# Exploring the Association of the Minnesota Department of Natural Resources' Satellite-Detected Change With the Forest Inventory and Analysis System of Observed Removals and Mortality

**Dale D. Gormanson**[1], **Timothy J. Aunan**[2], **Mark H. Hansen**[3], **and Michael Hoppus**[3]

**Abstract.—**Since 2001, the Minnesota Department of Natural Resources (MN-DNR) has mapped forest change annually by comparison of Landsat satellite image pairs. Over the same timeframe, 1,761 U.S. Department of Agriculture, Forest Service, Forest Inventory and Analysis (FIA) plots in Minnesota have been remeasured on a 5-year cycle, providing field data on growth, removals, and mortality. This study compares estimates of change from these two sources. The FIA-based estimate of annual removals compares closely to the average MN-DNR estimate. FIA plots showing large removals were generally included in Landsat-detected change polygons, but image analysis usually failed to map as changed those plots exhibiting only partial removals or tree mortality.

## Introduction

The Forestry Division of the Minnesota Department of Natural Resources (MN-DNR) employs two inventory systems. Forest managers use the map-based Cooperative Stand Assessment system, while strategic analysis relies on the Forest Service's plot-based Forest Inventory and Analysis (FIA) system. Between 1991 and 1999, the Division's Resource Assessment (RA) unit cooperated with the Forest Service's North Central and Rocky Mountain Research Stations in devising and testing the Annual Forest Inventory System (AFIS), a plan to transform the Federal FIA program in the Lake States from a periodic inventory conducted at 15-year intervals to a continuous inventory, with a proportion of plots examined every year (Hahn *et al.* 1992). The AFIS project prompted the adoption of annualized sampling nationwide by FIA. Remote sensing of forest change for the prioritization of plot visits was an integral part of the original AFIS design (Befort 2000), and RA was responsible for the design and implementation of remote sensing methods for AFIS.

Since the testing of the AFIS project, RA has continued to monitor and map changes in Minnesota forests by satellite image analysis, with the basic aim of compiling a continuous record of forest-cover disturbances on all ownerships (Aunan *et al.* 2006.). Ancillary objectives from year to year have included the detection of logging impacts on riparian zones, classification of disturbances by cause, and random targeting of individual harvest sites for field monitoring of forest practices. To date, five iterations have been conducted: 1999–2001, 2000–02, 2001–03, 2002–04, and 2003-–05. Meanwhile, FIA has been conducting annual inventories by plot remeasurement on a 5-year cycle. These plots provide ground-based observations of forest change (growth, removals, and mortality) that form the basis of FIA estimates. The purpose of the present inquiry was to compare satellite disturbance detection results against FIA's plot-based observations. Two questions were addressed:

1. Do satellite and FIA estimates of harvest acreage agree?
2. At site level, are satellite-detected changes being mapped at the locations where FIA plot data would lead us to expect them?

[1] Supervisory Forester, U.S. Department of Agriculture (USDA) Forest Service, Northern Research Station, 1992 Folwell Avenue, St. Paul, MN 55108.
[2] Assistant Supervisor, Minnesota Department of Natural Resources, Division of Forestry, Resource Assessment, Grand Rapids, MN 55744.
[3] Research Forester, USDA Forest Service, Northern Research Station, 1992 Folwell Avenue, St. Paul, MN 55108.

## Data and Methods

MN-DNR's change monitoring effort has been detailed in a series of project reports (Aunan *et al.* 2004, 2006; Befort and Deegan 2002; Befort *et al.* 2003; and Deegan *et al.* 2005) from which the following synopsis of methodology is taken. Each year's project has followed the same general plan.

### Imagery

The two Landsat satellites presently in service (Landsats 5 and 7) provide 30-meter 7-band multispectral Thematic Mapper (TM) images of Minnesota in five overlapping orbital paths, revisiting each path every 8 days in a sun-synchronous orbit.

To detect forest changes, a summer image from 2 years previous (Time 1) is matched against a current summer image (Time 2) at each of 19 Landsat scene locations covering Minnesota. MN-DNR purchases 10 new images from even-numbered Landsat orbital paths in even years and 9 from odd-numbered paths in odd years, thus obtaining 70 percent coverage of the State every year, a 2-year interval between image pairs, and a manageable analyst workload.

