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Land use change monitoring in Maryland using a probabilistic sample and rapid photointerpretation

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ABSTRACT

The U.S. state of Maryland needs to monitor land use change in order to address land management objectives. This paper presents a change detection method that, through automation and standard geographic information system (GIS) techniques, facilitates the estimation of landscape change via photointerpretation. Using the protocols developed, we show a net loss of forest land, with losses due primarily to urban development and most gains in forest land coming from agricultural land conversions. This study indicates that about 75,000 photo plots would be needed to estimate land use change in Maryland at the county-level, assuming a uniform sampling intensity and a maximum desired county-level sampling error of 20 percent, with an estimated time requirement of 125 h. The protocol we present for designing, planning and conducting a photointerpretation-based land use change procedure can be used by other regions and is well suited for land use change monitoring, assuming that analysis of opportunity costs suggests that existing or new remotely sensed imagery classifications do not meet user needs.

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Introduction

Several recent studies have predicted that urban expansion will continue to be a significant factor affecting forests in many areas of the United States (Stein et al., 2005). For example, Nowak and Walton (2005) predicted that urban land in the United States would nearly triple from 2000 to 2050. Stewart, Radeloff, Hammer, and Hawbaker (2007) documented the current status of forests on the urban fringe, and highlighted potential impacts that continued urban expansion might have on them. Ecological impacts of urban expansion vary, but are generally related to loss of forest or other vegetative cover and increased edge habitat. Increases in edge habitat have been shown to affect populations of forest interior-dwelling species and affect other ecological processes associated with forest patches (Forman, 1995). Loss of forest cover also leads to loss of soil by both wind (Whicker, Pinder, & Breshears, 2008) and water (Rice & Lewis, 1991). The loss of topsoil has the potential to not only lower the productivity of agriculture crops and forest ecosystems, but also to impact aquatic ecosystems through sedimentation, nutrient enrichment, and other factors (Faulkner, 2004).

Data from the U.S. National Resources Inventory (NRI) indicate that more than 40,000 km^2 of forest land in the U.S. state of Maryland were lost to developed land uses between 1982 and 1997 (U.S. Department of Agriculture, 2000). Nowak and Walton (2005) predicted that the percent of forest land in urban areas in Maryland would more than double to 37 percent by 2050. For these reasons, Maryland resource agencies are interested in assessing and monitoring land use change. Of particular concern are the potential impacts of forest change dynamics on the ecologically-sensitive Chesapeake Bay, the watershed that occupies a large portion of the state (Claggett, Jantz, Goetz, & Bisland, 2004; Sprague, Burke, Claggett, & Todd, 2006). The Maryland legislature has adopted legislation (Maryland House Bill 706) that requires "no net loss of forest" by 2020, defined as at least 40% of the state having tree cover. The state must thus implement an affordable, repeatable, detailed assessment of "tree cover" on a periodic basis.

Estimation of forest loss with remotely-sensed data is generally done in three ways: direct observation of the attribute of interest with design-based estimation (e.g., Nowak & Greenfield, 2012), model-assisted estimation (also a design-based approach, e.g., McRoberts, 2010), or model-based estimation (e.g., Stahl et al., 2011). Gregoire (1998) describes the theory behind the use of

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remote sensing images in either a design-based or model-based approach. Generating estimates by creating summaries of pixels most closely resembles a model-based approach to estimation; this is what is typically done when products based on remote sensing are summarized in a geographic information system (GIS).

Olofsson, Foody, Stehman, and Woodcock (2013) point out that traditional remote sensing accuracy assessment methods are often flawed. Furthermore, a significant challenge with the pixel-summary approach to error reporting is that estimators are not necessarily unbiased (Thompson, 2012) and it can be complicated computationally to generate estimates of their variance (e.g., McRoberts, 2010). Probabilistic or design-based sampling, on the other hand, can be used with or without remotely-sensed information, and relies on traditional sampling theory from which to derive inferences (Thompson, 2012). One primary advantage of the direct observation approach with traditional probabilistic sampling is that the estimators can easily be calculated in a spreadsheet using well-understood, common procedures. Furthermore, practitioners and policy makers are very familiar with error indices that are commonly reported like confidence intervals and margins of error. Map-based estimates, on the other hand, require more complicated approaches like Bayesian inference (e.g., Finley, Banerjee, Ek, & McRoberts, 2008) and a reliance on either user-generated or pre-existing land cover products.

