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DEFORESTATION AND FOREST HARVEST MAPPING WITH INTEGRATED AUTOMATED AND MANUAL METHODS: PILOT STUDY PRINCE GEORGE, BRITISH COLUMBIA, CANADA

D. Leckie, S. Tinis, M. Henley, F. Eichel, N. Walsworth, D. Hardman, W. Burt,
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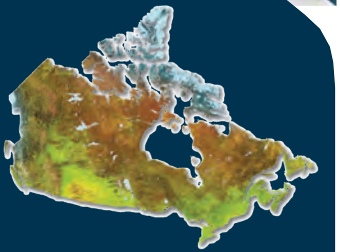

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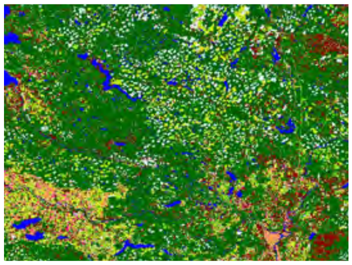

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Deforestation and Forest Harvest Mapping with Integrated Automated and Manual Methods:
Pilot Study Prince George, British Columbia, Canada

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Abstract

It is important to monitor and understand disturbances in forests at a national and regional level. Key among these disturbances are stand-replacing changes, such as harvest, deforestation, and burns. Possible sources of disturbance information include remote sensing, whether through automated techniques or manual interpretation, and forest inventories with inventory updates. This report uses a pilot study to explore the synergy and combination of such data sources to map human-induced changes such as harvest and deforestation.

The pilot region was the Prince George area of central British Columbia. This area has characteristics representing several major types of landscapes and human activity found across Canada, and contains some of the more difficult settings for deforestation mapping. Decadal change (1990–1999) was used to explore methods of capturing forest change. Methods examined in detail were: automated two-date change classification using Landsat imagery, manual interpretation of the same imagery supported by ancillary data and quality control steps, and use of updated provincial forest inventory maps. A particular focus was on the effectiveness of data sources and methods for deforestation mapping (e.g., ancillary data, site familiarization and local records, the interpretation environment, the interpretation process, field verification, second-cycle mapping review, automated classification, and forest inventory data).

Automated change classification with post-processing was very effective for clearcut mapping in a simple industrial forest setting. However, it was not sufficient to utilize directly or as a main source of polygons for deforestation mapping, especially in more complex urban or mixed rural residential, agriculture, and forest areas. Forest inventory was lacking in terms of being up to date and, for deforestation mapping, did not provide enough spatial, cover type, or land use information. Nevertheless, the forest inventory still provided useful harvest polygons and information for deforestation assessment. The effort to undertake automated change classification was not warranted for deforestation mapping alone. In environments with mixed forest management and agriculture, and (or) rural development, automated techniques will require some human interpretation to differentiate harvests from deforestation as there can be considerable confusion between them.

Results informed the development of Canada's National Deforestation Monitoring System and provide insight into how to monitor forest harvest and other changes at regional and national levels.

Keywords: accuracy assessment, automated change classification, deforestation, forest disturbance mapping, forest inventory, Prince George

Résumé

Il est important faire le suivi et de comprendre les perturbations dans les forêts aux échelles régionale et nationale. Parmi les perturbations, les plus importantes sont celles qui ont pour effet de remplacer les peuplements, comme la récolte, le déboisement et les feux. Les sources possibles d'information sur les perturbations comprennent la télédétection, avec des techniques d'interprétation informatisée ou manuelle, et les inventaires forestiers avec mises à jour. Le présent rapport se fonde sur une étude pilote pour explorer la synergie et la combinaison de ce genre de sources au service de la cartographie des perturbations d'origine humaine comme la récolte et le déboisement.

La région pilote était celle de Prince George dans le centre de la Colombie-Britannique. Cette région se caractérise par plusieurs grands types de paysage et d'activité humaine qui se retrouvent au Canada, et elle renferme certaines des conditions les plus difficiles pour la cartographie du déboisement. Nous avons retenu l'évolution décennale (1990–1999) afin d'étudier des méthodes de saisie des modifications de la forêt. Nous avons examiné en détail les méthodes suivantes: classification automatisée du changement entre deux dates d'images Landsat, interprétation manuelle des mêmes images en s'appuyant sur des données accessoires et en suivant des étapes de contrôle de la qualité, et utilisation des cartes provinciales d'inventaire forestier mises à jour. Nous nous sommes concentrés en particulier sur l'efficacité des sources de données et des méthodes de cartographie du déboisement (données accessoires, familiarisation avec le site et registres locaux, environnement d'interprétation, processus d'interprétation, vérification sur le terrain, examen de la cartographie du deuxième cycle, classification automatisée et données d'inventaire forestier).

La classification automatisée du changement avec post-traitement a été très efficace pour la cartographie de la coupe à blanc dans un contexte simple de forêt industrielle. Toutefois, elle ne suffisait pas pour utilisation directe ou comme source principale de polygones pour la cartographie du déboisement, en particulier dans des contextes plus complexes, urbains ou à occupation mixte résidentielle, agricole et forestière. Les inventaires forestiers n'étaient pas à jour et, aux fins de la cartographie du déboisement, ne donnaient pas suffisamment d'informations sur l'occupation des sols ou le type de couverture, ni suffisamment d'informations spatiales. Néanmoins, les inventaires ont fourni d'utiles polygones de récolte et des informations pour l'évaluation du déboisement. L'effort à consentir pour réaliser la classification automatisée des modifications n'en valait pas la peine pour la seule cartographie du déboisement. Dans les environnements alliant aménagement forestier et agriculture et (ou) développement rural, les techniques automatisées exigeront une certaine interprétation humaine pour distinguer la récolte du déboisement, qui sont très faciles à confondre.

Les résultats ont guidé l'élaboration du Système national de surveillance du déboisement du Canada et ils éclairent sur la façon de faire le suivi du changment apportées par la récolte forestière et d'autres perturbations aux échelles régionale et nationale.

Mots-clés: évaluation de l'exactitude, classification automatisée du changement, déboisement, cartographie des perturbations forestières, inventaire forestier, Prince George

1. Introduction

There is a need to monitor, document, and understand the nature of human-induced forest disturbances at the national, regional, and local level. Important among these disturbances are stand-replacing depletions such as harvest (clearcuts and partial cuts) and deforestation. Several international obligations also require reporting on such changes through the United Nations Food and Agriculture Organization, United Nations Framework Convention on Climate Change (UNFCCC), and the Kyoto Protocol, Copenhagen Accord, Durban Platform, and other agreements. Land managers, policy makers, and politicians, as well as the public and environmental organizations need clear and transparent information on forest harvest and deforestation, including their type, location, extent, and rate. Such information also provides a foundation for monitoring greenhouse gas emissions from forests in order to understand the role of forests in climate change, develop mitigation strategies, and meet international reporting needs.

A national program for deforestation estimation is in place and has reported deforestation estimates since 2007. The program is led by the Canadian Forest Service and uses a combination of satellite remote sensing change analysis and records information (Leckie et al. 2006a; Dyk et al. 2015). Results are converted to greenhouse gas emissions (GHG) by applying a carbon accounting model (the CBM–CFS3; see Kull et al. 2007; Kurz et al. 2009) that considers the carbon content of the forest prior to deforestation, soil carbon, and decay of associated dead organic matter over time to estimate greenhouse gas emissions from deforestation, according to the rules and guidelines set forth for U.N. Framework Convention on Climate Change and Kyoto Protocol reporting in Good Practice Guidance (GPG) documentation (Intergovernmental Panel on Climate Change 2003). The deforestation area estimates and associated greenhouse gas consequences are reported annually in Canada's National Inventory Report on Greenhouse Gas Sources and Sinks (Environment Canada 2007; 2014). Deforestation estimation to date has focused on the periods 1970–1990, 1990–2000, 2000–2008, and some from 2008 onward. The general deforestation mapping approach is to use Landsat data from these time periods (say, 1990–2000), examine them visually for forest clearings, and then determine whether the clearing is a result of deforestation (permanent land use change to another land use), or some other change such as forest harvest. To facilitate this process, ancillary data are also examined, including: aerial photography, winter imagery, records, forest inventory, Geographic Information System (GIS) coverage of wetland areas, roads, and settlements, as well as specialty databases (e.g., power transmission lines, hydroelectric developments, and oil and gas well pads and pipelines), and field observations. Deforestation is mapped on a sample or full-coverage basis and compiled to produce annual deforestation area estimates on an ecozone and national basis, subdivided by general category of causal agents (e.g., urban, industrial, agriculture, hydroelectric, oil and gas).

National and regional land cover maps of Canada based on medium-resolution satellite imagery are now practical to produce. The Canadian Forest Service and provincial partners supported by the Canadian Space Agency have produced a 30-m resolution land cover map (Earth Observation for Sustainable Development of Forests [EOSD]) for the forest regions of Canada for circa year 2000 (Wood et al. 2002; Wulder et al. 2008). This gives land cover in broad classes and concentrates on forest classes. Examples of the EOSD classes are: exposed land, herb, and graminoid cover. In terms of forest cover, there are three composition classes, namely conifer, mixedwood, and deciduous, and each is divided into three density classes--dense, open, and sparse (Wulder et al. 2004). The National Lands and Wetlands Information System, led by Agriculture and Agri-Food Canada, generated a similar product in the agriculture zones in southern Canada concentrating on agriculture classes (Agriculture and Agri-Food Canada 2008). In addition Agriculture and Agri-Food Canada (Fissette et al. 2013) currently produces annual crop maps at 30-m resolution based on earth observation and other data for the agricultural regions of Canada. Olthof et al. (2009) also created a land cover map of Canada from Landsat data and more recently from SPOT imagery. It is desirable to update these maps periodically, such that any differences in the land cover between successive maps is compatible with true changes, and to produce an associated change map giving the area and type of change (Cranny et al. 2008; Leckie et al. 2008).

A change map of disturbances such as forest harvest is also useful at the local and regional levels and for Canada's national forest inventory. Integrated change mapping procedures suitable for such a national application at the 30-m resolution are desirable. Numerous techniques are currently available to achieve this. Hansen and Loveland (2012) provide a review of change-detection methods, programs, and issues relevant to Landsat and large-area programs.

In Canada, annual burned area maps are produced through the Fire Monitoring, Accounting and Reporting System (FireMARS) using Landsat and other earth observation as a main tool.[1] Maps of annual large forest disturbance from 2001 to 2011 were produced using 250-m spatial resolution Moderate Resolution Imaging Spectroradiometer (MODIS) imagery (Guindon et al. 2014). Visual interpretation and combined automated and visual analysis

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[1] See: the Natural Resources Canada Fire Monitoring, Accounting and Reporting System (FireMARS) website at: http://www.nrcan.gc.ca/forests/fire/13159.

of Landsat data for disturbed areas have been generated over large regions (Lee et al. 2010; Pasher et al. 2013). An automated technique for large area forest change mapping was developed under the EOSD program (Walsworth and Leckie 2004). Furthermore, recent techniques are starting to use the time sequence of annual imagery and imagery within a year to help detect change. Detection and delineation of changed areas is one component; a more difficult element is attributing a cause for the disturbances, as in differentiating among clearcuts, partial cuts, insect damage, wind blowdown, burns, and deforestation. A general approach to change mapping and attributions is to use medium-resolution satellite imagery to identify areas of forest change, aggregate them into spatial units, and then use available evidence to ascribe change type (Walsworth et al. 2003).

This study reports on a pilot project undertaken to help develop and test techniques to be used in the deforestation estimation procedure and to be available for national or broad region forest change mapping or sampling. The purpose of this pilot was to produce a forest disturbance map for the period 1990–1999 that incorporates deforestation, harvest, and burns. The methods and products are designed to be suitable for input to regional, national, and international analysis and reporting; and for a complete analysis of greenhouse gas emissions from the forests in the pilot region.

The pilot site was located in the Prince George region of central British Columbia, Canada. It has landscapes that represent high use industrial forests and agriculture that is similar to the prairie fringe regions of Canada, and a growing resource-based city in a forest setting. In addition, areas of mixed use exist, including forest harvest, agriculture, and rural residential development. Such mixed use areas are one of the most difficult environments in which to estimate deforestation and differentiate forest harvest from land use change.

The full deforestation mapping procedure used to estimate Canada's deforestation calls for the following six components:

1. exploration of available records data for possible direct use;
2. interpreter calibration, preferably with a site visit;
3. deforestation mapping with Landsat imagery and using available ancillary data, such as forest inventory;
4. quality control, including field observations usually from light aircraft;
5. revision of the initial mapping; and
6. final vetting.

During subsequent deforestation mapping of a region for later time periods, a review and revision of the mapping, referred to as "second-cycle mapping review", is conducted. If automated change detection or mapping is available, this is also used as seed sites (possible candidate events) in the deforestation interpretation. Deforestation monitoring in Canada is an ongoing activity that progressively maps deforestation within new time periods (e.g., 1970–1990, 1990–2000, 2000–2008, 2008–2012). In the mapping of new periods or cycles, previous deforestation mapping is reviewed for errors of commission and omission, and other possible improvements and revisions are incorporated to produce an updated map. This pilot includes all of these steps and integrates procedures to also map forest harvest. The most recent updated forest inventory at the time of mapping was used to help capture both harvest and deforestation.

Factors affecting the mapping and usefulness of the automated change polygons, inventory data, and manual interpretation were also analyzed. Accuracy of the final product was assessed against independently mapped deforestation and harvest using aerial photography supported by field observations, 2003 orthophotos, and additional Landsat imagery up to year 2006. The benefit of the review process was also investigated as it was undertaken for the operational second-cycle (2000–2008) deforestation mapping, approximately eight years after completion of the initial mapping. Findings on the effectiveness of the various procedures and data sources, issues encountered, and accuracies achieved are summarized in Section 5 ("Summary and Discussion"). Although conducted as a method development and trial study, the results and lessons learned are appropriate for operational implementation of a full system of forest change and land cover updates, and for deforestation mapping.

2. Site and Data

2.1. Study Area

An approximately 135 × 105 km test site, centred near Prince George, British Columbia (123°20′W; 54°15′N), was extracted from the area covered by Landsat scene path 49, row 22 (Figure 1). The time period of interest for this study was 1990–1999. A 351-km2 zone on the east side was excluded from the study area as it represented part of Tree Farm Licence 30 and forest inventory data was not readily available.

Figure 1. Study site location with the pilot region boundary in red.

The total study area was 13 824 km2 and covers a diversity of land use and landscape patterns that are representative of forestry, agricultural, urban, and mixed settings (Figures 2 and 3). The Prince George region of central British Columbia lies within the Montane Cordillera ecozone (Wiken 1986). Terrain is generally gently rolling and much of the area has a northeast–southwest pattern of drumlinoid ridges. Forestry is one of the area's primary economic drivers and focusses mainly on lodgepole pine (Pinus contorta var. latifolia), white spruce (Picea glauca), and subalpine fir (Abies lasiocarpa). Annual harvest area during the 1990s was approximately 8000 ha. Harvests conducted within the pilot area are mainly clearcuts within conifers (predominantly lodgepole pine); cuts are commonly 30–150 ha in size and generally have straight or smooth edges and rectilinear shapes. New cuts are either additional cuts within active regions with existing harvest and access roads, or cutblocks extending into new harvest regions. The cutting is accompanied by forest access road development. Older clearcuts were in varying stages of ground vegetation cover and regeneration. No burns occurred over the study period. The region was hit by a mountain pine beetle (Dendroctonus ponderosae Hopkins) outbreak that caused considerable mortality of the lodgepole pine; however, this occurred largely in the early and mid-2000s and did not affect this study.