### Image Preparation

Much extraneous variation must be filtered out before multispectral scanner scenes from different dates can be compared to detect particular types of vegetation change. Steps under the heading of "image preparation" are geared to ensure that detected changes represent actual alterations of ground reflectance rather than unrelated mismatches between images.

- Image preparation includes geometrically correcting and referencing images to the MN-DNR-standard NAD83 Universal Transverse Mercator extended Zone 15 projection. The Minnesota Department of Transportation statewide roads coverage serves as the accuracy standard. Original multispectral brightness values are converted to at-satellite reflectance. This radiometric calibration adjusts for differences in solar elevation, distance, and sensor differences over time between image pairs. Image preparation follows the procedures of Chandler and Markham (2003).
- Clouds and cloud shadows are detected and excluded from analysis by Normalized Difference Cloud Index techniques.
- The Gap Analysis Project vegetation map of Minnesota is used to "mask out" nonforest lands.

### Change Detection Algorithm

Within cloud-free forested portions of the scenes, RA employs two straightforward image differencing algorithms for detecting vegetation changes between T1 and T2: a three-band difference using Landsat Bands 3 (visible red), 4 (near infrared), and 5 (first middle infrared)[4], and a two-band difference omitting Band 4:

Three-band = (T1 - T2, Band 3) + (T2 - T1, Band 4) + (T1 - T2, Band 5)

Two-band = (T1 -T2, Band 3) + (T1 -T2, Band 5).

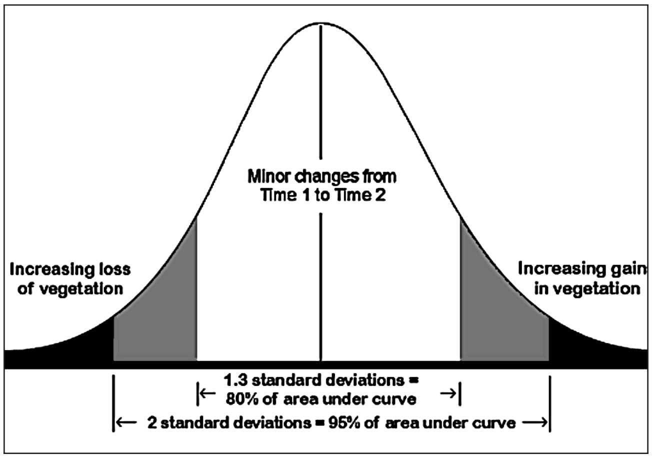
A change image is produced by differencing the values of corresponding pixels in each image for each band and then summing the results. The "change image" consists entirely of pixel-by-pixel difference scores. These scores usually display a frequency distribution that is bell shaped (i.e., nearly normal), with most values clustering around a mean of "no change" (fig. 1). Note in figure 1 that the arbitrary statistical margins depicted display the same level of "change" and "no change" no matter what has actually happened in the area analyzed. For this study, the focus was confined to the left side of the frequency distribution, representing vegetation losses.

### Reconciliation and Analysis

In addition to satellite detection and mapping of forest disturbance, the MN-DNR uses an aerial photo sampling stage to identify the detected sites positively as harvests. In this application,

[4] *Three-band differencing*—Landsat Bands 3, 4, and 5 are useful for vegetation analysis. Band 3 has a wavelength of 0.63 to 0.69 µm and it has a nominal spectral location of red. Band 3 can detect chlorophyll, which aids in plant identification. Band 4 has a wavelength of 0.76 to 0.90 µm and its nominal spectral location is the near infrared. Band 4 is useful for interpreting different types of vegetation, detecting moisture in soils, and delineating water and land. Band 5 has a wavelength of 1.55 to 1.75 µm and its nominal spectral location is the mid-infrared. Band 5 can be used to detect the moisture content of various plants and soils.

