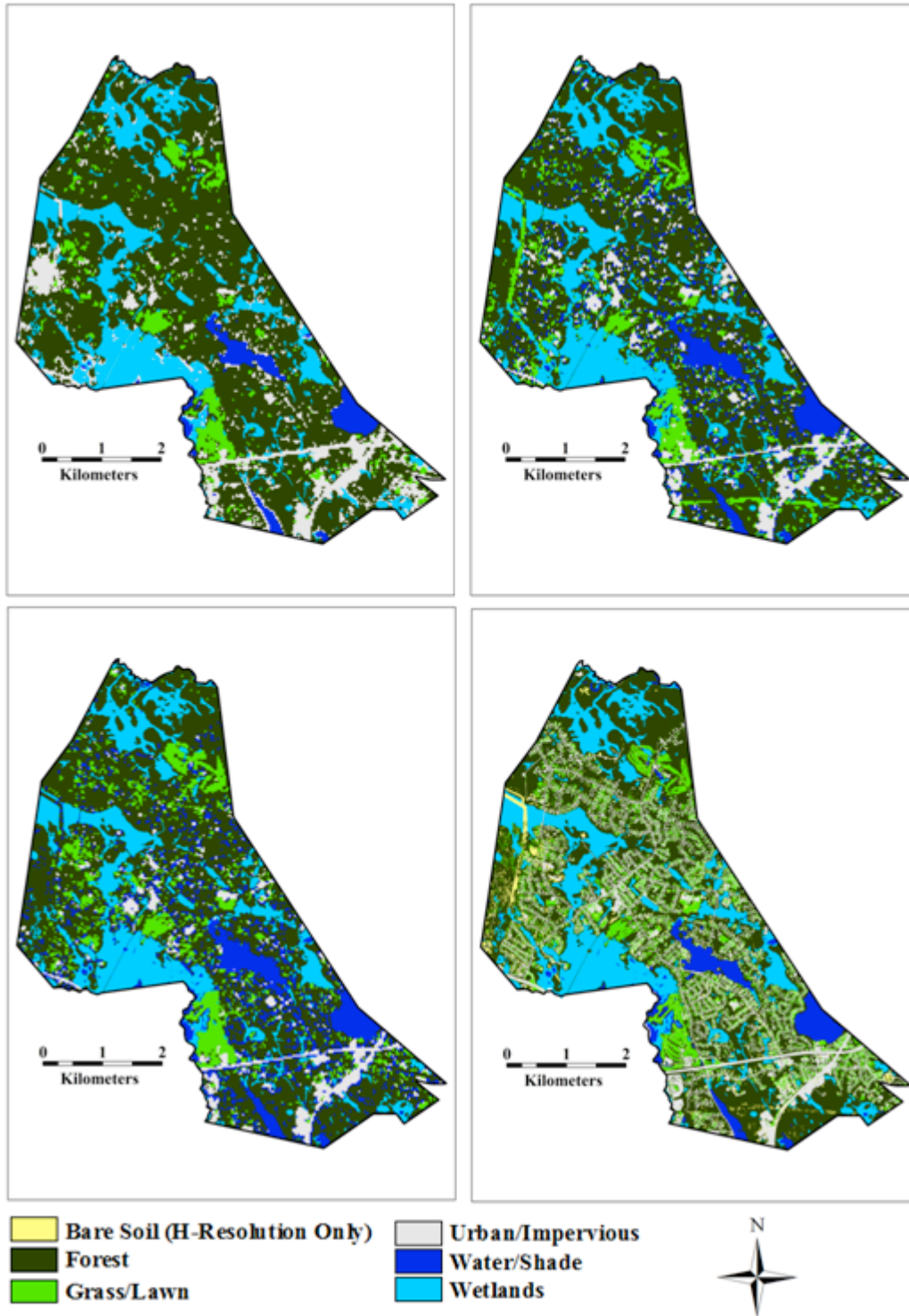


Figure 2. Classification outputs of a) Landsat leaf-off (top left), b) Landsat leaf-on (top right), c) Landsat leaf-off/leaf-on combination (bottom left), and d) H-resolution classification (bottom right).