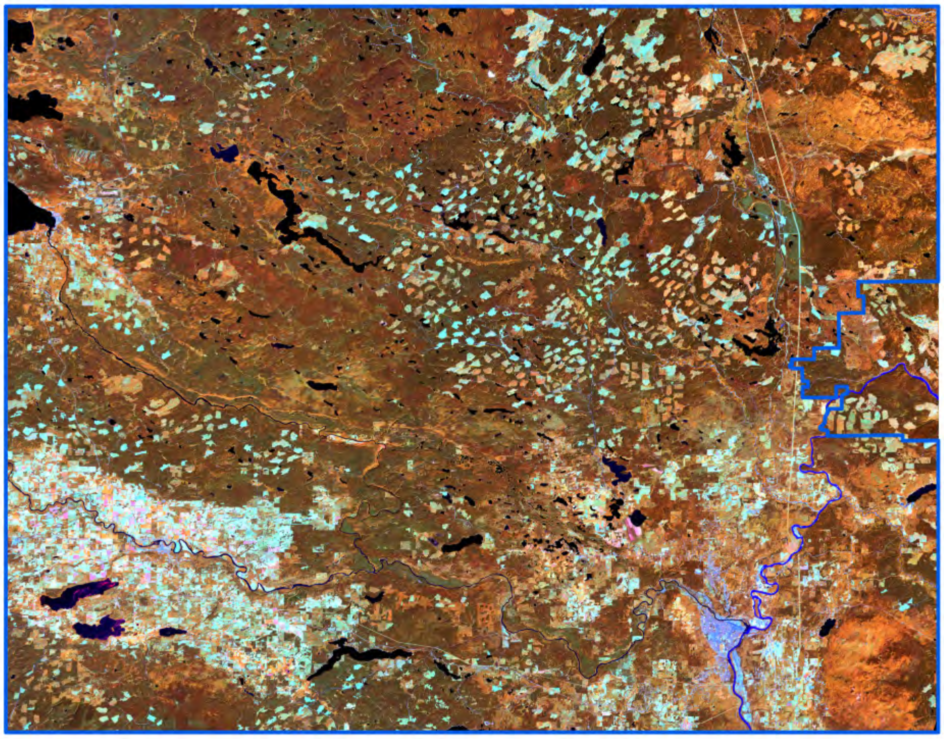

Figure 2. 1990 Landsat image of the pilot region. Near infrared, shortwave infrared, and red bands (4, 5, 3) are displayed as red, green, and blue, respectively.

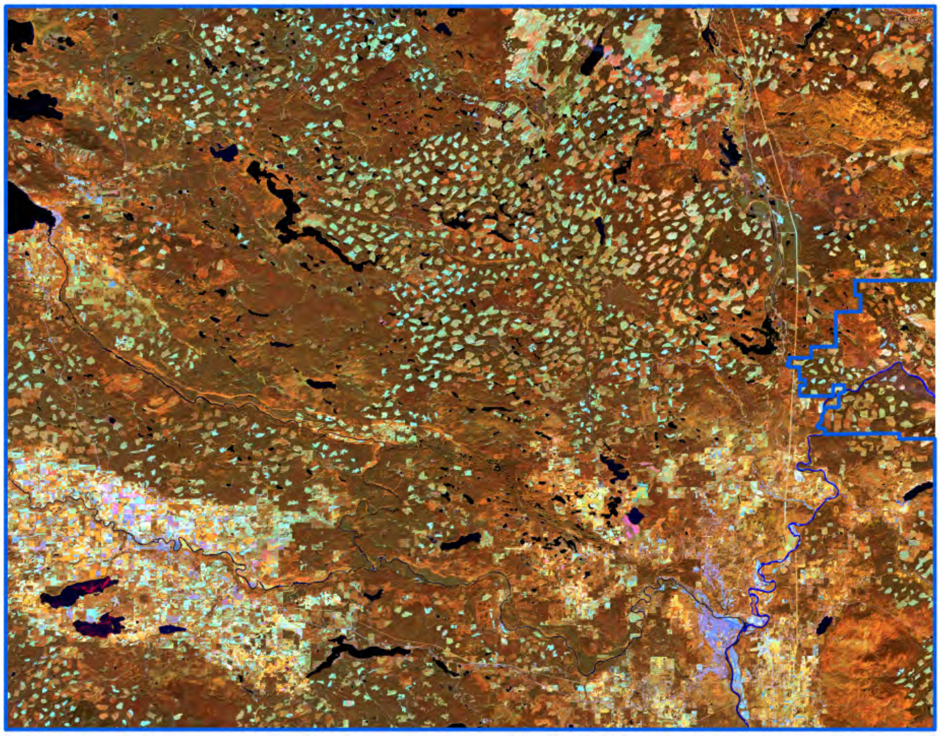

Figure 3. 1999 Landsat image of pilot region. Near infrared, shortwave infrared, and red bands (4, 5, 3) are displayed as red, green, and blue, respectively.

The other major industry in the area is agriculture, which is concentrated in two regions. One of these regions is in the vicinity of Prince George and is intermixed with forests, forestry activity, and rural residential development. The second is an approximately 45 × 22 km region on the west side of the site, around the town of Vanderhoof. Cattle with pasture, hay, and forage crops plus cereal crops are the main agricultural activities. In the Vanderhoof region, farms are generally large and of a similar nature to those in the Peace River district of British Columbia and Alberta as well as other prairie fringe regions. Near Prince George there are also smaller farms and hobby farms. Property boundaries and field boundaries are commonly on a grid system, often based on a section (1 × 1 mile) and quarter section survey pattern, and thus field boundaries are frequently linear.

The study area contains three major communities. Prince George is a large urban centre, which experienced significant growth during the period 1990–1999, with the population growing from 70 860 to 76 990. The city also had visible expansion and development in the service, recreation, and housing sectors. It is also an industrial city with several large established forest product processing plants. During the 1990s, the University of Northern British Columbia was created and a campus built within a forest setting on the outskirts of the city. Vanderhoof (1999 population of 4629) is a centre for agricultural activity while Fort St. James (1999 population of 2060) is a smaller, mainly forestry-based community.

2.2 Data for Forest Disturbance (Harvest and Deforestation) Mapping

To determine forest harvest and deforestation over the 1990s, core mapping and analysis was done with 1990 and 1999 Landsat imagery (Figures 2, 3, and 4). Landsat scenes for path 49, row 22 were acquired and orthorectified (10 August 1990, Landsat 5 Thematic Mapping [TM], 30 m resolution with visible, near infrared, and shortwave infrared bands [1–5 and 7]; and 12 September 1999, Landsat 7 Enhanced Thematic Mapping [ETM+], also with 30-m resolution bands 1–5 and 7 plus a 15-m resolution panchromatic band). For the 1999 image, there was some senescence on the hardwood trees and to a lesser extent on the ground vegetation, but there was no leaf fall. These images were used in both an automated two-date, unsupervised classification of forest type and change, and a visual interpretation of deforestation and harvest events.

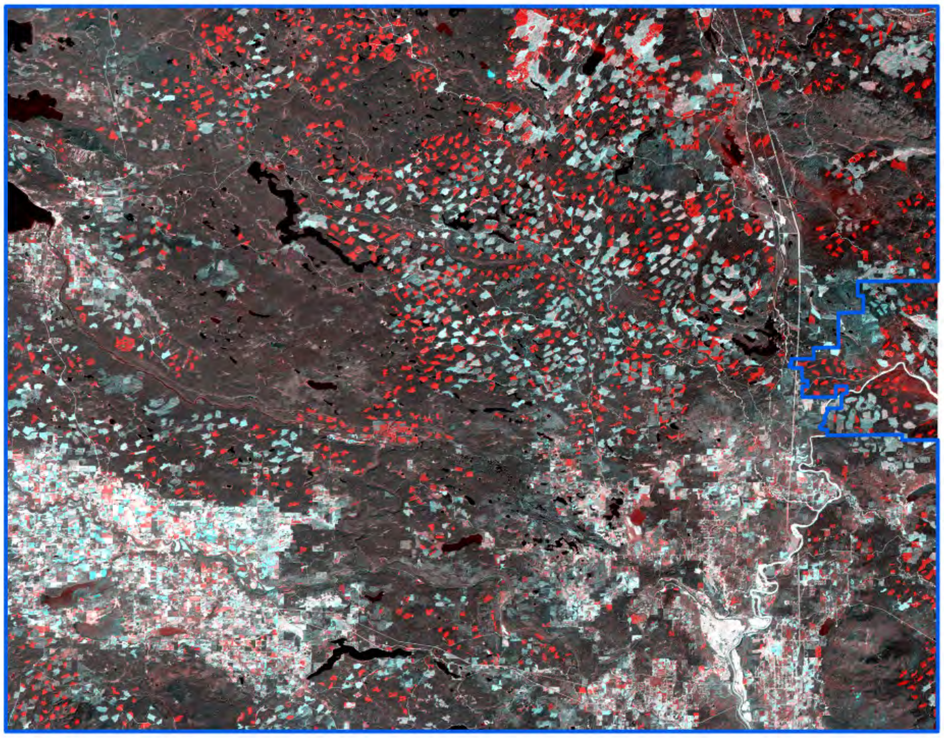

Figure 4. Landsat change enhancement image of pilot region. The 1999 red band (band 3) is displayed as red and the 1990 red band as green and blue.

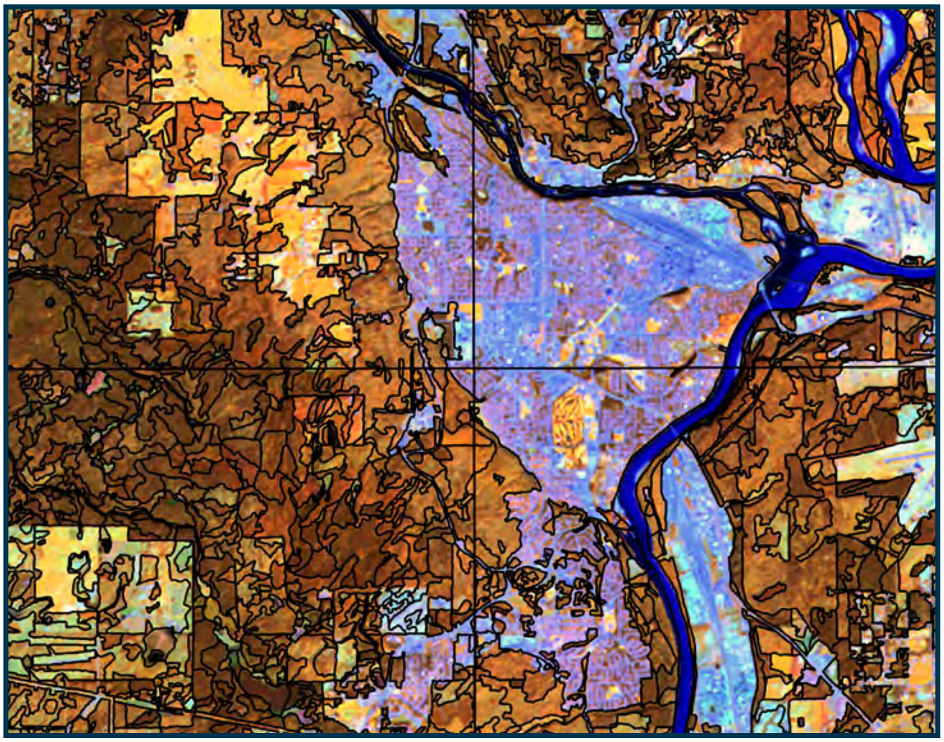

Figure 5. Example of the forest inventory polygons used in the study. Landsat image from 1999 is in the background.

Forest inventory from the British Columbia Ministry of Forests, Lands and Natural Resource Operations was used as an independent source of forest harvest information and also as an aid in the interpretation of deforestation (Figure 5). The inventory is a 1:20 000 scale stand map within a Geographic Information System (GIS), giving species composition, crown closure, height, and other data. The inventory is produced from aerial photography and updated through standard procedures for forest harvest and other disturbances (Leckie and Gillis 1995; Gillis and Leckie 1996; B.C. Ministry of Sustainable Resource Management 2002). The inventory used was dated 2000 and should have been updated for disturbances up to 1999; however, within the inventory process these updates are not always complete or up to date.

The deforestation mapping protocol employed for national deforestation estimation (Leckie et al. 2002, 2006a) calls for the use of as much available ancillary data as possible to augment the Landsat interpretation. Common ancillary data for 1990–2000 deforestation estimation are circa-1990 digitized aerial photographs, later photography preferably close to year 2000, GIS coverages of road networks and wetlands from provincial base maps or the national topographic survey map series, and winter 1990 Landsat imagery. In addition, the availability of local records is explored and if readily available, appropriate, and easily applied, these are assembled and used either directly or to aid deforestation interpretation.

The ancillary data set available and assembled for this project included the following information sources.

- National Topographic Service base map layers at 1:50 000 scale. These layers include a range of data from contours to waterways, wetlands, wooded areas, roads/trails, and buildings.
- Provincial base maps from the TRIM (Terrain Resource Information Management) program. The incorporated "TRIM Control" data were features such as rivers, lakes, reservoirs, ponds, marshes and swamps, fields, roads, railways, transmission lines, mines, pits, quarries, and golf courses.
- 1988 black and white aerial hardcopy photographs at 1:70 000 scale.
- 1996 black and white TRIM digital orthophotography with 1-m pixels, acquired at a scale of 1:30 000. This was the most recent photography available for the time period of the forest disturbance mapping.

3. Procedures and Methods Evaluation

The goal of this project was to generate a complete map of forest disturbance during the period 1990–1999 for the study area. This map should be high quality and be produced with operationally viable methods. The focus was on three main methods that can be applied operationally for much of Canada and the synergy among these methods:

1. automated change classification,
2. manual interpretations of Landsat imagery, and
3. utilization of forest inventory data.

Forest disturbances examined were harvest clearcuts and partial cuts, plus deforestation, which refers to forest clearings permanently converted to another land use. Although burned areas and wind blowdown would normally be among the disturbances mapped, the pilot area did not experience these over the time period of the study. The overall procedure was to conduct a two-date unsupervised change classification to extract forest clearing or depletion events, and then to carry out a visual interpretation and mapping of forest clearing. The change polygons from the automated classification or from forest inventory maps were an alternative to manual delineation of the forest clearing events and could be used when they represented the change well. Change types (e.g., clearcut, partial cut, deforestation by causal factor) were ascribed and labelled via the visual interpretation process. The interpretation environment and procedures followed those developed for deforestation mapping (Leckie et al. 2006a; Paradine et al. 2003a). The steps are:

1. interpreter calibration/training, including gaining knowledge of the local landscape and land management practices;
2. search for useful local data sets and records;
3. interpretation using Landsat and ancillary data;
4. visual check for any clearing polygons generated from the forest inventory and automated classification as a trigger to look for possible events and to use the polygon directly, if appropriate;
5. quality control including field checks;
6. revision; and
7. final vetting.

In addition, when deforestation mapping is conducted for the next time period, the previous mapping is reviewed for errors. This later review process often has more data available (e.g., high-resolution imagery after the deforestation event) and the passage of time permits the new land use to become better established and more conclusive, or allows regeneration to begin and become visible on harvest sites. This review, referred to as "second-cycle review," results in an updated deforestation map. The mapping is reviewed again using similar methods and with updates made if needed in the third mapping cycle.

3.1 Generation of Automated Forest Change Polygons

A two-date, unsupervised classification approach was used to generate forest clearing polygons. Numerous change detection and classification techniques exist with the most common being post-classification comparison, supervised and unsupervised change classification, change vector analysis, and change index thresholding (Malila 1980; Singh 1989; Collins and Woodcock 1996; Lunetta and Elvidge 1998; Franklin et al. 2000). Two-date, unsupervised classification for change detection is a standard approach that has been examined and applied operationally for forestry (Hame et al. 1998; Kalluri et al. 2001; van Lier et al. 2011). It is relatively simple, flexible, robust, and (if required) can be used with data sets containing different vegetation phenology.

The 1990 image was radiometrically normalized to the 1999 image with a relative calibration method (Joyce and Olsson 1999) using stable forest regions as input to establish the gain and offset for the calibration. Landsat bands 1–5 and 7 from each date of the image pair were entered into a K-means clustering algorithm (PCI Geomatics 2001) and run with 241 requested classes, 12 iterations, and an input data sample of 20% of the pixels in the test site. Clusters were labelled according to both time 1 (T1) and time 2 (T2) surface types and thus represent either stable or changed areas. The forest-type classes included three cover types (conifer, broadleaf, or mixed), three density classes (dense: > 60% crown closure; open: 25–60% crown closure; or sparse: < 25% crown closure), and four age classes (old, mature, young, or regeneration). Open areas were categorized on the basis of ground vegetation density (i.e., bare or sparse, low, moderate, or dense) and included a class termed agriculture that included crop, fallow, and pasture. Several other classes completed the suite of classes (e.g., urban, road, wetland, and water). For example, a classification label of "conifer dense mature–conifer dense mature" would mean that the cluster represents dense mature conifer in both 1990 and 1999, whereas "conifer dense mature–low ground vegetation" would represent a clearcut in a conifer forest that in 1999 had low-density ground vegetation. Not all two-date class combinations were present. Clusters representing the same class were aggregated, whereas clusters representing several surface types or changes were re-clustered and labelled. The end product was a classification with stable areas classified into cover type and change areas with a "from" and "to" class label (e.g., Figure 6).