Figure 1.—*Generalized distribution of picture elements in an idealized change image. For this study, interest was confined to the left side of the frequency distribution, representing vegetation losses. Courtesy Minnesota Department of Natural Resources.*




photos serve as a double sample to refine satellite-derived estimates of harvest acreage. Briefly,

- From the thousands of disturbances detected, 200 to 300 sites are randomly selected and photographed from the air.
- Disturbance acreages measured on the high-resolution aerial photos are used to adjust acreage estimates made from the coarse-resolution satellite data.
- Computer and visual analysis is used to distinguish forest harvests from other classes of forest land use change; this process includes thresholding the image margin to identify areas of high change.

**MN-DNR Statewide Harvest Acreage Estimation**

To estimate statewide rate of harvest, satellite-detected removals are first annualized: their acreage is divided by the years separating the two images from which they had been detected. The similarly adjusted photo-measured acreage of each double-sampled harvest site is then regressed on annualized satellite-estimated harvest acreage, and total annual harvest acreage is calculated from the regression relationship. The adjusted acreage is converted to an annual basis and expanded to include the remaining 30 percent of the State and becomes the MN-DNR statewide timber removal estimate.

**FIA Plot Data**

FIA field plot data include plot- and tree-level observations. Trees 1.0 to 4.9 in in diameter at breast height (d.b.h.) (4.5 ft) are measured on 1/300-acre microplots, and trees 5.0 in d.b.h. and larger are measured on four plots, each of which is 1/24 acre. Plot locations are monumented using Global Positioning System (GPS) technology. In order to facilitate tree relocation, field crews identify and map trees by polar coordinates (i.e., bearing and distance from the plot center to each tree). Crews identify which trees have died or have been removed since the previous inventory with a series of codes used to track tree history. As new trees grow into the microplots and subplots, they, too, are tracked until death. These tree histories along with measurements of tree diameter and other characteristics provide plot-based observations of the total volume that was removed and/or lost to mortality over the 5-year period between plot measurements.

FIA plot-level removal and mortality data for trees 5 in d.b.h. or greater were obtained from remeasurement plots initially observed during the first 2 years of FIA's 5-year annual inventory in Minnesota (1999–2003). In 2004, 577 forest plots initially observed in 1999 were remeasured and, in 2005, an additional 1,184 forest plots from 2000 were remeasured. Twice as many plots were observed in 2005 because of intensified field sampling made possible through the cooperation and assistance of MN-DNR.

**Linking MN-DNR Harvest Polygons and FIA Plots**

The mapped satellite-detected change harvest data set contained 44,964 forest harvest polygons derived from Landsat image pairs taken 2 years apart (1999–2001, 2000–02, 2001–03, 2002–04, and 2003–05). Years 1999–01 had a 5-acre minimum mapping unit. For the other periods, the detection threshold for forest removals was 2 acres. The largest polygon in the data set was approximately 250 acres. FIA plots observed with removals and FIA plots observed with mortality were linked spatially by GPS plot coordinates to the mapped satellite-detected harvest polygons they were closest to or contained in.

### FIA Average Annual Removals

FIA timber removal and mortality estimates are typically provided on a volume basis following procedures explained in Bechtold *et al.* (2005). Estimates of acres harvested have not been typically reported in standard FIA reports. Such estimates require classification of conditions measured on an FIA plot as either harvested or not harvested. The MN-DNR classification is intended to identify areas that are clearcut or had major harvesting activities, not areas where a few scattered trees had been removed, such as a thinning or partial cut. It would be ideal if the Landsat Thematic Mapper could identify such partial harvests; however, these types of disturbances are beyond the capability of the sensor. To estimate annual removals, it was necessary to classify FIA conditions as clearcut based on the condition observed at T2. The estimated acres clearcut per year for the intersurvey period 1999/2000 to 2004/2005 are based on an estimate obtained from trees measured in the initial survey and cut or otherwise removed from the timberland base using the following criteria:

- A starting volume of 560 cubic ft per acre (all live trees).
- At least 75 percent of initial volume was observed cut.

Out of the 1,761 forest plots remeasured in this study, 68 plots contained conditions that met these criteria. In addition to theses 68 plots, another 138 plots had conditions that did not meet the "clearcut" rule but had some observed tree removals.