The National Land Cover Data (NLCD) (Fry et al., 2011) is a good example of a pre-existing land cover product that is commonly used for resource assessments. The NLCD is a 30×30-m pixel-based dataset created by automated classification of Landsat imagery. It is comprised of per-pixel estimates of percent canopy cover, land cover class for 2006, and change in land cover class between 2001 and 2006. Pre-existing image products like NLCD are not suitable for all applications, however. For example remote sensing-based products do not always provide information that meets user needs. In the case of the USDA Forest Service's Forest Inventory and Analysis Unit (FIA), which is responsible for generating national estimates of forest area dynamics, the definition of "forest" includes areas with ten percent tree cover that are at least 0.4 ha in size and greater than 37 m at their narrowest point (U.S. Department of Agriculture, Forest Service, 2012). Since Landsat pixels are 30-m squares, there is no combination of Landsat pixels that corresponds precisely with this definition. Raciti, Hutyra, Rao, and Finzi (2012) similarly found that differing definitions of "urban" can lead to very different estimates of carbon sequestration when calculated with remotely sensed data.

There are also contextual variables that are included in land cover or use definitions – the FIA forest land use definition, for example, is modified by the presence or absence of structures and roads. Along the same lines, most image classification processes can't incorporate landscape context into decisions – for example, a human observer's identification of cows in a grassland can help identify it as pasture, whereas this information is not available on a satellite image.

Another problem associated with using remote sensing products for resource assessments is simple classification inaccuracy – the model used to generate estimates does not consistently perform well across the landscape. For example, Nowak and Greenfield (2010) found that there were large discrepancies between known tree cover classifications and those contained in the NLCD, due mainly to poor performance of classifiers in heterogeneous areas and definitional differences. They thus chose to perform their own nation-wide photointerpretation-based estimation of tree and impervious cover using their own definitions and in a way that met their accuracy criteria (Nowak & Greenfield, 2012). Hansen et al. (2013) found that accuracy of a global 30-m land cover change product varied by climate zone and vegetation type, leading to both over- and underestimation of some change categories in certain ecosystems. Zheng, Heath, and Ducey (2012) also came to the conclusion that the inappropriate use of remote sensing for carbon quantification can lead to overestimates if fine-scale forest loss that is not detectable in the remote sensing product is not considered. Claggett, Irani, and Thompson (2013) determined that estimates of anthropogenic land cover classes from Landsat classifications were approximately 50% lower than those from more authoritative sources, probably due to some of the same resolution and radiometric limitations identified in Jones and Jarnagin (2009).

While many of these problems can be mitigated by creating new classifications with multitemporal, high resolution imagery, LiDAR and object-based image analysis procedures, creation of these more advanced products can require high levels of skill, specialized software, and significant hardware investments – something many resource agencies can't afford to maintain. These agencies thus often rely on pre-existing imagery products for resource monitoring, and would benefit from an alternative.

An example of the direct observation approach is field-based monitoring of land use change. FIA conducts a field-based, continuous, national forest inventory of the U.S. using standardized methods. FIA is national in scope, and uses standardized variable definitions and a standard timetable. However, by design, the plot and sample designs and variable definitions are not easy to change, making it difficult to adapt to novel monitoring requirements or new classification systems. Furthermore, the intensity of the FIA sample may not be sufficient to provide precise estimates of the area of forest conversion to other land use classes if it is a rare occurrence.

Another example of direct observation is photointerpretation (PI) from high resolution aerial imagery. Modern methods for conducting PI (e.g., computer-aided PI (Pithon, Jubelin, Guitet, & Gond, 2013)) exist, but suffer from some of the aforementioned problems. Ocular PI, on the other hand, has been found to be cost-effective and accurate when conducting large area resource assessments (e.g., Mena, Ormazabal, Morales, Santelices, & Gajardo, 2011; Nowak & Greenfield, 2012). Recent examples include Riva-Murray, Riemann, Murdoch, Fischer, and Brightbill (2010) and Ecke, Magnusson, and Hornfeldt (2013), both of whom conducted a large area PI to assess landscape fragmentation patterns. Canada uses PI as one of the foundations of its national forest inventory (Magnussen & Russo, 2012). The US Forest Service's FIA program has used and currently uses PI in different ways at the local, regional, and national scales (Bechtold & Patterson, 2005, 85 pp.). The primary advantages of ocular PI are that the technology is generally accessible to resource agencies that use GIS, it is easily teachable, land use or cover classes can be chosen to meet detailed user needs, and imagery is often served freely over the Internet and updated frequently, at least in the United States.

To address the challenges associated with using model-based or ground plot-based estimation of landscape change, we created a flexible, inexpensive procedure to supplement FIA land use change estimates using ocular observations on high resolution aerial photography. The objective of the study was to conduct an assessment of land use change in Maryland using methods that could serve to meet Maryland's needs for a repeatable, detailed, probabilistic sampling-based protocol for assessment of forest cover. A goal was to develop a method that could be implemented by resource agencies that might not have a large budget, nor possess the institutional knowledge to perform advanced satellite remote sensing analyses, nor be willing to accept some of the aforementioned challenges of satellite image classification. Additionally, we wanted to obtain information that was compatible with the FIA data and useful to federal and state resource agencies in Maryland.