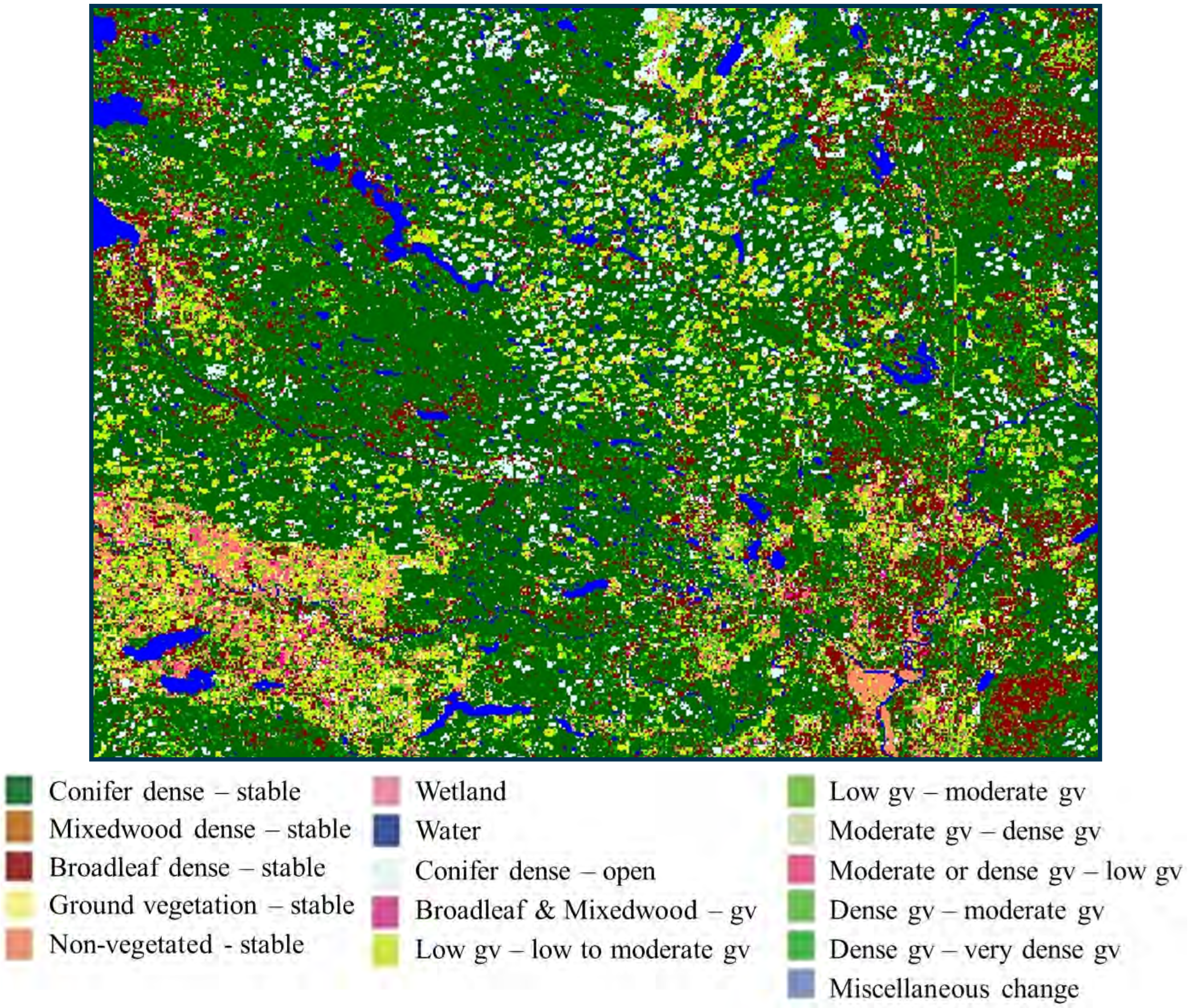

Figure 6. Example of two-date change classification of pilot region (gv = ground vegetation).

The classification procedure produced approximately 170 clusters related to land cover with at least 100 pixels in the cluster. Of these, 30 clusters were related to stable forest types. Seventy-four clusters were associated with land cover change, of which 21 were related to forest clearing, 36 with changes in ground vegetation in previous clearcut or agricultural areas, and 17 were associated with change in vegetation related to senescence. Leckie et al. (2002) described the classification procedures and results in more detail. For convenience, a forest clearing category was created in which all classes changing from a forest class to an open or non-forest class were amalgamated and considered forest clearings that represent candidate harvest or deforestation events. A few clusters remained mixed with combinations of varying degrees of forest clearing and stable pixels, or with spurious changes such as treed wetland, senescence, or change pixels at edges between dense conifer and open areas. These clusters were not common and were included in the forest clearing category. Overall, the classification was effective (Leckie et al. 2002). Moreover, stable forest was well classified as a forest class. Pixel-based accuracy according to test sites of known change was close to 100% for clearcut sites in dense conifer forest—the predominant type of harvest. This was also true for the more recent clearcuts in mixedwoods. Clearcuts in older mixedwoods with moderate or dense ground vegetation were less well classified as were cuts in mature broadleaf. The pixel-based accuracies were in the range of 66–71%. The senescence on the September 1999 image led to some confusion, which accounted for part of the reduced accuracy observed and indeed produced most of the error for mixedwoods that were cut and had moderate-density ground vegetation.

After change classification, it is often useful to aggregate the change pixels into spatial change units (Walsworth and Leckie 2004). One project goal was to produce quality harvest and deforestation polygons. It was thus desirable for the polygons generated from this automated process to be compatible with and similar to those generated from a manual delineation. To accomplish this, two post-classification processes were instituted. First, a sieving was conducted to eliminate small, isolated units of change, followed by a vectorization and smoothing to create a less pixelated and serrated boundary. The forest clearing pixels from the two-date classification were sieved (PCI Geomatics 2001) to remove clusters of forest clearing pixels consisting of three or fewer pixels, connected diagonally or along coincident sides. These clusters were replaced with the class of the largest adjacent group of pixels so that non-change classes were not altered (i.e., not sieved). The data were then converted to line vector format and exported as an Arc/GIS shapefile.

In the second post-classification process, ArcGIS's spline utility was used to smooth the vectors of the forest clearing class. The parameter (tolerance) settings were derived from a set of trials over a subsection of the study area to determine which produced a smooth boundary best reflecting the true boundary shape (fuzzy = 13.48; nodesnap = 1; snap = 1; weed = 20). The spline routine was run twice, first with a grain size of 55, and the second time with a grain size of 15. The method was modelled on the process used in the Fire Mapping, Monitoring and Modelling System (Fire M3) (D. Raymond, Natural Resources Canada, pers. comm.). This process worked well for most polygons, but for small polygons (especially those with convoluted boundaries) it sometimes created artefacts such as cutting polygon corners or inappropriately splitting, combining, or eliminating polygons.

3.2 Preparation and Use of Forest Inventory

British Columbia Ministry of Forests, Lands and Natural Resource Operations' forest inventory map sheets were loaded into the interpretation station within an ArcGIS environment and overlaid on the imagery. Some adjustment was necessary to register the map data with the image data. The maps used had been updated to the year 2000 and should be typical of British Columbia forest inventory maps of that era that would be available several years after the end of a change mapping period (1999 for this study). Each forest stand has a series of forest type attributes that were condensed and displayed on the screen within the stand polygon. Open or regenerating polygons possibly representing harvest could, therefore, be quickly recognized. The date of the clearing is also within the stand attributes; however, not all forest change is updated immediately on forest inventory maps, and thus some forest clearings were not depicted in the inventory map. Nonetheless, for forest clearings that have not been updated in the inventory, the forest type before clearing (i.e., the "pretype") can be determined from the inventory. The pretype can provide a clue about whether the site was deforestation or harvest. For example, if the cleared area was young or immature, one would not expect a forest harvest to occur and the site was more likely to have been deforestation. Also, commercial harvest of hardwoods was not common in the region.

It is not always clear from the inventory whether a clearing or open area on the map is harvest, a land use change or other change since details are not given on the nature and land use of the open areas. Moreover, if the clearing is a land use change, the new land use is not given. Open areas are usually just labelled in broad classes, such as herb, shrub, or exposed land. As well, the inventory concentrates on forest land and Crown land without details within urban, agricultural, or developed areas. Also, if land cover patterns are complex and consist of small units of several hectares or less, the inventory merges them into one polygon. Hence, zones of mixed urban, suburban, rural residential, agricultural, and small forested units are often either not mapped or are combined into one or several large polygons (e.g., Figure 5).

3.3 Visual Interpretation and Mapping Procedures

3.3.1 Interpreter Calibration and Site Familiarization

Following initial assembly of image and ancillary data, interpreters familiarized themselves with the site. This process involved inspection of the Landsat imagery and aerial photography, forest inventory, and other available data. After this examination and some preliminary interpretation, the lead interpreter conducted a field visit to the site (July 2002). The main purpose was to become familiar with the landscape and land management practices, and to help resolve issues identified as part of the preliminary interpretation. The availability of local records that could provide useful information for deforestation estimation was also explored.

Visits were made to the Prince George City GIS co-ordinator, the Fraser–Fort George Regional District Planning Department, and the local office of the B.C. Ministry of Forests, Lands and Natural Resource Operations to enquire about potential data sources that could be incorporated into the deforestation mapping system. The municipal GIS data holdings included high-resolution orthophotos, forest area polygons from circa 1993 within the city limits, and a layer containing sites where subdivision and industrial development permits were issued. The potential of this data set for identifying deforestation is clear, although it is spatially limited to city boundaries. However, the City did not have sufficient staff resources to access and extract the data for a non-city project. Moreover, considerable resources, time, and effort would be needed to gain the necessary permissions, agreements, and City council approvals to use and extract the information. Since one aspect of the project was to use readily available information for most areas in Canada, no efforts were made to further pursue these data.

The Fraser–Fort George Regional District Planning Department, which represents the rural region surrounding Prince George City, had a building permit system entirely based on paper records and searchable only through physical files. This situation is not untypical of much of Canada, with varied but sometimes useful and relevant data found in larger cities and less useful data in rural municipalities (Leckie et al. 2000). In addition, most building permits and development plans neither explicitly specify whether a forest clearing is involved nor can they be related to forest cover. As well, each case, like Prince George, needs special arrangements to be made in order to access the data.

Alternatively, there is a wealth of local knowledge in municipal staff. For example, the regional planner had extensive personal knowledge of both the region and the history of permits issued in the area. Upon inspecting the Landsat single date and change enhancement images, the planner was able to explain exactly what had taken place at a number of the apparent change event sites, and also provided an approximate date for each. This information was recorded and used in the interpretation stage as "local knowledge." Staff at the B.C. Ministry of Forests, Lands and Natural Resource Operations office also informed us of local logging and land use practices and patterns. For example, they explained that some local farmers employed a "log-and-leave" practice, whereby an area of their land was logged and cattle grazed in the resulting clearing for several years, after which the land was left to regenerate, although sometimes it was later used for grazing as the need arose. Thus, it is difficult to tell whether an area is harvest or a pasture conversion and, in some cases, the farmers do not necessarily know their own intentions. Staff also noted another specific land use pattern that occurred over the time period of this study in which rural residential and some urban development was undertaken in stages. Clearing of road and street rights-of-way took place first, followed by the development of housing and roads several or many years later. Alternatively, building lots were sometimes cleared but never developed; these areas usually regenerate gradually to forest but are occasionally re-cleared later and developed.

A second component of the site visit was a reconnaissance aerial observation flight in a light aircraft. It consisted of a half-day mission that concentrated on visiting the various landscape and land management types and examining difficult-to-interpret sites identified during the preliminary Landsat interpretation. Oblique aerial photographs were taken of these sites, other candidate forest clearing events, and the general landscape. These photos were used later for training and calibrating the other interpreters, in the interpretation itself, and in the quality control process.

3.3.2 Harvest and Deforestation Mapping

The interpretation process was conducted and tracked on a grid of 10 × 10 km cells across the study site (Figure 7). During interpretation, each grid cell was categorized by major landscape type and human activity (Table 1). Interpretation was performed in the fall of 2002 and winter 2003 by a team of three interpreters, with the bulk of the work conducted by two people.

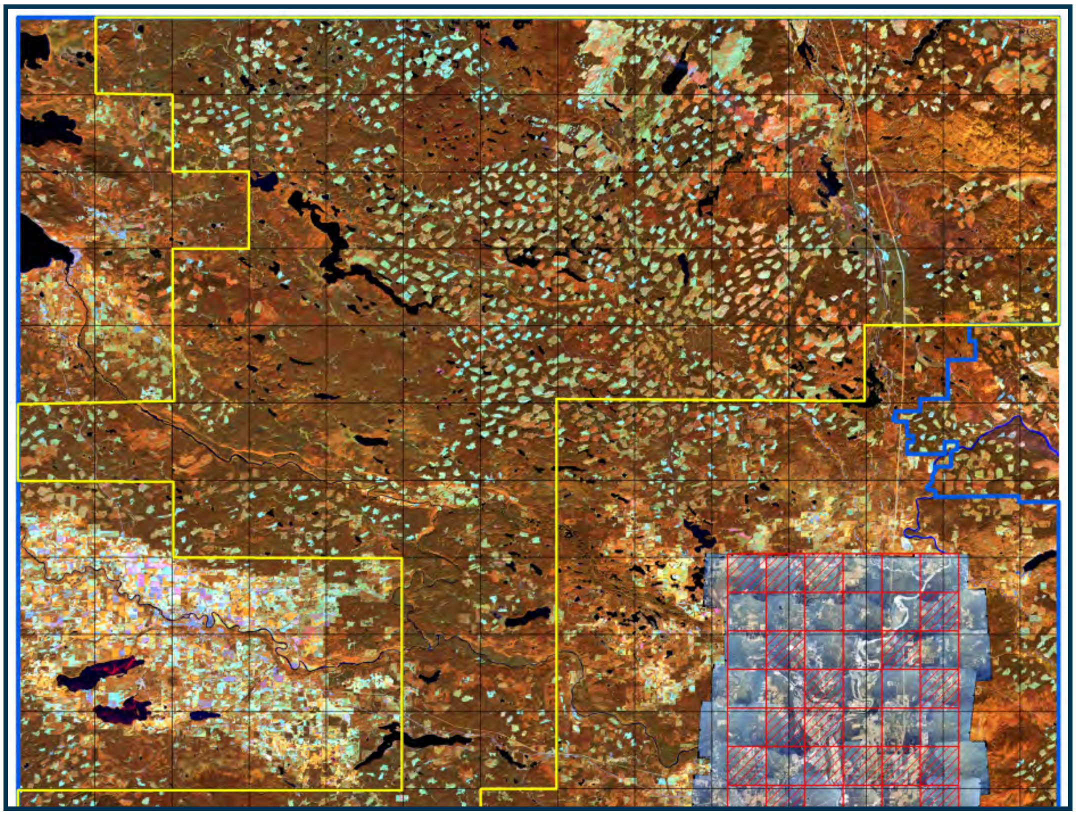

Figure 7. Data set coverages, showing: pilot study area (blue), forest activity only zone (yellow), 10 x 10 km interpretation cells (black), accuracy assessment test area (red), 5 x 5 km accuracy assessment test cells used (red cross-hatched), and 2003 orthophoto coverage available for accuracy assessment (normal colour photo mosaic). The Landsat 1999 image is shown in the background.

Table 1. Interpretation grids cells by landscape and activity type

Cell type	Description	No. cells
Forestry	Mainly forestry activity: cutblocks and roads	43
Forestry–sparse	"Forestry" but region of change activity covers half the cell or less	45
Agriculture	Mainly agricultural activity	17
Urban	Mainly urban activity	13
Mixed use	Mixed land use changes: often forestry & agriculture, or agriculture & urban	17
Mixed use–sparse	Mixed land use but region of change activity covers half the cell or less	5
Miscellaneous	Partial cells that are mostly outside the study area or cells with no change	14
Total		**154**

The interpretation environment was as specified for deforestation mapping in the Deforestation Interpretation Guide (Paradine et al. 2003a). One display monitor was set up in an image analysis environment based on PCI Ltd. software with various band combinations displayed side-by-side and in image planes such that the interpreter could toggle between images within display windows. The following imagery was displayed:

- 1990 and 1999 Landsat images in three band combinations: (1) normal colour composite (bands 3, 2, and 1 as red, green, and blue); (2) colour infrared composite (bands 4, 3, 2); and (3) a band 4, 5, 3 composite;
- panchromatic 1999 Landsat image and a stretched version of the panchromatic image to show detail in high-reflectance, exposed surface areas such as recent clearing and urban areas; and
- the two-date automated Landsat change classification.