## Results

### FIA and MN-DNR Annual Removal Estimates Compared

The MN-DNR yearly average harvest estimate was 140,121 acres. This figure is based on estimates reported in Aunan *et al.* (2004) (112,000 acres), Aunan *et al.* (2006) (160,180 acres), Befort and Deegan (2002) (157,212 acres), Befort *et al.* (2003) (133,082 acres), and Deegan *et al.* (2005) (138,133 acres).

The FIA per-year removal estimate for the intersurvey period between 1999/2000 and 2004/2005 was 142,534 acres, with an average of 1673 cubic ft per acre cut and a range of between 532 and 6,380 cubic ft per acre cut. The sampling error on the FIA estimate is 11.8 percent, indicating no statistically significant difference between the two independent removal estimates.

### MN-DNR Harvest Polygons and FIA Plot Intersections

**Removals.** Figure 2 shows boxplots and histograms[5] of FIA plots with observed tree removals. Out of the 1,761 plots remeasured, 206 were observed by field crews to have trees removed from the plot during the remeasurement period by harvesting, cultural operations such as timber stand improvement, land clearing, or changes in land use. The top boxplot and histogram to the immediate right were derived from plots that landed in harvest polygons (67 FIA plots).

The bottom boxplot and histogram to the immediate right were derived from plots that did not fall into harvest polygons (139 FIA plots). For the 67 plots that landed in harvest polygons, a statistically significant difference occurs in the mean plot-level volume (218 cubic ft) when compared to the mean plot-level volume of the 139 plots that do not occupy harvest polygons (129 cubic ft).

Figure 3 is a boxplot and histogram of plots with tree removals in relation to the nearest harvest polygons that conceivably might but did not contain them. Thirty of the 139 plots were located within 100 m of a harvest polygon. The average distance between mapped plots with tree removals that did not occupy satellite-detected harvest polygons was 1,238 m.

**Mortality.** Boxplots and histograms of FIA plots with observed tree mortality are shown in figure 4. The top boxplot and histogram to the immediate right were derived from plots that landed in harvest polygons (49 FIA plots). The bottom boxplot and histogram to the immediate right were derived from plots that did not fall into harvest polygons (837 FIA plots). Only about 5 percent of all plots observed with tree mortality land

[5] Each boxplot gives an idea of the spread (i.e., the data's symmetry and skewness at a glance). The box itself contains 50 percent of the data. The upper edge (hinge) of the box indicates the 75th percentile. The lower hinge indicates the 25th percentile. The range of the middle two quartiles is the interquartile range. The line in the box indicates the median value of the data. The ends of the vertical lines (whiskers) indicate minimum and maximum data values unless outliers are present, in which case whiskers extend to a maximum of 1.5 times the interquartile range. The histogram bins show the plot distribution frequency. The number of plots (n), mean (x bar), and standard deviation (s) for each data set are also shown.

Figure 2.—*Boxplots and histograms of Forest Inventory and Analysis removal plots intersected with Minnesota Department of Natural Resources harvest polygons. The top boxplot and histogram to the immediate right were derived from plots with observed tree removals that landed in harvest polygons. The bottom boxplot and histogram to the immediate right were derived from plots with observed tree removals that did not fall into harvest polygons.*