Figure 3. Comparison maps of a) forest areas in both the Landsat leaf-off/leaf-on combination and H-resolution classifications (top left), b) forest areas in *only* the Landsat classification (Landsat commission) (top right), and c) forest areas in *only* the H-resolution classification (bottom left).

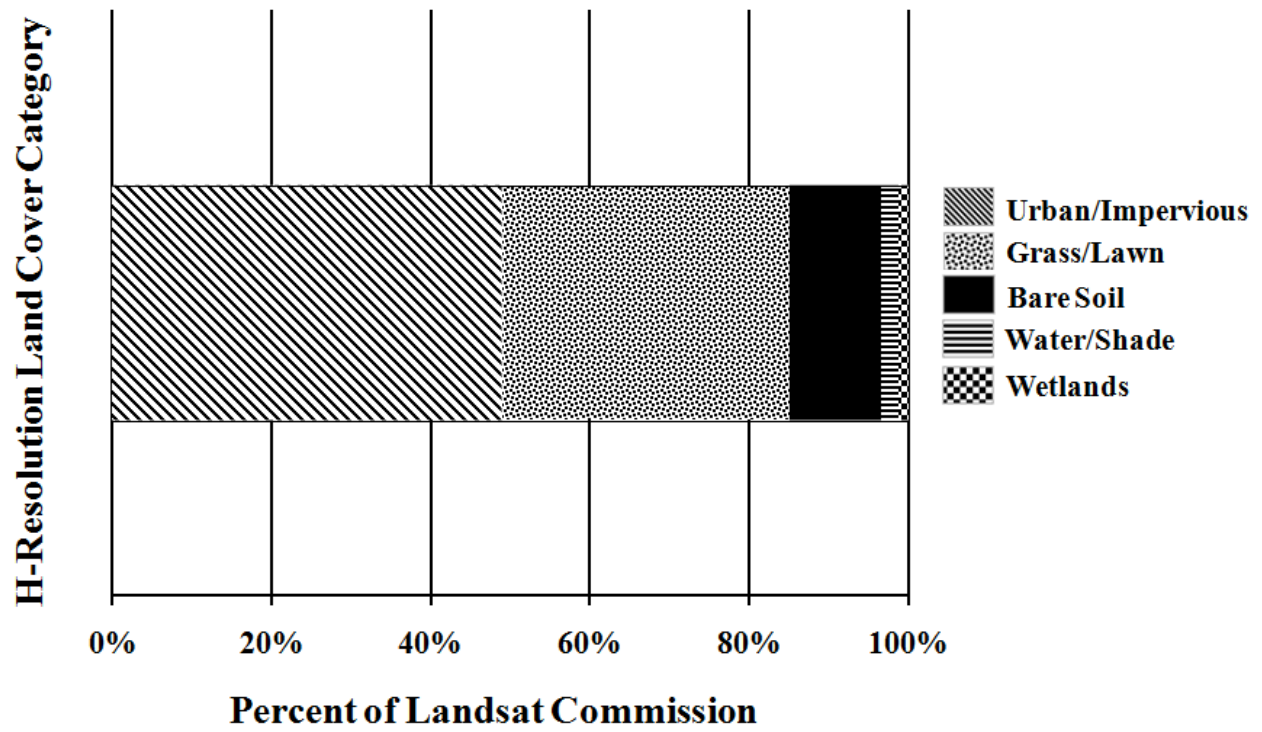


Figure 4. H-resolution land-covers included in the 27% commission error of the Landsat leaf-off/leaf-on classification.

A COMPARISON OF LANDSAT ETM+
AND HIGH-RESOLUTION AERIAL
ORTHOPHOTOS TO MAP URBAN/
SUBURBAN FOREST COVER IN
MASSACHUSETTS, USA

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OCTOBER 2011

By Nicholas M. Giner and John Rogan



HUMAN

NATURAL

CONSTRUCTED



CLARK UNIVERSITY
George Perkins Marsh Institute