In a larger, main window, the 1990 and 1999 composites and a specialized change enhancement were displayed so that the interpreter could toggle between them. The specialized change enhancement displayed the red spectral band of Landsat as red for 1999, and blue and green for 1990 (see Figure 4). Red has been found to effectively highlight areas of change from vegetated to open while grey best shows unchanged areas. This enhancement provides enough detail to give good insight into the nature of the unchanged and sometimes changed land cover (Leckie et al. 2000). Occasionally, a similar change enhancement with shortwave infrared band 5 was produced and used as additional information.

A second display monitor, set up in an Arc/GIS environment, was used for the actual delineation and data entry. The digital ancillary data, including the co-registered 1996 orthophotos, were available as well as visually enhanced versions of the 1990, 1999, and change enhancement Landsat imagery. The interpretation grid cells, forest inventory, and automated forest clearing polygons were also available. Detection of potential forest clearing sites (candidates) was done on either the image analysis or GIS side. Site delineation was undertaken in the GIS environment by toggling between the image sources, as required. The image analysis system was used to examine imagery in detail if needed for delineation. It was also utilized to confirm harvest or a new land use by fully using the quick image stretching and manipulation tools, and by being able to view multiple images at a time.

The general mapping procedure used was to carefully and systematically scan through each interpretation cell, examining and identifying possible forest clearing events from clues or triggers on the imagery. Triggers might be patches of red on the change enhancement, areas of change observed when toggling between the 1990 and 1999 image, or areas of fresh or recent disturbance on the 1999 Landsat image or 1996 aerial photographs. Since automated change detection was also conducted for this study, the forest clearing polygons from the two-date classification provided additional triggers. Once identified, triggers and ancillary data within their vicinity were investigated more closely. For example, map layers were checked for features such as wetlands, waterways, or quarries; the provincial inventory was reviewed for information on pre-change forest type or the presence of harvesting; and the 1996 orthophoto was used to help confirm deforestation and to assist in assigning the post-change class, when appropriate. Where available, field data such as the July 2002 oblique aerial photographs were examined when questions regarding the interpretation arose. If a site was deemed a forest clearing, then a polygon boundary was created and the following attributes (Paradine et al. 2003a) were ascribed to the event:

- **Pretype:** The forest type before the area was cleared, usually at broad levels of forest type, density, and maturity (e.g., conifer dense mature).
- **Post class:** General new land use category (e.g., agriculture, urban, rural residential, forestry road) or type of harvest (e.g., clearcut, clearcut with residual, or partial cut).
- **Post-class modifier:** More detailed description (e.g., pasture or crop for agriculture; primary, secondary or tertiary for roads).
- **T1 deforestation confidence:** Time 1 (1990) confidence of the interpreter that the site interpreted as deforestation was forest in 1990 and thus eligible to be deforestation (confidence levels used were: very high, high, medium, and low).
- **T2 deforestation confidence:** Time 2 (1999) confidence that the site was a new land use and thus indeed deforestation (very high, high, medium, and low).
- **Quality control comment or request:** Requests by the interpreter for help either in the form of additional fieldwork or another interpretation during the quality control step.
- **Time period:** Time period within which the interpreter can determine the event took place.

It is the post-class specification that differentiates the forest clearing as deforestation, harvest, or another disturbance.

In deforestation mapping, it is desirable to be aggressive in terms of calling a possible forest clearing "deforestation" during the initial interpretation step. This is because, based on human nature and previous experience, the quality control and vetting stages are easier and less prone to error if questionable events are included as deforestation. In other words, it is more difficult to detect omissions during these quality control stages than to reject already identified candidate events. This is true at the field validation stage as well. The calibration field visit and discussions with local foresters indicated that harvest versus agriculture and "log-and-leave" practices were going to cause difficulties and interpreters were given instructions to be aggressive in calling clearings "deforestation."

Where it was clear that the forest inventory had been updated since T1 and the forest change was on the inventory map, the forest type prior to the change was interpreted from the T1 Landsat imagery with additional support, if needed, from the characteristics of the surrounding forested polygons in the inventory. The 1996 orthophotos were often used to verify T1 forest type for changes occurring later than 1996. Because the 1988 airphotos were in hardcopy form during the interpretation phase, they were less convenient to use and were, therefore, checked only when needed. Winter Landsat imagery from 1989 was also available; treed versus open areas are usually distinct on winter imagery with snow cover and it was sometimes used help determine forest type and density. When the inventory had not been updated since the deforestation event, inventory data were frequently used to verify the presence of T1 forest. In these cases, interpreters left the T1 forest type attributes blank and the T1 forest attributes were extracted automatically from the inventory.

The actual year of deforestation or harvest occurrence was recorded for some events where ancillary data provided date information, or where clearing was obviously underway as observed in the imagery. In the majority of cases, however, a range of possible years was assigned based on whether the event was visible in the T2 imagery or in the 1996 orthophoto. For example, a clearing observed at T2 but not in the orthophoto would receive a "not before" value of 1996 and a "not after" value of 1999.

Note that roads were digitized as line features and consisted of new roads through forest. In the automated classification, old roads within new clearings will often appear as part of the clearing event. Pre-existing roads within new forest clearings were digitized manually in order to eliminate them from the forest clearing event. Once the initial interpretation was complete for the entire study area, buffers were applied to all linear road events converting them into polygons. Buffer widths for the three levels of forestry roads mapped (primary, secondary, and tertiary) were taken from the results of a forestry operations survey conducted by the Canadian Forest Service (Eichel and Leckie 2006), whereas typical widths for non-forestry roads were estimated based on familiarity with the road types within the province of British Columbia.

As part of the interpretation process, the number of triggers and potential candidates in each grid cell was recorded along with the main cause of false alarms (triggers that were not forest clearings). This permitted analysis of the effectiveness of the methods used.

3.3.3 Use of Forest Inventory and Automated Forest Clearing Polygons

Because there are triggers and potential candidate sites derived from the forest inventory and the automated forest clearing polygons, a variation of the above general mapping procedure was used. This variant had a two-fold purpose. One was to speed the mapping process by using these polygons if they were as good as those that could be generated manually. The second was to aid in the design of operational mapping procedures by determining how often polygons from these sources might be acceptable for use and thus whether it is worth the effort to assemble and create such data sets.

The base procedure was modified such that the interpreters tracked the potential for use of the automated forest clearing polygons and forest inventory data as a substitute for complete manual delineation. For each harvest and deforestation event with an associated inventory or automated polygon, interpreters assessed whether each was suitably representative of the change event, or whether new manual delineations were required. Data were recorded stating whether the polygons were acceptable, acceptable with minor changes, or not acceptable. The decision on whether a polygon was considered acceptable without changes was based on the interpreter's visual analysis, which to a degree, was subjective. However, in general, a separation between polygon edge and visible feature edge on the order of 1.5–2 pixels was enough to merit an adjustment of the polygon boundary. An adjustment of more than half the boundary length or an adjustment resulting in a change to the polygon area of more than approximately 10–15% would usually indicate that the existing polygon was "not acceptable." There was sometimes local misregistration between forest polygons sourced from provincial inventory data and the imagery, and this needed to be accounted for. If the inventory polygon shape was essentially the same and the polygon outline clearly mimicked that of the event, it was considered acceptable or useable regardless of the misregistration. In addition to assessing whether the inventory and automated polygons could be used, interpreters also made decisions regarding which polygon to use in the final map (i.e., to accept the automatic or inventory polygon, to edit one or the other, or to create a new delineation).

A variant to the above procedure was implemented for part of the site. There was a large region of the study site where forestry operations were the only anthropogenic activity affecting the landscape. Of the 154 interpretation grid cells, 84 were observed to contain only forestry-related forest change events (Figure 7). It was therefore hypothesized that polygons over 1 ha derived from the two-date, unsupervised classification change classes could be used to automatically generate the set of harvest event polygons for this "forestry-only" area. This variation was implemented to help minimize interpretation time.

For the clearcuts in the forest harvest region, the product of the automated classification, sieving, and smoothing process generally resulted in a small underestimation of the actual area of the cuts and a boundary that was generally somewhat inside the true boundary. This observation was generated from comparison of the automated forest clearing polygons with forest inventory polygons of the cuts and the clearcuts as seen on the 1996 orthophotos, as well as a close comparison of a sample of 130 clearcuts. In addition, where newly built roads intersected the edge of a new cutblock, the event boundaries were sometimes observed to deviate outward from the cut area following the road for a short distance. To alleviate these issues within the forestry-only grid cells, an additional post-processing erosion and dilation procedure was applied to all forest clearing polygons greater than 1 ha. A 7.5 m inside buffer was created, followed by a 15 m outside buffer. The resulting data set showed better agreement with total area of the inventory polygons, as well as reduced boundary errors at locations where new roads met the new clearcuts.

Therefore, within the forestry-only region, the buffered polygons were accepted as delineations for the cutblocks. All events were assigned a classification of "clearcut" as this was the overwhelmingly predominant harvest type in the active forestry area. An interpreter reviewed all polygons assigned in the forestry-only area, rejecting those associated with wetlands or deforestation events, or showing other signs of error. Cuts considered partial cuts or clearcuts with residual were re-labelled as such. As elsewhere in the study area, roads were delineated manually.

3.3.4 Quality Control and Validation

Quality control was conducted during the summer of 2003 by a senior interpreter, and for some areas, additionally by one of the interpreters that did not map the area. This process consisted of a scan of the imagery and all events for boundary anomalies, omissions (missed events), and commission errors (false alarms). Greater care was taken in difficult-to-interpret areas such as the mixed use region around the city of Prince George and difficult-to-interpret classes such as deforestation to agriculture pasture, which can be confused with harvests. Events with low interpreter confidence were also stressed. Moreover, particularly active areas in the pilot region were subjected to close inspection for interpreted post-class type. If a site required deletion, addition, reattribution, or boundary change, it was marked for revision. As in the interpretation itself, if the call was uncertain and would benefit from a field check, it was marked for a priority validation visit (Paradine et al. 2003b).

A validation field visit was planned and conducted on September 8–10, 2003. It consisted mainly of aerial observation flights in a light aircraft. Priority was assigned to sites that the interpretation and quality control process identified for field visits, such as sites of low confidence, difficult-to-interpret types of change, and some clearcuts within the agriculture and mixed use regions. For example, recognition of probable high interpretation error in the agriculture pasture class led to giving these sites higher field visit priority, regardless of their individual interpreter confidence. Priority was also given to the larger deforestation events. The list of priority sites was used to design a flight plan that encompassed as many of the higher-priority events as possible and included other non-priority sites when convenient. The visits were concentrated in the region surrounding the city of Prince George, the Vanderhoof agricultural zone, and the Fort St. James area. The forestry-only interpretation grid cells were of low priority.

The field visit was conducted by the lead interpreter, the main quality control person, and a representative from the B.C. Ministry of Forests, Lands and Natural Resource Operations. Four flights were made over two days. As many priority sites as possible, plus additional "sites of opportunity" were assessed. For each site examined, a "call" was made whether it was deforestation or not based on the current land use, cover, and context. The post class and post-class modifier were also recorded. Oblique aerial photographs were taken of the priority sites, other sites, and the general landscape, and were used for future reference and to help confirm sites used in accuracy assessment. In some cases, events were too closely spaced to make individual calls, or were difficult to locate from the air. Oblique photographs of these sites were taken and later assessed on the interpretation station in the laboratory. Flight tracks were recorded with GPS and the photographs taken were related to their position on the track so that photo locations could be displayed overlain on the imagery and forest clearing map. A total of 14 flight hours and 2000 km were flown. Candidate sites were also visited on the ground on the mornings of September 8th and 10th. In total, 950 sites were called and 1400 photos taken.

3.3.5 Revision

After the field visit data were compiled, revisions were made to the initial mapping. Event type changes and confirmations were recorded in a separate GIS layer, as were any deleted polygons. Mapping revisions were made for the:

- planned and assessed air calls;
- planned air calls not assessed in the plane but available from the photos;
- unscheduled "opportunity" air calls;
- unscheduled calls based on the oblique photos; and
- previously suggested revisions based on the quality control step.

During the revision process, it is again possible to add quality control notes. For example, if a site's interpretation is still uncertain, it can be marked for long-term check. This means the site should be examined in the future (e.g., during future forest change mapping) to see if the site has been converted to another land use or has regenerated to forest.

The approximately 950 sites assessed through the field validation program represented approximately 20% of all the forest clearing sites in the study area. As the field work did not concentrate on the forestry-only regions, the validation likely represented 35% of the sites in the more mixed land use regions. The field validation was effective and necessary in resolving the known issue of confusion between harvest and deforestation, especially agriculture conversion in the agriculture and mixed use regions.

Harvest versus deforestation, especially agricultural conversion, was the dominant change made during the revision process, but other post class changes were also made. During the field visit and revision process, clues in terms of image characteristics and context were identified to help differentiate agriculture from harvest. This information was used during the revision and subsequent vetting process to identify some additional sites requiring revision. Between the revisions resulting from field observations and from additional interpretation, 512 sites (excluding roads) were changed from deforestation to clearcuts (363) or partial cuts (149); most of these (469) were changed from agriculture, with 30 sites coming from rural residential events and only small numbers of changes from other deforestation classes. Far fewer events were changed from harvest to deforestation (33 events of approximately 2650 original harvest events, 25 of which were assigned to agriculture and 6 to open field). Table 2 summarizes the post class changes made during revision. Note that changes in the road class were often related to specific rules regarding how roads are dealt with within harvest and deforestation events (Paradine et al. 2003a), and there were additional changes at the post-class modifier level; therefore changes in road post-class modifiers are not described in Table 2. The large numbers of changes related to confusion between harvest and agriculture were not unexpected as it was a known issue, field verification focused on this problem and the initial interpretation was deliberately aggressive in attributing deforestation over harvest.

Table 2. Summary of changes made as a result of the quality control and revision processes

		Pre-revision class											
		CC	**CL**	**PC**	**AG**	**OF**	**RR**	**SD**	**IN**	**UR**	**RC**	**RD**	**CR**	**Total no. sites post-revision**
Post-revision class	**CC (clearcut)**	**2220**	30	20	302	2	20	4	2	1	0	30	1	2632
	CL (clearcut w/ residual)	3	**155**	2	25	2	4	0	0	0	0	0	0	191
	PC (partial cut)	5	6	**170**	142	0	6	1	0	0	0	0	0	330
	AG (agriculture)	16	6	3	**428**	0	1	0	0	0	0	0	0	454
	OF (open field)	2	3	1	56	**30**	4	0	3	0	0	0	0	99
	RR (rural residential)	0	1	0	21	3	**304**	2	0	5	0	0	0	336
	SD (soil disturbance)	1	0	0	2	0	0	**52**	0	0	0	0	0	55
	IN (industrial)	0	0	0	3	0	1	1	**34**	0	0	0	0	39
	UR (urban)	0	0	0	1	0	1	0	2	**57**	0	1	0	62
	RC (recreation)	0	0	0	1	0	0	0	0	0	**10**	0	0	11
	RD (road)	50	0	0	0	0	0	0	1	0	0	**493**	0	544
	CR (corridor)	0	0	0	1	0	0	0	0	0	0	0	**2**	3
	Total no. sites pre-revision	2297	201	196	982	37	341	60	42	63	10	524	3	4756

3.3.6 Vetting

The final step of the deforestation and harvest mapping process is a vetting of the revised mapping by an independent and senior interpreter. This is to make sure there are no biases and that blunders did not occur during the final stages of mapping and processing, and to ensure consistency in interpretation within the mapping area and with other mapping areas. All available information can be used during this step. For this pilot study, the vetting was done by the senior interpreter involved in the validation fieldwork. Most revisions based on vetting were related to agricultural deforestation and the fine-tuning of boundaries for deforestation events. This produced the deforestation maps that are used to estimate deforestation for the 1990–1999 time period. These deforestation events, along with the harvest polygons, form the final map product from the mapping process (see Section 4.3; Figure 8).