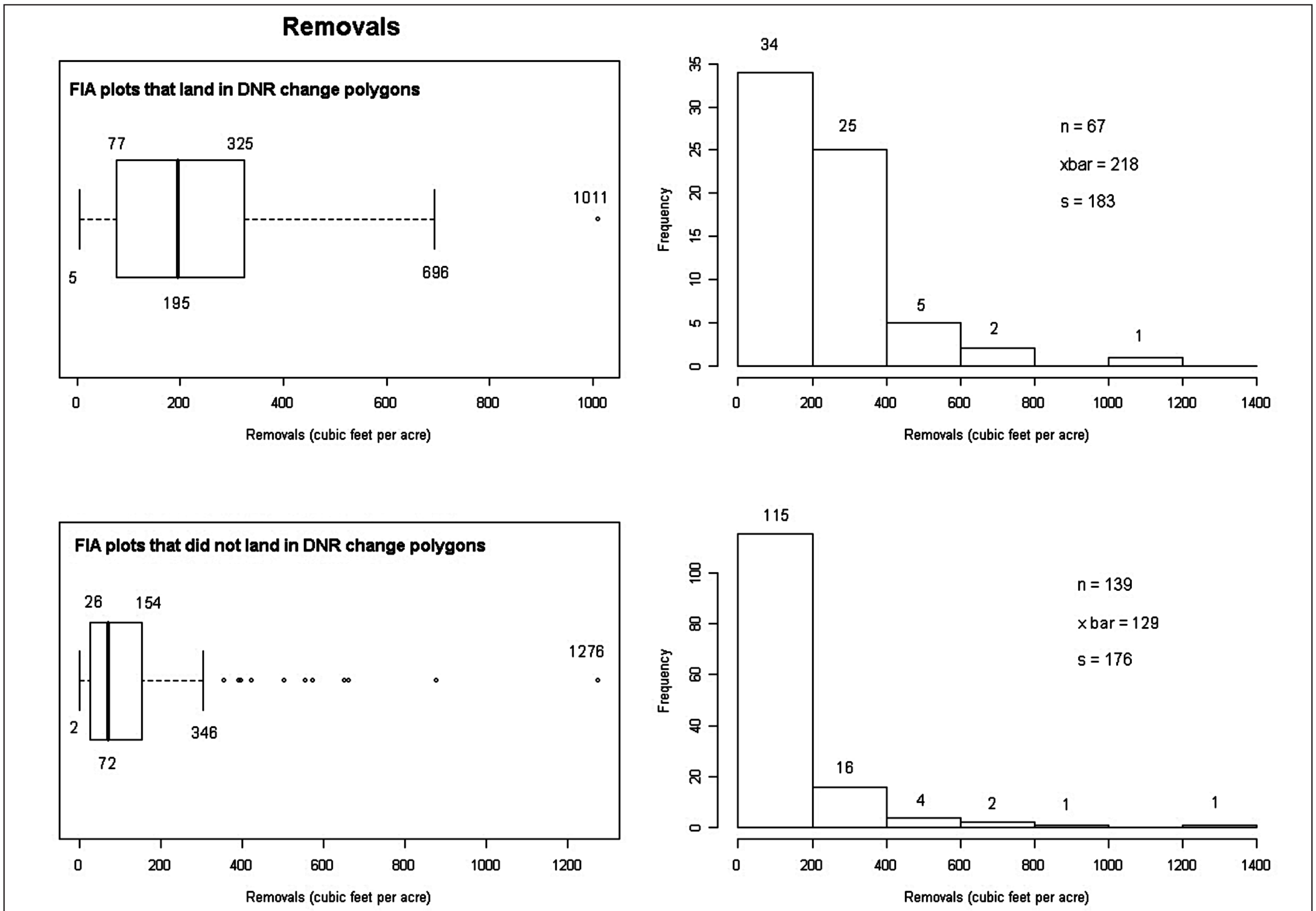



Figure 3.—*Proximity boxplot and histogram of Forest Inventory and Analysis removal plots that did not land in satellite-detected harvest polygons.*

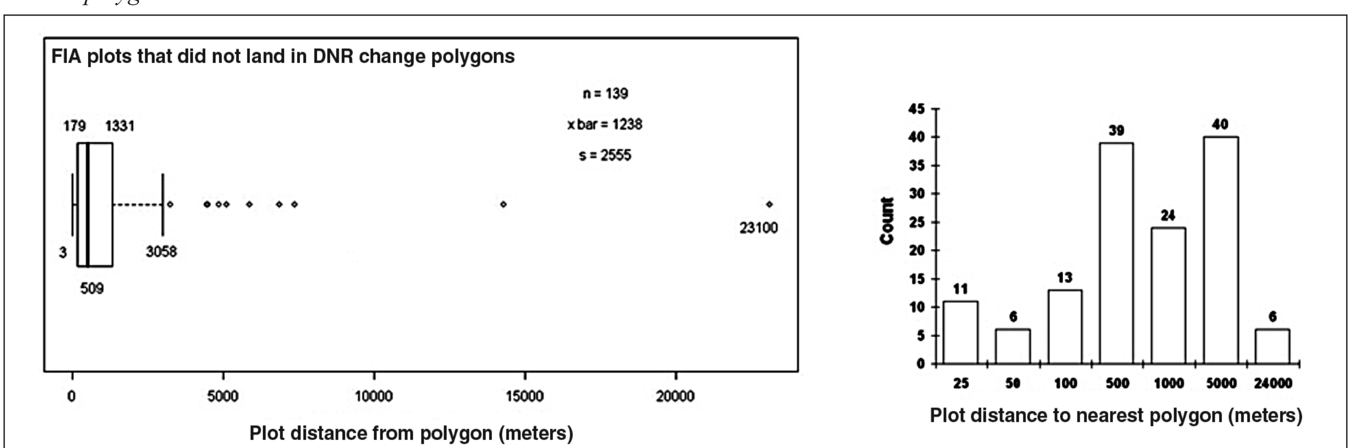
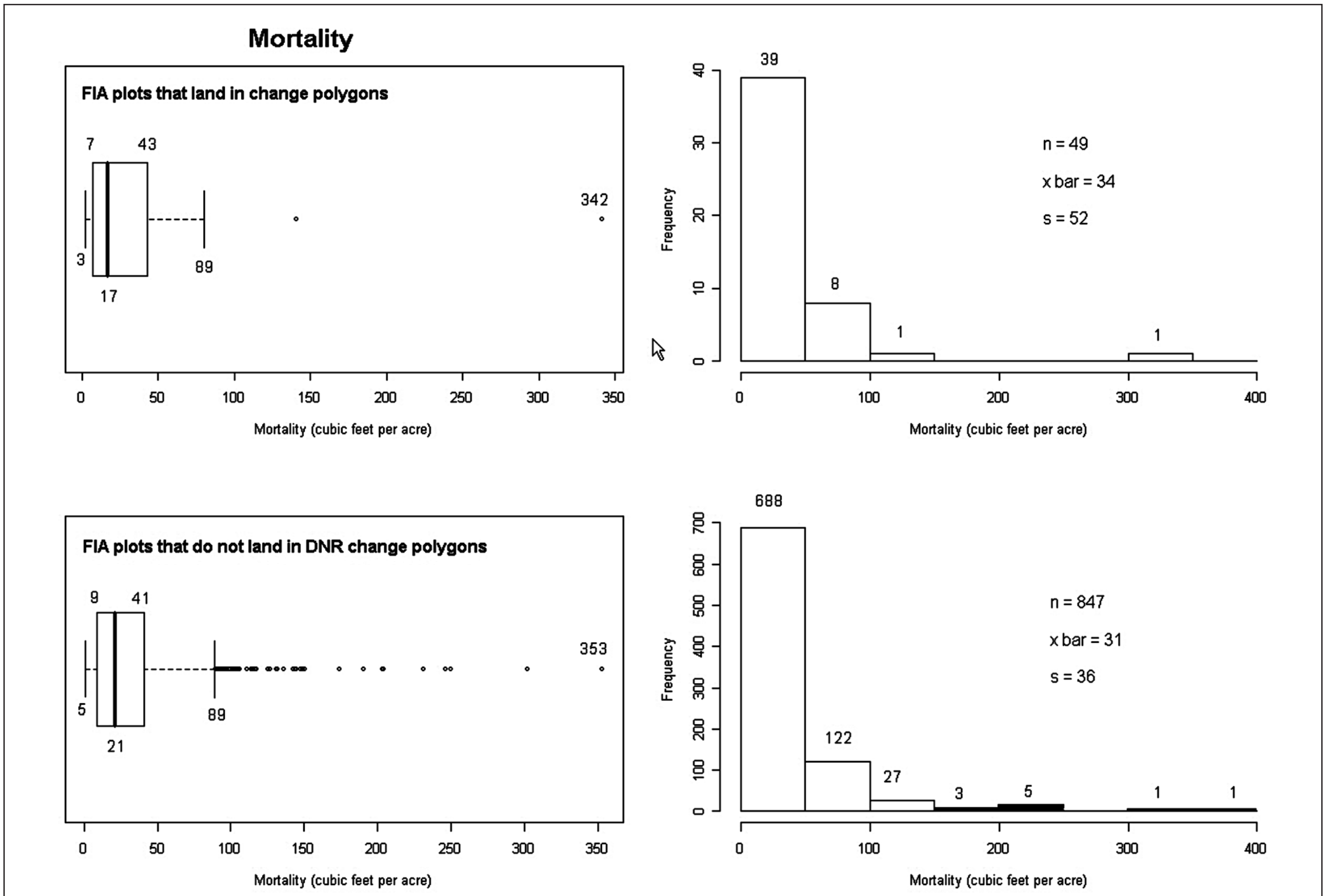