3.3.7 Second-cycle Review

When deforestation for a region is mapped for the next time period, the previous mapping is reviewed. During this mapping, the previous deforestation polygons are displayed, as well as any quality control points specifically requesting site checks. While mapping the new period's deforestation (in the Prince George area this was 1999–2006), the interpreter takes a quick look at the current imagery for the previous sites and quality control points to determine if they are indeed a new land use and are not regenerating to forest. While the focus during this review is on commissions, omissions as well as needed boundary or post class attribution changes can also be found. The passage of time and establishment of the new land use or regrowth of forest on sites provides more clues and certainty to the interpretation of the old sites. Recent high-resolution imagery may also be available for this review. Thus, the interpreter has a considerably improved capability to ascertain the true nature of forest clearings during the second-cycle mapping. The quality control and vetting steps for the new mapping period also look at the previous mapping. Experience shows that although the interpreters doing the new period mapping do find issues in the previous mapping, the quality control and especially the vetting processes are more effective for this task. The mapping interpreter's main attention seems to be focused on production mapping for the new period, not the review of previous mapping.

For the Prince George pilot area, the main mapping was completed from 2002 to 2003. The deforestation mapping for the 1999–2006 period was done in summer 2008, with quality control conducted in the fall and revisions in early 2009. This was part of operational deforestation mapping for Canada and no special procedures or extra attention was paid to the pilot area. A sequence of additional Landsat imagery, including 2000, 2003, 2004, and 2005, plus the 2003 normal-colour orthophotos and a considerable amount of high-resolution Google Earth imagery were available for this review. Accuracy assessment truth data was not used. The 1999–2006 mapping was done on a 12% sample, as opposed to the full-coverage mapping of 1990–1999. The sample consisted of 3.5 × 3.5 km cells on a 10-km grid. The minimum mapping unit was 1 ha, as opposed to 0.5 ha and lower for the 1990–1999 pilot study mapping. Operational considerations did not permit a review of all 1990–1999 mapping of the pilot area in the 2008–2009 time frame and thus, the 2008–2009 second-cycle review and revisions were only performed on sites within the 12% sample of 1999–2006 mapping cells.

An additional process was implemented to check and vet all the 1990–1999 mapping in September, 2012. All 1990–1999 mapping including those within the 1990–1999 mapped cells were reviewed. This was considered an operational vetting process. As well as the previous Landsat imagery and 2003 orthophotos, a 2010 image was examined along with additional high-resolution Google Earth coverage. This process resulted in a complete second-cycle review of the full 1990–1999 mapping. This permitted deforestation estimates for the 1990–2000 period in the Prince George region to be improved and incorporated into a revised and updated estimate that was used operationally for national deforestation reporting.

4. Results

The effectiveness of the methods used to produce the combined forest harvest and deforestation map was evaluated, especially the use of an integrated approach using forest inventory, automated classification, and manual interpretation. The accuracy of the final product produced by this integrated approach was then evaluated using independent truth information.

4.1 Analysis of False Alarms during Manual Interpretation

The efficiency of the mapping procedure partly depends on how effective the triggers (indicators of possible forest clearings) are in quickly leading the interpreter to possible deforestation events without missing many or causing a lot of time and effort to dismiss false alarms. These false alarms are generated by the Landsat band 3 change enhancement (i.e., red features) and changes identified by toggling between images. Errors in the automated change classification resulting in false alarms are discussed later.

For the forestry-only grid cells, the overwhelming cause of false alarms was wetlands, and the spectral changes related to different vegetation conditions and water levels associated with wet conditions. Misregistration of the Landsat imagery, although minimal, was also a source of false triggers that were mostly associated with existing roads or edges of existing harvest cuts. There were commonly 80–220 triggers per interpretation grid cell, although only 20–40 triggers were actual forest clearing events (usually clearcuts), giving typical event-to-trigger ratios of 10–20%. Dealing with the false alarms was generally easy and swift. For both the wetland and misregistration cases, the change enhancement itself provided enough information and the Landsat images provided confirmation. The wetland polygons from BC TRIM and the National Topographic Series maps were useful but were neither consistent enough nor were their boundaries detailed enough to use as an automatic mask to eliminate wetland false alarms. In the mapping process, these map-based wetland polygons were rarely used. The fact that clearcuts were generally large and regular in shape also helped with quick elimination of false alarms.

In mixed agriculture and forestry grid cells, wetlands and misregistration remained an important source of false alarms, but crop changes also contributed. The crop changes were generally easy to identify but sometimes took considerable investigation on the imagery and 1996 orthophotos. Changes on the agriculture fields were due to: different crops on the same field; different stages of growth on the August 1990 imagery compared to the early September 1999 imagery; the harvest of some fields by September 1999; and fields left fallow. Event-to-trigger ratios in these grid cells were on the order of 15–25%, with more triggers than the forestry-only cells at 200–400 triggers per cell.

Within cells that had mixed agriculture and residential or mixed residential and forest, forest clearings that were too small were an additional source of false alarms and sometimes the most common type of false alarm. Such clearings were often associated with rural residential areas and development. Indeed they were not really false alarms as most were forest clearings, but were just too small (i.e., below the 0.5 ha minimum mapping unit of this study). Analyzing these small clearings was time consuming as interpreters had to determine if they were large enough and, in the extreme, some had to be digitized first to determine whether they met the minimum mapping unit size. As well, within the mixed use regions there were sometimes many small triggers to deal with. For example, in these regions event-to-trigger ratio generally varied between 15 and 30%, with 200–350 triggers and 40–90 events per cell. Considering all the cells outside the forestry-only cells, the average number of triggers was approximately 250 per cell.

Therefore, while considerable numbers of false alarms were present, these were generally easily and quickly resolved. They were not major issues in terms of time and effort. Improvements to reduce them would be good, but a trade-off exists between the effort required to decrease false alarms and the time taken to address them manually and, of course, concerns about any erroneous elimination of true events. The principle is to err on the side of caution, letting the interpreter see and evaluate possible events rather than miss events.

4.2 Analysis of Inventory and Automated Change Polygon Use

The usefulness of forest clearing polygon sources other than those from the core manual interpretation process was also examined. Important considerations for their efficacy were acceptability for use, meeting the quality of a manual delineation; and usefulness as part of an operational procedure (either directly or with manual modification). A final consideration was whether they were used in this trial, which specified to use them if they were as good as the manual interpretation or if it would speed the delineation process if part of the polygon was used and the remaining part was modified manually. The interpreter examined forest inventory polygons representing forest clearings and the forest clearing polygons generated by the automated process, recording whether the polygons were acceptable for use and, of those acceptable, how many of these were actually used unmodified directly and how many required some manual editing of the boundary. In an independent process conducted after the mapping was complete, a senior interpreter used all available imagery and information to assess each polygon chosen for the final map on the basis of how well it captured the true event and the quality of the polygon outline versus the true boundary of the event (Appendix 1).

4.2.1 Forestry-only Region

Analysis of acceptability and final use of different polygon sources was conducted separately for the forestry-only versus other interpretation grid cells. In the forestry-only grid cells, forest clearings are almost exclusively forestry roads and harvest cuts that are simple in shape and at least several hectares in size. The automated polygons were generally of good quality and taken as the primary source. Thus, the inventory polygons in this area were not used or assessed. All 1284 automated forest clearing polygons were visually assessed to determine whether they were acceptable, needed manual modification or required a completely new delineation. The imagery was also checked for omissions (forest clearings missed or not identified). Moreover, commissions (sites falsely called forest clearings) were an issue. For example, 222 automated polygons associated with wetlands showed changing spectral signatures between the two images. Most of these were less than 10 ha and were concentrated in the central portion of the study area. In addition, seven small sections of new roads or road junctions still remained after the sieving and polygon smoothing process. Only one case of a commission was evident within an existing cut and it was where the site was vegetated, but then redisturbed to exposed soil. All 230 of these commissions were deleted by the manual inspection process and did not enter into the final map product. Although the automated process (through cluster labelling) did eliminate many of the wetlands, a rigorous procedure or re-clustering to eliminate more wetlands was not conducted. There were only two small omissions identified by the polygon checking process, which were added. In only two cases was the default labelling of forest polygon clearings in the forestry-only zone as clearcuts wrong and had to be changed to partial cuts.

After deleting the 230 commissions and adding the two omissions, there were 1056 polygons in the final map of the forestry-only section. Of these, 98% were captured boundary acceptable (CBA) and 2% were captured boundary poor (CBP). Ninety-one percent had "very good" boundary delineation, 7% "good" and 2% "poor." Appendix 1 defines these terms. The automated polygons with "very good" boundaries were used in the final map as is, whereas the others used the automated boundary manually modified. Of the 93 events having some issues with boundary delineation (i.e., were not classed as "very good" delineations), 13 events had problems because the boundary delineated around inclusions (internal polygons) of forest or wetland within the cut was poor. Eight of these were inclusions of trees and five were inclusions of wetlands; most were between 1.5 and 2.5 ha. Of 73 events with discrepancies in the exterior boundary of the event, 42% were poor because they included wetlands that were adjacent to the cutting event, and 18% were due to roads protruding a short distance from the cuts. There were three cases of stream valleys of predominantly hardwoods where the bright reflectance on the east-facing slope caused a change event to fall into one of the mixed clusters that contained both forest clearing and other features. The pixels were bright on one image and darker on the other. Not separating narrow protrusions into cuts or inclusions of trees within the cuts (primarily along riparian leave strips) accounted for 29% of the cases of poorly captured cutting events, most of which were 100 m or less wide by several hundred metres long and 2–4 ha in size. The sieving and smoothing process applied to the initial classified forest clearing polygons strongly contributed to this source of error by eliminating these areas, which were often at least partially classified as not cleared in the original pixel classification. In the final product, 91% of the forest clearing polygons in the forestry-only region used the automated polygons directly; the remainder, except the two small omissions, used the automated polygons modified manually.

4.2.2 Outside the Forestry-only Region

Outside the forestry-only region, 1475 non-road polygons had polygon source selection assessed. In the final map product, approximately one-half (731) of these events were from manual delineation, 261 were from forest inventory boundaries, 139 were inventory boundaries with manual adjustment, 197 were the automated forest clearing polygons, and 147 were the automated polygons with manual adjustment.

Of the 1475 events assessed, 33% had automated forest clearing polygons that were determined as "acceptable." Of those deemed "unacceptable," 87% were considered visually too far off in terms of boundary and 13% were omissions. Many of the omissions were smaller events in mixed use and rural residential areas. Similarly, 35% of the 1475 events assessed had "acceptable" forest inventory polygons representing the event. Of the events with "unacceptable" inventory polygons, most (94%) had not been updated yet and only a few (6%) were a visually unacceptable match. The forest inventory polygons were only useful for forest harvests and agriculture clearings. There were almost no acceptable inventory polygons related to deforestation other than agriculture. Even for agriculture deforestation, only slightly over 10% of the inventory polygons were acceptable. These low values are understandable since the forest inventory concentrates mainly on forest stands.

The classification polygons were less effective for deforestation events than for harvest events. For clearcuts and partial cuts, 42% of the polygons were "captured boundary acceptable", whereas 26% of the deforestation polygons were considered acceptable. For the deforestation types, agriculture was among the best captured by the automated polygons, with approximately 35% of the agriculture deforestation events assessed for use being acceptable. The events with high change (i.e., forest to sites with no or little vegetation) were also captured reasonably well at 30–45%. These included conversion to industrial and gravel pits, and usually had regular and smooth boundaries. Alternately, urban events were captured poorly (none captured acceptably), as were rural residential events (just 13% were classed as "acceptable" and only 7% were actually used). Rural residential sites are generally small and mixed with vegetated areas and residual trees, often are convoluted in shape, and commonly have at least some edges adjacent to existing roads or open areas. This makes it difficult to extract an accurate boundary with automated techniques.

The smoothing algorithm applied, although helpful for larger polygons by making the boundary smoother and matching reality better, had a tendency to make a poorer boundary for smaller convoluted events, such as rural residential sites. In total over the study area outside the forestry-only zone, 15% of the automated polygons were actually used as is. For forest harvest events, 18% of the final polygons were automated polygons; for deforestation events, 13% were automated polygons.

4.2.3 Combined Forestry-only and Other Region

Over the entire study area (forestry-only and the remainder), the following is an approximate breakdown of sources for the forest clearing polygons used:

- 50% automated forest clearing polygons;
- 27% manual delineation;
- 10% manually modified automated polygons;
- 8% inventory polygons;
- 5% manually modified inventory polygons.

Note also that all 524 road events were manually delineated.

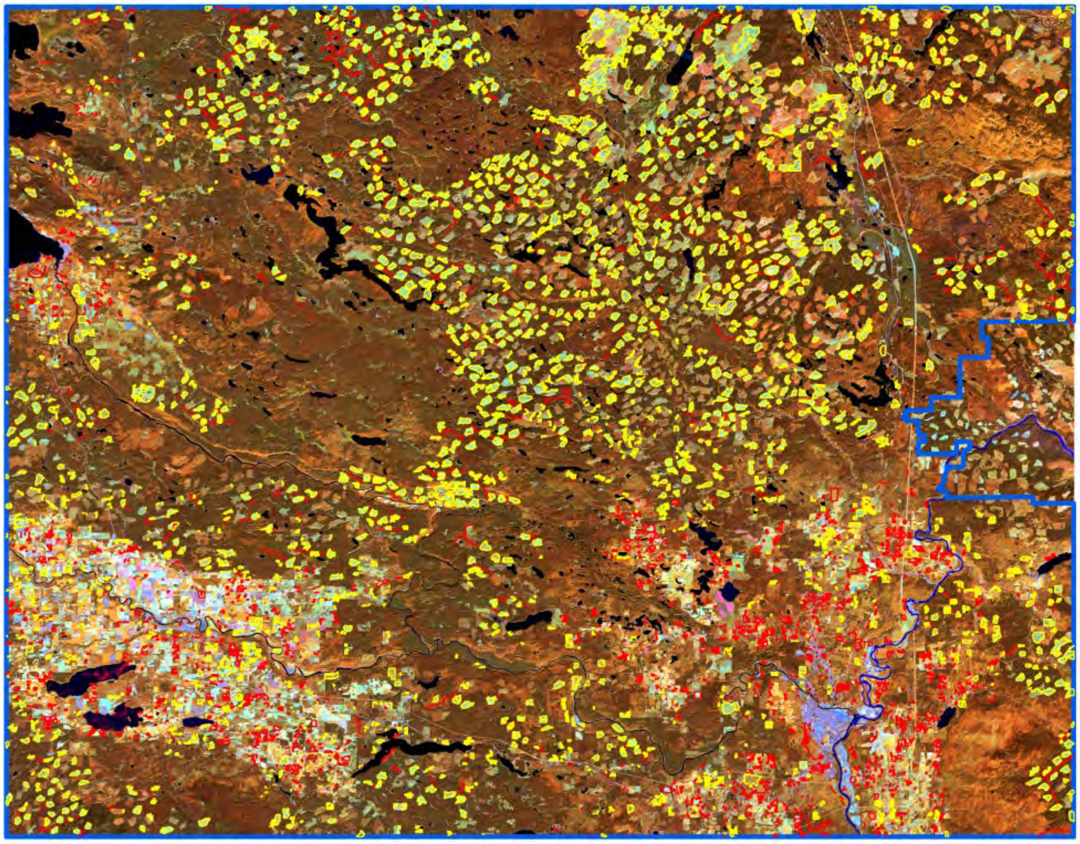

Figure 8. Harvest (yellow) and deforestation (red) events as mapped (before second-cycle review); 1999 Landsat image in background.

4.3 Analysis of Final Map Product

The integrated approach defined in the methodology section, including features of the individual data sources and how they are combined (Section 3), as well as the analyses outlined in Sections 4.1 and 4.2, led to the creation of a final forest harvest and deforestation map (Figure 8). The effectiveness of this final map product is described below, as is its improvement through the second-cycle mapping review process.

4.3.1 Accuracy Analysis Procedures

In the main forest regions of the study area, forest harvest was quite distinct being represented by regular generally trapezoidal-shaped cuts surrounded by forest. These cuts had smooth boundaries and were typically 30–150 ha in size. These types of cuts are less common in the rest of the study area where cuts were frequently smaller, more convoluted in shape, and had residual trees. As well, partial cuts were more common and sometimes graded into uncut areas without a distinct boundary. Edges may be adjacent to existing cuts, agriculture, or other open areas. Therefore, a separate accuracy assessment of forest harvest polygons was undertaken for the forestry-only interpretation grid cells and the rest of the image. Also remember that in the forestry-only zone, the final product harvest polygons were derived from the automated classification, which was examined and manually modified when necessary.