Figure 4.—*Boxplots and histograms of Forest Inventory and Analysis mortality. The top boxplot and histogram to the immediate right were derived from plots with observed tree mortality that landed in harvest polygons. The bottom boxplot and histogram to the immediate right were derived from plots with observed tree mortality that did not fall into satellite-detected harvest polygons.*




in harvest polygons. For the 49 plots that landed in harvest polygons, a statistically significant difference did not occur in the mean plot-level volume (34 cubic ft) when compared to the mean plot-level volume of the 847 plots that do not land in harvest polygons (31 cubic ft).

## Discussion

The FIA-based estimate of annual removals compares closely to the average annual MN-DNR estimate. Analysis of site-specific change suggests FIA plots with observed high-volume removals tend to be located in harvest polygons. Plots observed with tree mortality tend not to land in harvest polygons satisfying the RA harvest mapping objective. Partial removals, however, are not typically mapped as change in satellite-mapped harvest polygons. Plot-polygon proximity does not seem to be a reason, but it cannot be ruled out. The following factors may help explain why FIA plots with observed partial tree removals fail to get mapped inside Landsat-detected harvest polygons:

- Temporal differences between FIA field observations and image acquisition date(s). Change detection work over time requires close correspondence between data sets representing T1 and T2. Some FIA field plots were probably observed after image acquisition and vice versa.
- Resolution differences. The FIA field plot is spread out over approximately 1 acre compared with the minimum 2-acre mapping unit of MN-DNR polygons. Befort *et al.*

(2002) notes that a 2-acre harvest minimum might be expected to press the limits of possibility in Landsat-based disturbance detection. A Landsat 5 Thematic Mapper or Landsat 7 Enhanced Thematic Mapper multispectral scene consists of a rectangular array of approximately 6,000 x 6,000 picture elements (pixels) covering an area of 180 x 180 km (110 x 110 mi). Each pixel measures 30 x 30 m in ground dimensions—about 100 x 100 ft, or roughly ¼ acre. A 2-acre harvest may thus involve only 8 of the 36 million pixels in the scene. As reported in Befort *et al.* (2002), "This is near the level of random 'noise' likely to arise in any between-date satellite image comparison through geometric misregistration, atmospheric interference, and other inexactitudes."

- Practically speaking, nothing in nature is permanent except change. Forest ecosystems are dynamic. In particular, deciduous vegetation undergoes dramatic seasonal changes. Each satellite image imparts a unique collection of illumination, atmospheric conditions, and canopy cover that exists once and never recurs exactly the same way twice. The purpose of the change algorithm is to filter out, using clues provided by reflected light, unique types of change that are discernible. In many cases, change is detected and validated, but some uncertainty at the margin threshold is inevitable (Aunan *et al.* 2006).
- No two instruments are identical and they deteriorate over time. In 2003 and 2004, RA employed a mix of data from Landsat 5, which has been in continuous service since 1984, and Landsat 7, which was launched 15 years later in 1999. Since being placed in orbit, Landsat 7 has developed a mechanical fault with the scan line corrector that affects sensor performance. Although standard normalization routines are applied, it is unlikely that any calibration can completely remove all performance differences between both sensors (Aunan *et al.* 2006).
- Satellite forest removal detection is complicated by unrelated forest stressors. For example, Miles *et al.* (2005) reports that, over the 5-year period from 1999 to 2003, millions of acres of Minnesota's northern boreal forests were defoliated in early summer by the forest tent caterpillar (*Malacosoma disstria* Hubner). Other problematic defoliators during the time period include jack pine and spruce budworm. Such defoliation produces reflectance effects that mimic partial removals. In order to avoid confusing defoliation with removals, RA makes every attempt to obtain late-summer imagery taken after refoliation, but refoliation is sometimes late and therefore the timing of image acquisition is imperfect. The imagery used throughout this period probably incorporates defoliation effects and contributes to mismatch between FIA removal plots and MN-DNR harvest polygons.
- Finally, forest practices change. Clearcutting is the prevalent logging method used in Minnesota; however, partial cuts form an increasing fraction of harvests. The satellite image differencing method detects many partial cuts, but, as noted, a threshold exists at which a change in canopy density ceases to be obvious. We cannot precisely map that limit, because in marginal cases the other dynamics pointed out may lead to sentinel-site–specific change mapping uncertainty.