The accuracy of the forest clearing events was assessed against the truth sites determined independently from aerial photography and field observations. Within the forestry-only grid cells, every cut was assessed to determine whether the boundary was acceptable, how well it was delineated, and whether it was labelled as a harvest event. For some sites, recent high-resolution satellite imagery was available and also used to assess accuracy.

For both deforestation and harvest mapping in the rest of the image, a 30 × 35 km "test area" centred on Prince George was used in the accuracy assessment. This test area was chosen to include landscape types that were representative of those across the entire study area, but were more representative of deforestation and harvest polygon accuracy in mixed agriculture forest regions, as well as zones of mixed rural residential, urban, and forest activity. For this analysis, an additional data set was assembled after the completion of the mapping. This included the 1988 aerial photography digitized to 5 m, orthorectified, and rendered as a mosaic. In addition, the B.C. Ministry of Forests, Lands and Natural Resource Operations supplied a 2003 orthophoto mosaic based on 1:30 000 normal-colour aerial photography that was digitized to 5 m (Figure 7). These two data sets were overlain and a comparison was made to detect and map deforestation events in high detail. This accuracy data was mapped by a senior interpreter affiliated with an independent contractor, who did not have access to the deforestation and harvest mapping conducted in this study or to the Landsat imagery used to map it.

The 10 × 10 km interpretation grid cells in the accuracy test area were divided into quarters to create 42, 5 × 5 km accuracy grid cells. In a randomly selected subset of 17 accuracy grid cells, the truth was evaluated for use in accuracy assessment (Figure 7). Because the aerial photography used in the truth mapping was from 1988 and 2003, and the imagery was from 1990 and 1999, some sites mapped as change events occurred outside the time frame in which the forest clearing events were mapped. Events were removed from the truth database if the clearing occurred, or part of it occurred, outside the time frame of the Landsat images. Where possible, the remaining events were confirmed as deforestation or harvest by using the field observations and oblique aerial photography from the 2002 and 2003 fieldwork. In addition, the B.C. Ministry of Forests, Lands and Natural Resource Operations supplied a sequence of orthorectified annual Landsat TM imagery from 1999 to 2006 that helped confirm the truth events. In total, approximately 190 deforestation truth and 180 candidate events, covering the range of post-class land use types in the study area, were available for the accuracy assessment. Approximately 85 harvest truth events and a similar number of candidate events were also available. Figure 9 gives an example of the accuracy data set.

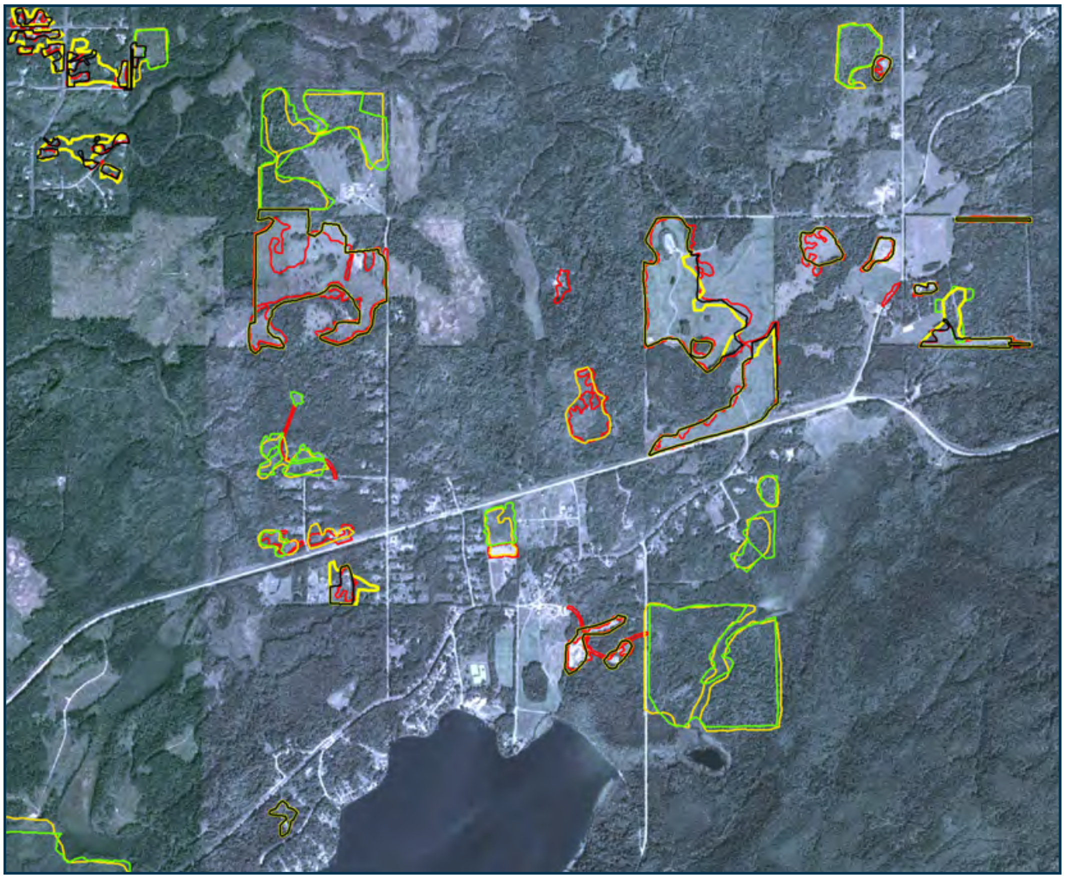

Figure 9. Example of truth and candidate polygons used for accuracy assessment, showing truth harvest polygons (green), candidate harvest (yellow), truth deforestation (red), and candidate deforestation (yellow). Black lines show deforestation polygons revised through operational second-cycle mapping. Background is high-resolution Google Earth image from September 2014 and September 2012. Area shown is 5.5 × 6.6 km.

For those truth events unencumbered by occurring outside the time period of the Landsat images, event-by-event evaluation was done by a senior interpreter not involved in their initial mapping. Also, a subset of accuracy cells was evaluated a second time by another interpreter as a quality check of the truth data.

For each truth event (truth-centric analysis), the information below was recorded (see Appendix 1 for definitions):

- how well the truth event was "captured" (classed as acceptable, poor, or omission);
- whether it was represented by only one candidate or was a "split" case (i.e., with several candidates associated with it);
- whether the truth event was associated with a "grouped" candidate event (i.e., part of several truth events represented by one candidate or several associated candidate events);
- how well the boundary of the truth event(s) was delineated (overall delineation) on a scale from very good to very poor; in the split cases it was how well the combination of associated candidate polygons represented the boundary of the truth event;
- what the "Truth Overlap," or percent of the truth event (or the group of truth events) was covered by candidates;
- if the event was omitted or poorly captured, a note as to the likely cause was made;
- how close the match of the post-class labels of candidate events was to that of the truth event (i.e., "matched," "acceptable," or "wrong"). This was evaluated for both post-class and post-class modifiers. For split cases the post class of the most associated candidate was used. In the case of more than two candidates involved in the split case, the post class that was dominant in terms of area of the candidates was used.

In terms of each candidate event (candidate-centric analysis) the following items were recorded:

- how well the boundary of the candidate "matched" a truth event or group of events;
- whether it was associated with only one truth event or a "group" of events;
- whether the candidate event was associated with a "split" truth event (i.e., part of several candidate events associated with one truth event);
- how well the boundary of the candidate event corresponded to that of the truth event; in the "grouped" cases it was how well the candidate represented the boundary of the group of truth events;
- the "Deforestation Proportion" or percent of the candidate event that was covered by deforestation; and
- if the candidate was a commission and there was no forest clearing event, a note as to the likely cause was made.

For grouped and split cases, overlap percentages at the individual polygon level were also recorded. All information was entered into a database along with the area of each candidate and truth event, and any group of related truth and candidate events. These procedures were adapted from methods outlined in Leckie et al. (2006b) and are somewhat similar to an automated approach used for assessing the effectiveness of automated tree crown delineation algorithms versus manually delineated truth boundaries of crowns (Leckie et al. 2005).

4.3.2 Final Map Product Accuracy (Effectiveness)

Forestry-only Region

For the forestry-only cells, the final map product was excellent with virtually no omissions and commissions for the forest harvest polygons; all events were captured boundary acceptable and matched boundary acceptable. All boundaries were delineated very well. Most events were clearcuts. Some minor discrepancies occurred at the edges of cuts with wetlands and in the details of the delineation of inclusions within the cuts and along riparian strips. In the forestry-only zone, the polygons were generated using the two-date classification, were visually examined, and were modified if necessary to achieve a "very good" boundary. Almost all (91%) of the polygons in the final product were from the automated approach without manual modification; in fact, 98% of the automated boundaries were acceptable and could have been used. This indicated the automated procedure worked well in this environment. Manual modification of the boundaries and identification of commission errors, such as classification of wetlands as forest change, effectively eliminated the discrepancies caused by the automated approach.

Test Area

The accuracy within the test area was taken to represent the accuracy of the remaining area. The accuracy within the test area was assessed in terms of the relationship between the candidate events and truth, how well the boundaries were delineated, and the overlap between them. These can be assessed from both a truth-centric viewpoint and candidate-centric perspective. Truth-centric refers to how well each truth event is captured or delineated by a candidate event and candidate centric relates to how well a candidate event represents the truth. In addition to examining the relationship between truth and candidate events, the size of related candidate and truth events were compared, and overall estimates were made of numbers and areas of deforestation and harvest events. Table 3 quantifies the relationship of deforestation events from both a truth- and candidate-centric perspective in terms of event capture or matching and the quality of boundary delineation. The table presents results by truth event size class and post class, but the data can also be analyzed at the post-class modifier level and for different candidate size classes.

Table 3. How well each truth event was captured and delineated by the candidates, how well each candidate event was matched with associated truth events, and how well the delineation represents the truth. Results are given for each truth event class type and size class. Appendix 1 provides definitions of capture and match classes . CBA = captured boundary acceptable; CBP = captured boundary poor; OP = omission pure; MBA = matched boundary acceptable; MBP = matched boundary poor; CI = commission impure; CP = commission pure; CS = commission too small; CN = commission too narrow). Descriptions of delineation quality classes are in Appendix 1 and text. (VG = very good, G = good, P = poor, VP = very poor).

		Percentage by Truth Count				Delineation quality Percentage by Truth count without OP					Delineation quality Percentage by Truth count with OP					Percentage by candidate count of MBA, MBP, CI, CP, CS and CN							Percentage by candidate count of MBA, MBP, CI and CP				
Post-class	**truth event size**	**CBA**	**CBP**	**OP**	**Total Count**	**VG**	**G**	**P**	**VP**	**Total Count**	**VG**	**G**	**P**	**VP**	**Total Count**	**MBA**	**MBP**	**CI**	**CP**	**CS**	**CN**	**Total Count**	**MBA**	**MBP**	**CI**	**CP**	**Total Count**
All with Rd[a]	≥ 0.5 ha	66	13	21	184	34	45	18	3	146	27	36	14	3	184	73	14	1	7	4	1	168	77	15	1	8	159
	≥ 1.0 ha	70	13	17	150	37	44	16	3	124	31	36	13	3	150	77	14	1	7	1	1	137	78	14	1	7	135
	≥ 0.36 and < 0.50 ha	44	33	22	9	33	29	29	0	7	33	22	22	0	9	36	27	0	9	18	9	11	50	38	0	13	8
	≥ 0.50 and < 1.0 ha	50	15	35	34	9	55	27	5	22	9	35	18	3	34	55	16	0	6	19	3	31	71	21	0	8	24
	≥ 1.0 and < 2.5 ha	67	11	22	81	23	52	14	3	63	23	41	11	2	81	78	13	0	6	1	1	69	81	13	0	6	67
	≥ 2.5 and < 5.0 ha	62	19	19	37	32	33	20	7	30	32	27	16	5	37	68	21	0	12	0	0	34	68	21	0	12	34
	≥ 5.0 and < 10.0 ha	71	21	7	14	36	31	31	0	13	36	29	29	0	14	67	20	7	7	0	0	15	67	20	7	7	15
	≥ 10.0 ha	100	0	0	18	56	39	6	0	18	56	39	6	0	18	95	0	0	5	0	0	19	95	0	0	5	19
All without RD	≥ 0.5 ha	65	13	22	176	31	47	18	4	138	24	37	14	3	176	73	15	1	8	4	0	158	76	15	1	8	151
	≥ 1.0 ha	69	13	18	143	35	45	16	3	117	29	37	13	3	143	77	14	1	8	1	0	129	77	14	1	8	128
	≥ 0.36 and < 0.50 ha	43	29	29	7	29	40	20	0	5	29	29	14	0	7	38	25	0	13	25	0	8	50	33	0	17	6
	≥ 0.50 and < 1.0 ha	48	15	36	33	6	57	29	5	21	6	36	18	3	33	55	17	0	7	21	0	29	70	22	0	9	23
	≥ 1.0 and < 2.5 ha	66	11	23	79	22	54	15	3	61	22	42	11	3	79	79	14	0	6	2	0	66	80	14	0	6	65
	≥ 2.5 and < 5.0 ha	62	18	21	34	29	37	19	7	27	29	29	15	6	34	68	19	0	13	0	0	31	68	19	0	13	31
	≥ 5.0 and < 10.0 ha	69	23	8	13	31	33	33	0	12	31	31	31	0	13	64	21	7	7	0	0	14	64	21	7	7	14
	≥ 10.0 ha	100	0	0	17	59	35	6	0	17	59	35	6	0	17	94	0	0	6	0	0	18	94	0	0	6	18
AG (agriculture)	≥ 0.5 ha	55	13	33	40	59	19	22	0	27	40	13	15	0	40	63	14	3	20	0	0	35	63	14	3	20	35
	≥ 1.0 ha	58	11	32	38	62	19	19	0	26	42	13	13	0	38	67	12	3	18	0	0	33	67	12	3	18	33
	≥ 0.36 and < 0.50 ha				0					0					0	0	0	0	100	0	0	1	0	0	0	100	1
	≥ 0.50 and < 1.0 ha		50	50	2	0	0	100	0	1	0	0	50	0	2	0	50	0	50	0	0	2	0	50	0	50	2
	≥ 1.0 and < 2.5 ha	47	7	47	15	33	25	13	0	8	33	13	7	0	15	78	11	0	11	0	0	9	78	11	0	11	9
	≥ 2.5 and < 5.0 ha	38	13	50	8	38	0	25	0	4	38	0	13	0	8	43	14	0	43	0	0	7	43	14	0	43	7
	≥ 5.0 and < 10.0 ha	40	40	20	5	20	25	50	0	4	20	20	40	0	5	33	33	17	17	0	0	6	33	33	17	17	6
	≥ 10.0 ha	100	0	0	10	70	20	10	0	10	70	20	10	0	10	91	0	0	9	0	0	11	91	0	0	9	11
OF (open field)	≥ 0.5 ha	71	4	25	24	44	44	11	0	18	33	33	8	0	24	94	6	0	0	0	0	18	94	6	0	0	18
	≥ 1.0 ha	79	5	16	19	50	44	6	0	16	42	37	5	0	19	94	6	0	0	0	0	16	94	6	0	0	16
	≥ 0.36 and < 0.50 ha	0	33	67	3	0	0	100	0	1	0	0	33	0	3	0	100	0	0	0	0	1	0	100	0	0	1
	≥ 0.50 and < 1.0 ha	40	0	60	5	0	50	50	0	2	0	20	20	0	5	100	0	0	0	0	0	2	100	0	0	0	2
	≥ 1.0 and < 2.5 ha	75	0	25	12	33	56	0	0	9	33	42	0	0	12	100	0	0	0	0	0	9	100	0	0	0	9
	≥ 2.5 and < 5.0 ha	75	25	0	4	50	25	25	0	4	50	25	25	0	4	75	25	0	0	0	0	4	75	25	0	0	4
	≥ 5.0 and < 10.0 ha	100	0	0	1	100	0	0	0	1	100	0	0	0	1	100	0	0	0	0	0	1	100	0	0	0	1
	≥ 10.0 ha	100	0	0	2	50	50	0	0	2	50	50	0	0	2	100	0	0	0	0	0	2	100	0	0	0	2
RR (rural residential)	≥ 0.5 ha	71	11	17	70	10	67	19	3	58	9	56	16	3	70	77	12	0	3	8	0	65	83	13	0	3	60
	≥ 1.0 ha	73	11	16	55	13	65	20	2	46	11	55	16	2	55	82	12	0	4	2	0	49	83	13	0	4	48
	≥ 0.36 and < 0.50 ha	67	33	0	3	33	67	0	0	3	33	67	0	0	3	40	20	0	0	40	0	5	67	33	0	0	3
	≥ 0.50 and < 1.0 ha	67	13	20	15	0	75	17	8	12	0	60	13	7	15	63	13	0	0	25	0	16	83	17	0	0	12
	≥ 1.0 and < 2.5 ha	70	14	16	37	11	65	23	0	31	11	54	19	0	37	76	15	0	6	3	0	34	79	15	0	6	33
	≥ 2.5 and < 5.0 ha	69	8	23	13	15	60	10	10	10	15	46	8	8	13	90	10	0	0	0	0	10	90	10	0	0	10
	≥ 5.0 and < 10.0 ha	100	0	0	4	0	75	25	0	4	0	75	25	0	4	100	0	0	0	0	0	4	100	0	0	0	4
	≥ 10.0 ha	100	0	0	1	0	100	0	0	1	0	100	0	0	1	100	0	0	0	0	0	1	100	0	0	0	1

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[a] Includes main, secondary, and tertiary roads.