## Conclusions

Three conclusions can be gleaned from this study:

1. FIA and MN-DNR statewide area estimates of annual clearcutting are fundamentally the same when a threshold of 560 cubic ft per acre and 75 percent of initial volume is applied to FIA plot data.
2. FIA plots with observed partial removals and mortality are not typically contained in one of the satellite-detected harvest polygons. FIA plots have the resolution to show change that cannot be detected by Landsat satellites unless a significant change in canopy cover occurs.
3. There appears to be a relationship between Landsat satellite-detected clearcuts (polygons) and FIA plots with large observed removals.

RA combines satellite imagery and aerial photography as an effective means of estimating annual harvest in Minnesota forests. The satellite imagery provides not only an estimate of change but also a moderately high-resolution map that has value in evaluating forest loss using other high-resolution data. The satellite-based change map has great potential as an ancillary data layer for increasing the precision of FIA removal estimates.

## Literature Cited


Aunan, T.J.; Deegan, G.; Befort, W.A. 2004. Satellite-based forest change monitoring: 2003 report. Resource Assessment. Grand Rapids, MN: Minnesota Department of Natural Resources, Division of Forestry. 9 p.

Aunan, T.J.; Deegan, G.; Rack, J. 2006. Minnesota forest change monitoring: 2003-2005 report. Resource Assessment. Grand Rapids, MN: Minnesota Department of Natural Resources, Division of Forestry. 9 p.

Bechtold, W.A.; Patterson, P.L. (eds.). 2005. The enhanced Forest Inventory and Analysis program—national sampling design and estimation procedures. Gen. Tech. Rep. SRS-80. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 85 p.

Befort, W.A. 2000. Change detection, stratification and mapping for continuous forest inventory. Proceedings, 1999 section on statistics and environment, joint statistical meetings. Alexandria, VA: American Statistical Association: 7-12.

Befort, W.A.; Aunan, T.J.; Deegan, G. 2003. Satellite-based forest harvest monitoring: 2002 report. Resource Assessment. Grand Rapids, MN: Minnesota Department of Natural Resources, Division of Forestry. 12 p.

Befort, W.A.; Deegan, G. 2002. Change analysis applications in DNR resource monitoring. Resource Assessment. Grand Rapids, MN: Minnesota Department of Natural Resources, Division of Forestry. 16 p.

Chandler, G.; Markham, B. 2003. Revised Landsat 5 TM radiometric calibration procedures and post-calibration dynamic ranges. U.S. Geological Survey online document. http://landsat.usgs.gov/documents/L5TMCal2003.pdf. [Date accessed unknown].

Deegan, G.; Aunan, T.J.; Befort, W.A. 2005. Minnesota forest change monitoring: 2004 report. Resource Assessment. Grand Rapids, MN: Minnesota Department of Natural Resources, Division of Forestry. 10 p.

Hahn, J.T.; McRoberts, R.E.; Befort, W. 1992. Annual forest inventory system (AFIS): integrating data base techniques, satellite imagery, annual designed sampling and modeling. Proceedings, Conf. Integrated Forest Resource Information, Space, Time. Canberra, Australia: 314-324.

Miles, P.D.; Brand, G.J.; Mielke, M.E. 2005. Minnesota's forest resources in 2003. Resour. Bull. NC-246. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Research Station. 36 p.