(Cont'd)

Table 3. (cont'd)

		Percentage by Truth Count				Delineation quality Percentage by Truth count without OP					Delineation quality Percentage by Truth count with OP					Percentage by candidate count of MBA, MBP, CI, CP, CS and CN							Percentage by candidate count of MBA, MBP, CI and CP				
Post-class	**truth event size**	**CBA**	**CBP**	**OP**	**Total Count**	**VG**	**G**	**P**	**VP**	**Total Count**	**VG**	**G**	**P**	**VP**	**Total Count**	**MBA**	**MBP**	**CI**	**CP**	**CS**	**CN**	**Total Count**	**MBA**	**MBP**	**CI**	**CP**	**Total Count**
SD (soil disturbance)	≥ 0.5 ha	86	14	0	7	43	43	14	0	7	43	43	14	0	7	67	11	0	0	22	0	9	86	14	0	0	7
	≥ 1.0 ha	100	0	0	6	50	50	0	0	6	50	50	0	0	6	100	0	0	0	0	0	6	100	0	0	0	6
	≥ 0.36 and < 0.50 ha	100	0	0	1	100	0	0	0	1	100	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1
	≥ 0.50 and < 1.0 ha	0	100	0	1	0	0	100	0	1	0	0	100	0	1	0	33	0	0	67	0	3	0	100	0	0	1
	≥ 1.0 and < 2.5 ha	100	0	0	4	50	50	0	0	4	50	50	0	0	4	100	0	0	0	0	0	4	100	0	0	0	4
	≥ 2.5 and < 5.0 ha	100	0	0	1	0	100	0	0	1	0	100	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1
	≥ 5.0 and < 10.0 ha	100	0	0	1	100	0	0	0	1	100	0	0	0	1	100	0	0	0	0	0	1	100	0	0	0	1
	≥ 10.0 ha				0					0					0							0					0
IN (industrial)	≥ 0.5 ha	71	7	21	14	73	18	7	0	11	57	14	7	0	14	77	8	0	15	0	0	13	77	8	0	15	13
	≥ 1.0 ha	88	13	0	8	75	13	13	0	8	75	13	13	0	8	70	10	0	20	0	0	10	70	10	0	20	10
	≥ 0.36 and < 0.50 ha				0					0					0							0					0
	≥ 0.50 and < 1.0 ha	50	0	50	6	33	33	0	0	3	33	17	0	0	6	100	0	0	0	0	0	3	100	0	0	0	3
	≥ 1.0 and < 2.5 ha	75	25	0	4	50	25	25	0	4	50	25	25	0	4	60	20	0	20	0	0	5	60	20	0	20	5
	≥ 2.5 and < 5.0 ha	100	0	0	2	100	0	0	0	2	100	0	0	0	2	67	0	0	33	0	0	3	67	0	0	33	3
	≥ 5.0 and < 10.0 ha	100	0	0	1	100	0	0	0	1	100	0	0	0	1	100	0	0	0	0	0	1	100	0	0	0	1
	≥ 10.0 ha	100	0	0	1	100	0	0	0	1	100	0	0	0	1	100	0	0	0	0	0	1	100	0	0	0	1
UR (urban)	≥ 0.5 ha	42	37	21	19	0	53	27	20	15	0	42	21	16	19	50	44	0	6	0	0	16	50	44	0	6	16
	≥ 1.0 ha	47	40	13	15	0	54	23	23	13	0	47	20	20	15	54	46	0	0	0	0	13	54	46	0	0	13
	≥ 0.36 and < 0.50 ha				0					0					0							0					0
	≥ 0.50 and < 1.0 ha	25	25	50	4	0	50	50	0	2	0	25	25	0	4	33	33	0	33	0	0	3	33	33	0	33	3
	≥ 1.0 and < 2.5 ha	43	29	29	7	0	60	0	40	5	0	43	0	29	7	60	40	0	0	0	0	5	60	40	0	0	5
	≥ 2.5 and < 5.0 ha	40	60	0	5	0	40	40	20	5	0	40	40	20	5	40	60	0	0	0	0	5	40	60	0	0	5
	≥ 5.0 and < 10.0 ha	0	100	0	1	0	0	100	0	1	0	0	100	0	1	0	100	0	0	0	0	1	0	100	0	0	1
	≥ 10.0 ha	100	0	0	2	0	100	0	0	2	0	100	0	0	2	100	0	0	0	0	0	2	100	0	0	0	2
RC (recreation)	≥ 0.5 ha	100	0	0	2	100	0	0	0	2	100	0	0	0	2	100	0	0	0	0	0	2	100	0	0	0	2
	≥ 1.0 ha	100	0	0	2	100	0	0	0	2	100	0	0	0	2	100	0	0	0	0	0	2	100	0	0	0	2
	≥ 0.36 and < 0.50 ha				0					0					0							0					0
	≥ 0.50 and < 1.0 ha				0					0					0							0					0
	≥ 1.0 and < 2.5 ha				0					0					0							0					0
	≥ 2.5 and < 5.0 ha	100	0	0	1	100	0	0	0	1	100	0	0	0	1	100	0	0	0	0	0	1	100	0	0	0	1
	≥ 5.0 and < 10.0 ha				0					0					0							0					0
	≥ 10.0 ha	100	0	0	1	100	0	0	0	1	100	0	0	0	1	100	0	0	0	0	0	1	100	0	0	0	1
RD (road - main & secondary)	≥ 0.5 ha	50	50	0	2	0	50	50	0	2	0	50	50	0	2	50	50	0	0	0	0	2	0	0	0	0	2
	≥ 1.0 ha	50	50	0	2	0	50	50	0	2	0	50	50	0	2	0	0	0	0	0	0	2	0	0	0	0	2
	≥ 0.36 and < 0.50 ha	50	50	0	2	50	0	50	0	2	50	0	50	0	2	50	50	0	0	0	0	2	50	50	0	0	2
	≥ 0.50 and < 1.0 ha				0					0					0							0					0
	≥ 1.0 and < 2.5 ha				0					0					0							0					0
	≥ 2.5 and < 5.0 ha	0	100	0	1	0	0	100	0	1	0	0	100	0	1	0	0	0	0	0	0	1	0	0	0	0	1
	≥ 5.0 and < 10.0 ha				0					0					0							0					0
	≥ 10.0 ha	100	0	0	1	0	100	0	0	1	0	100	0	0	1							1	0	0	0	0	1
RD (road tertiary)	≥ 0.5 ha	100	0	0	6	100	0	0	0	6	100	0	0	0	6	75	0	0	0	0	25	8	100	0	0	0	6
	≥ 1.0 ha	100	0	0	5	100	0	0	0	5	100	0	0	0	5	83	0	0	0	0	17	6	100	0	0	0	5
	≥ 0.36 and < 0.50 ha				0					0					0	0	0	0	0	0	0	1					0
	≥ 0.50 and < 1.0 ha	100	0	0	1	100	0	0	0	1	100	0	0	0	1	0	0	0	0	0	0	2	0	0	0	0	1
	≥ 1.0 and < 2.5 ha	100	0	0	2	100	0	0	0	2	100	0	0	0	2	67	0	0	0	0	33	3	100	0	0	0	2
	≥ 2.5 and < 5.0 ha	100	0	0	2	100	0	0	0	2	100	0	0	0	2	100	0	0	0	0	0	2	100	0	0	0	2
	≥ 5.0 and < 10.0 ha	100	0	0	1	100	0	0	0	1	100	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1
	≥ 10.0 ha				0					0					0							0					0

Deforestation – For all truth events greater than or equal to 1 ha, 69% were captured acceptably, 14% were captured poorly, and 16% were omitted; however, these omissions represented only 7.5% of the area of all such truth events. For truth events of 0.5 ha and larger, 65% were captured acceptably, 13% were captured poorly, and 22% were omitted. Large events > 10 ha were captured very well, with all being "captured boundary acceptable," and delineation was also good with only 5% having a poor boundary. The proportion of truth events captured acceptably in each size class (1–10 ha) was equal for each size class at approximately two-thirds; however, the smaller events had a slightly higher omission rate. For example, of those truth events greater than 1 ha, 68% of the omissions were of truth events between 1 and 2.5 ha, with no large events (> 10 ha) omitted. For the 0.5–1 ha events, the omission rate (42%) was much higher than the 16% rate for events greater than 1 ha. Agriculture and rural residential deforestation were the most likely to be missed; 30% of the agriculture and 16% of the rural residential truth events greater than 1 ha were omitted. In addition, of all the truth events 1 ha or larger that were omitted, 80% were either agriculture or rural residential (44% agriculture and 36% rural residential). However, the overall omission rate in rural residential and agriculture in terms of area was less, with the 30% omission rate for agriculture events accounting for only 12% of the area of agriculture truth events and the 16% omission rate for rural residential translating to 9% in terms of area.

The reasons for the omissions were multi-fold. Notably, for deforestation omissions greater than or equal to 1 ha, just over one-half (52% by number and 56% by area) were actually identified as forest clearing but mislabelled as forest harvest events. Most were delineated well with "good" or "very good" delineations. Conversely, for 0.5–1.0 ha deforestation omissions, only 13% were omitted as deforestation because they were labelled as harvest events. Of the omissions greater than or equal to 1 ha that were deforestation events misinterpreted as harvest, approximately 70% were clearcuts, and the remaining were partial cuts. Agriculture accounted for about one-half of the omissions due to labelling as harvest and all of these were called clearcuts. As well, about one-half of the agriculture omission events were related to events interpreted as harvest. Rural residential accounted for most of the other omissions due to misinterpretation as harvest, both clearcuts and partial cuts.

For those omissions not associated with a site labelled as harvest, the most common causes of omission were:

- weak time 1 forest signal on the imagery because young or low-density hardwood looked like ground vegetation or shrub;
- narrow sites at the edge between open areas and forest sometimes confused by misregistration;
- lack of interpreter diligence in zones with a lot of activity or with small events; or
- occasionally, interpretation blunders.

In the case of rural residential, as well as confusion with harvest, omissions were due to the often convoluted shape combined with small size, intermixing with existing open areas, and the presence of vegetated land and residual trees for many of these events. This was also likely the reason why, of all event types except urban, rural residential was delineated most poorly (18% of the rural residential events were poor delineations and 2% very poor). Rural residential events with many trees remaining were delineated considerably more poorly than those that were more completely cleared (rural residential–few trees remaining).

Deforestation to urban was well detected with few omissions (7%); however, delineation was often poor (29% "poor" and 21% "very poor"). The "very poor" delineations were all much larger than the true events and had a significant effect in terms of area of deforestation within the urban class, accounting for most of a 30% over-delineation of the area of deforestation in the captured urban events. The poorly delineated urban sites were often convoluted mixes of small and narrow existing vegetated open areas at T1 and residual trees after development. Several were in areas partly cleared for development at least four years before the T1 imagery and subsequently developed.

In terms of deforestation accuracy from a candidate-centric perspective (Table 3), 80% of candidate events associated with truth events 1 ha or larger in size matched the truth event acceptably. Fourteen percent were matched poorly and 6% were pure commissions (CP). A small number were impure commissions (CI), that is cases where the deforestation polygon only minimally overlaps a truth event and the polygon clearly is not related to the truth event. When the 0.5–1 ha truth events were included, 78% were acceptable matches, 14.5% poor matches, 7% pure commissions, and 0.5% impure commissions. For the small events (0.5–1 ha), commission error (pure) was low in number but twice the rate of the larger events, representing 12% of all small events. Another source of error, not considered in the above analysis, is candidate events that were deemed large enough but not wide enough (i.e., < 20 m wide). There was only one such "too narrow event" (CN)--a tertiary forestry road. Some sites were delineated too large and were thus over the minimum size limit of deforestation although in reality they were below that limit and should not have been deforestation (commission event too small; CS). Only 1.5% of all candidate events 1 ha or greater were truly less than 0.5 ha (the minimum size for this study).

In general, commissions were mostly associated with agriculture and industry, with 16% of the candidates of these types being commissions. Some commissions were interpreted as rural residential events, but no commissions were urban, soil disturbance, open field or roads. Part of the deforestation commission error was not that there was no forest clearing, rather that the clearing was actually harvest (64% of commissions by number and 70% by area were forest harvest labelled as deforestation). Almost all of these were partial cuts and most were misidentified as agriculture pasture or rural residential deforestation. Agriculture, especially some pasture conversion, as noted earlier, can be a difficult situation to interpret. Interpreting rural residential candidates versus small clearcuts or partial cuts, in areas where both rural residential development and forestry activity took place, was also confusing and resulted in commission errors related to the misidentification of harvest as deforestation. Of commissions not associated with harvest, the main cause of error was development and land use change on vegetated open areas and the misidentification of vegetated or shrub areas as forest on the T1 imagery, especially in urban or industrial settings. Delineation quality was similar in both the candidate- and truth-centric perspectives. Considering all test area accuracy events of 1 ha or larger where there was a correspondence of candidates and truths, 81% of candidate events were delineated with very good or good quality and only 4% delineated very poorly (Table 3). When the area of these events was considered, commission error represented 6% of both the total candidate and truth event areas. For agriculture, industry, and rural residential events, the area of commission error represented 14, 9, and 3% of the total candidate area of each event type, respectively.

The percent overlap of truth and candidate events also provides insight into the quality of the deforestation interpretation. However, caution must be used. For example, high percent coverage of a truth event by a candidate (truth overlap) does not necessarily indicate good correspondence because although the candidate may completely cover the event; it may be much too large. Tables 4–6 provide information on the "deforestation proportion," "truth overlap," and "correspondence" (see these tables and Appendix 1 for definitions). There was overall good amount of overlap. For example, 92% of the captured truth events had a truth overlap of 80% or more, and 70% of captured candidate events had a deforestation proportion of 80% or more. When omissions were excluded, the number of events with high truth overlap was generally larger than those with a high proportion of deforestation, indicating that candidate events generally tended to be bigger and more inclusive. Forty-two percent of events captured as acceptable or poor had a "correspondence" of greater than 90%, 63% had a "correspondence" of greater than 80%, and only 2% had correspondence of less than 50% (Table 6). Regarding the actual area difference between associated truth and candidate events for the captured boundary acceptable and poor cases, 49% were within ± 0.5 ha and 71% within ± 1 ha (Table 7). There was a tendency towards overestimating the size of individual events.

Table 4. Number of candidates and percent of total number of candidates in different deforestation proportion categories (for truth events ≥ 1 ha)

Deforestation proportion[a] (%)	**100**	**90–99**	**80–89**	**70–79**	**60-69**	**50–59**	**25–50**	**1–25**	**0**	**Total**
Number of candidates	12	53	22	17	7	10	3	0	13	137
Total number of candidates (%)	9	39	16	13	5	7	2	0	9	
Number of candidates (w/o commissions)	12	53	22	17	7	10	3	0	0	124
Total number of candidates (%) (w/o commissions)	10	43	17	14	6	8	2	0	0	

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[a] "Deforestation proportion" represents the percentage of the candidate event covered by deforestation.

Table 5. Number of truth events and percentage of total number of truth events in different deforestation truth overlap categories (for truth events ≥ 1 ha)

Deforestation truth overlap[a] (%)	**100**	**90–99**	**80–89**	**70–79**	**60-69**	**50–59**	**25–50**	**1–25**	**0**	**Total**
Number of truth events	23	69	22	6	4	0	0	0	26	150
Total number of truth events (%)	15	46	15	4	3	0	0	0	17	
Number of truth events (w/o omissions)	23	69	22	6	4	0	0	0	0	124
Total number of truth events (%) (w/o omissions)	18	56	18	5	3	0	0	0	0	

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[a] "Deforestation truth overlap" represents the percentage of the truth event (or the group of truth events) covered by candidates.

Table 6. Correspondence of truth and candidate events (for truth events ≥ 1 ha). For truth events captured, acceptable or poor.

Correspondence (%)[a]	**100**	**90–99**	**80–89**	**70–79**	**60-69**	**50–59**	**25–50**	**1–25**	**0**	**Total**
Number of truth events	4	48	27	23	10	9	3	0	0	124
Total number of truth events (%) (w/o omissions)	3	39	22	19	8	7	2	0	0	

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[a] "Correspondence" is the area that corresponds to both the truth and candidate event, divided by the area of the larger of the two (i.e., the larger of either the candidate or truth polygon) (Appendix 1).

Table 7. Difference in area between candidate and truth events in each area difference class (for truth events ≥ 1 ha)

Area difference class (ha)	**Candidate larger than truth event**				**Candidate smaller than truth event**				**Absolute value of difference**			
(Truth minus candidate)	**over −2.5**	**−1 to −2.5**	**−0.5 to −1**	**0 to −0.5**	**0–0.5**	**0.5–1**	**1–2.5**	**over 2.5**	**± 0.5**	**± 0.5–1.0**	**± 1.0–2.5**	**± > 2.5**
Number of events by number in classes (CBA)	4	7	14	29	29	6	14	2	58	20	21	6
Total events by number (%)	3.8	13.3	13.3	27.6	27.6	5.7	13.3	1.9	55.2	19.0	20.0	5.7
Number of events by number in classes (CBP)	7	4	3	1	0	2	2	0	1	5	6	7
Total events by number (%)	36.8	21.2	15.8	5.3	0.0	10.5	10.5	0.0	5.3	26.3	31.5	36.8
Number of events by number in classes (CBA and CBP)	11	11	17	30	29	8	16	2	59	25	27	13
Total events by number (%)	8.9	8.9	13.7	24.2	23.3	6.5	12.9	1.6	47.6	20.2	21.8	10.4

Errors of omission and commission, as well as delineation discrepancies, such as inclusion of non-deforestation areas or exclusion of sections of deforestation within an event, can all be offsetting in terms of total area of deforestation reported from a mapping process. Over the entire test area, candidate events of 1 ha or larger totalled 800 ha of deforestation for the acceptable and poorly captured events (i.e., the mapped deforestation events that were related to true deforestation), whereas the area of true deforestation was 749 ha. Therefore the candidates represented a 7% overestimation of area versus the truth events. When both commissions and omissions were included, the truth area was 810 ha and candidates 853 ha for events 1 ha and larger, representing a 5% overestimate. Even when events between 0.5 and 1 ha were included, the overestimate of total deforestation area remained at 5%. The areas for the main post-deforestation categories and events of 1 ha or larger, (including commissions and omissions) were:

- Agriculture: 280 ha for candidate events and 270 ha for truth events;
- Urban/Suburban: 81 ha for candidate events and 64 ha for truth events;
- Rural Residential: 172 ha for candidate events and 162 ha for truth events; and
- Open Field: 89 ha for candidate events and 86 ha for truth events.

The deforestation area seemed to be consistently overestimated by a small amount. This was true whether or not omissions and commissions were included. Omissions, although larger than commissions (61 ha vs. 53 ha), did not fully compensate for the overestimation in the delineation of the candidate events. This type of offsetting error will occur in all surveys and will vary according to many factors; these results give an example of its magnitude.

Mapping Improvement with Second-cycle Mapping Review – The second-cycle mapping altered the delineation and (or) attributes of some existing events, as well as corrected omissions and commissions. For delineations within the accuracy assessment test cells, 34 events had boundary changes and 31 of these were greater than 1.0 ha in size. All events with delineation changes exhibited improved boundaries and for events greater than 1.0 ha, 20% of all events were re-delineated resulting in 14% (22 cases) of all events with an improved delineation assessment category (note that although all boundaries were improved, not all improvements increased the delineation quality category). Many (13) of the cases involved changes from "good" to "very good" delineation, but four cases were improved from "poor" to "very good." For the second- cycle mapping of previous events greater than 1.0 ha, delineation quality was approximately 46% very good, 41% good, 12% poor, and only 1% very poor. Most cases resulting in a delineation class change were rural residential, with a few urban and open field cases. The review of the mapping during the second cycle, with its availability of more high-resolution imagery, was especially effective for the difficult-to-map, smaller, and more convoluted events in zones of mixed development, forestry, and agriculture (Figure 9 gives examples).

The second-cycle review process did not capture many omitted events. Only two omitted events were added: a large 4.3 ha agriculture crop site and a 1.5 ha gravel pit. However, the second-cycle revisions created a new omission, in which a 5.2 ha pasture polygon was deleted, because it was interpreted as regenerating. This case involved a confusing site that was starting to undergo regeneration but then was re-established as pasture. It serves to illustrate the situation in the Prince George area and some other prairie fringe landscapes, as well as in a few other regions of Canada, where some sites change status back and forth over time between forest and pasture. As noted above, almost two-thirds of the omissions were captured as a clearing but labelled as harvest. The second-cycle review process did not use the harvest events (i.e., they were not specifically checked for deforestation); however, in a special analysis as part of this study, all the harvest events in the test cells were checked for deforestation using a process similar to the second-cycle review. In addition, the harvest events were also checked during a third cycle review simulation using all Landsat and high-resolution imagery available as of circa 2014. This analysis showed that approximately three-quarters of the 15 cases of deforestation captured as harvest in the test cells would have been identified as a deforestation event had they been checked during the second-cycle review. Several additional cases were uncertain and may have been identified. Indeed one site remained uncertain and may be permanently regenerating and thus was not truly deforestation. Four of the 15 cases would have been recognized if only Landsat data were available. In three cases, the deforestation constituted only a small portion of a much larger harvest area that was delineated as harvest. Results from the simulated third-cycle review indicated that a third cycle review would likely detect and revise all omitted deforestation events captured as harvests. For all the test cell sites, there was circa 2003–2014 high-resolution imagery available. However, it was estimated that even with only Landsat imagery, the most recent being 2011, nine cases (60%) would be identified as deforestation with high confidence, and an additional one or two possibly would be revised but with some uncertainty.

The second-cycle mapping review, as well as checking for omissions, quickly evaluates all previous events, and therefore some commissions are noticed and changed. For example, the test cells contained 26 commissions (total regardless of size and type of commission). Polygons labeled agriculture pasture were a common source of false alarms. Seven of the nine agriculture commissions (of any size) were deleted in the second-cycle mapping, representing 80% of the 44.3 ha of committed agriculture pasture events. Of these deleted sites, most could be determined as commissions using Landsat imagery alone based on the passage of time and resulting lack of signs of regeneration on the imagery, and a persistent uniformity in the image texture of the sites. However, in cases where high-resolution imagery was available, it provided conclusive evidence. Of the two unchanged agriculture commissions, both were greater than 1 ha; the first was a complex site where recognizing the presence of forest at T1 was difficult and the second was a narrow site adjacent to an open area that was confounded by slight image misregistration. For all commissions greater than 1.0 ha (including agriculture pasture), 6 of 13 were deleted by the second-cycle mapping, representing 53.2 ha (69%) of test cell commissions. Of the seven events not deleted, five were non-pasture sites consisting mainly of 1–2 ha rural residential polygons. A check of currently available (2014) high-resolution imagery on Google Earth or Bing Maps showed that all seven were covered by at least one and often several, images from 2005 onward. Using these, five of the sites would be easily detectable as deforestation. The other two commissions were due to the sites that were not forest at T1.

A second source of commission was commission too small (CS) or commission too narrow (CN) (Table 3). Only one of the nine commission-too-small events was removed by the second-cycle review. Most CS were classed as rural residential, and were in complex situations, subtle, and between 0.5 to 1 ha in size. They were not a high priority in the production mode of the second-cycle review process.

Similar observations were made when considering all changes made in the entire study area during the second-cycle review process. The original mapping did capture most events, with only two events added, although these did not necessarily represent all omissions in the original mapping. Commissions were greatly improved, with 97 of the non-road commission events deleted, representing 9% of the events initially mapped. Most were agriculture events that were known to be difficult to interpret because of the log-and-leave practice and general confusion with pasture sites. As well, areas cleared close to1999 may not have been treated or the new land use fully established at the time of the most recent imagery used; such cases can be difficult to confirm as deforestation during the review process. The small rural residential sites, and to a lesser extent open field sites, in mixed use agriculture, forest, rural residential areas were difficult to interpret. Most (80%) commissions were related to sites visibly regenerating on the later Landsat or high-resolution imagery. A further 8% were cases where T1 land use was estimated to be non-forest, and 12% were too small or were a configuration of forest patches, residual trees, and open deforested areas that did not meet deforestation requirements.

The second-cycle review process identified a considerable number of cases that called for re-digitizing or fine-tuning parts of the boundary of existing events (i.e., 94 of 1059 non-road sites). Many of these involved simply fine-tuning delineations that were already classed as acceptable. Although the fine-tuning was not necessary, it did improve the delineation and was possible due to the availability of high-resolution imagery for the review process. Most changes improved the delineation of small events, especially rural residential sites and usually resulted in a decrease in event size. Note that there were also 13 cases where the existing event was split into two new events with different post-class attributions.

Overall, the second-cycle review is a helpful process that benefits from the passage of time and establishment of the new land use or the onset of forest regeneration. The principle of erring on the side of false alarms seems justified as omissions are harder to find during a review and many of the commissions are captured. No high resolution imagery from after1999 was available for the 1990–1999 mapping of this study. The only high resolution imagery available was the 1996 ancillary aerial photography and this covered only some of the study site. Even the second-cycle, 1999–2006 mapping did not have a full complement of high-resolution imagery and some was from the early 2000 years. Thus, if new deforestation mapping was undertaken for a 2008–2013 time period, for example, it would benefit from the presence of high-resolution imagery and also multiple years of Landsat imagery during and after the mapping period. Landsat imagery is now freely downloadable from the United States Geological Survey and other sites. This 2008-2013 mapping would be third-cycle mapping and a review of the1990-1999 mapping would have access to high-resolution imagery, especially for developed areas, in the order of 10–15 years (or more) after the 1990–1999 events and some dates in between. Therefore, conclusive evidence of deforestation on most sites should be available to verify deforestation, fine-tune boundaries, and improve post-class attribution.

For operational deforestation mapping, the practice of erring on the side of deforestation remains, but due to experience gained by this study and others, the current practice is to be less aggressive in terms of calling uncertain sites deforestation. Nevertheless, instructions still specify to err on the side of deforestation and for uncertain sites to place a quality control point specifying a need to recheck the site in the second cycle review process.

Deforestation–Post-class Attribution Match – For all captured truth events of 1 ha or larger, 84% had matched post-classes, with 9% acceptable and 7% wrong; results were similar for small sites of 0.5–1 ha. However, considerable confusion existed at the post-class modifier level. For those post-classes with more than one post-class modifier, the percentage of events 1 ha or larger that matched both at the post-class and post-class modifier level was 59%, with 32% acceptable and 9% wrong. For those that matched at the post-class level and for which there were test sites of more than one post-class modifier type within that post-class, 67% matched exactly at the post-class modifier level. There was a slight trend in better matches for larger events and events > 5 ha tended to match very well. Overall accuracy and average class accuracy at the post-class level were both approximately 85% for events 1 ha or larger, with confusion mostly related to agriculture, open field, and rural residential (Table 8). For example, 12% of agriculture truth events were labelled as open field and another 12% as rural residential. Twenty-five percent of all events in the truth data set that were labelled agriculture were actually open field truth events (Table 8). Confusion involving agriculture events was mostly related to small events. Differentiation between agriculture crop and pasture was weak and many of the "rural residential–many trees remaining" were attributed to "rural residential–few trees remaining." This latter confusion was due in part to delineation differences, with the truth events often including more patches of residual trees than the deforestation candidates and thus being labelled "many trees remaining." Distinguishing pasture versus crop is difficult in general but was particularly problematic in the study area because many pasture sites were also used for hay, and cropped areas were sometimes used for pasture after harvest.

Table 8. Confusion matrix by post-class (for truth events greater than 1.0 ha (excluding omissions), showing percentage of truth events classified as each post-class. Total accuracy = 81.5%; average class accuracy = 86.6%.

		Candidate post-class								
		AG	**OF**	**RR**	**SD**	**IN**	**UR**	**RC**	**RD**	**Number of truth events**
Truth post-class	AG (agriculture)	**73.1**	11.5	11.5		3.9				26
	OF (open field)	25.0	**68.8**				6.2			16
	RR (rural residential)	2.2		**95.6**					2.2	46
	SD (soil disturbance)		16.7		**83.3**					6
	IN (industrial)			12.5		**87.5**				8
	UR (urban)			15.4			**84.6**			13
	RC (recreation)							**100.0**		2
	RD (road)								**100.0**	7
	Number of candidate events	24	15	50	5	8	12	2	8	124

Attribution Improvement with Second-cycle Mapping Review – The main purpose of reviewing events in the second-cycle mapping was to identify and correct commissions and omissions. If an event is determined to be acceptable in terms of commission and boundary, the review process does not require a check of post-class or pretype attributes, unless attribution of pretype or post class is specifically known to be a problem in a mapping project. Nevertheless, post-class attribute changes are noticed and made. Of all the events in the test cells, 18 events ≥ 1 ha, representing 14% of all events 1 ha or larger, had a change in either post class, post-class modifier, or both (another three events could be included if one considers events less than 1 ha). Approximately one-half (44%) had only a post-class modifier change. All changes either improved the attribution of the new land use or represented a neutral change. For example, 15 of the 18 events were changed to the correct post-class and post-class modifier while two of the other three were acceptable matches at the post-class and post-class modifier levels. Several large events were changed correctly from "Open Field undifferentiated" to "Agriculture pasture," reflecting the greater information available with the passage of time and new imagery. Other "Open Field undifferentiated" events were attributed to a more specific open field post-class modifier (e.g., playing field or development). During the initial mapping the open field post-class had no subcategories, it only had the class "Open Field undifferentiated", and thus some changes were due to the new subcategories and not improvements in the interpretation. The Urban class had changes at the post-class modifier level, from "many trees remaining" to "few trees remaining." These changes reflect the use of high-resolution imagery and hence, better discriminating capability and ability for finer re-delineation of the boundary to eliminate treed areas. Although the class of such re-delineated events was sometimes correct as "many trees remaining" before re-delineation, the new boundary necessitated a change of the post-class modifier to "few trees remaining."

Overall, the accuracy of the test events at the post-class level increased from approximately 85% to 90% through the second-cycle review and from 61% to 73% at the post-class modifier level. Thus, even the production process of the second cycle review, which does not focus on post-class attribution, improves the categorization of the new land use. A third-cycle review of the study area's deforestation mapping would be expected to further correct post-class attribution, as much more high-resolution imagery is available now than for the second-cycle review process. Post-class attribution could be improved even more if checks of post class were mandated in the review process. Post-class attribution is expected to be considerably better in new deforestation mapping (e.g., 2008–2013) because of increased availability of high-resolution imagery.

All attribute changes during the second-cycle review of the whole study area were examined. This indicated that of all of the 1059 non-road events (Table 2) mapped in the initial stage, attributes were changed in approximately 200. Some of these changes resulted from the introduction of new post-classes into the system after the initial mapping was done. These new categories (Leckie et al. 2012) are related to finer post-class modifiers that better attribute deforestation to the industrial classes or drivers. For example, the "Open Field" post-class did not have any subclasses, and all were termed "undifferentiated." For later mapping and the second-cycle review there were 10 additional post-class modifiers, six of relevance to the Prince George region (agriculture-related; industrial; recreational, such as playing fields; pit and quarry-related; rural residential; and urban/suburban development as in cleared but as yet undeveloped sites [sometimes referred to as "brown fields" by land use planners]). Agriculture also had a new post-class modifier added: "farm yard." Thus, many of the attribution changes were not related to initial interpretation error but rather to a fine-tuning of the post-class modifiers. The most common revisions were related to the open field class, with 42 "Open Field undifferentiated" changed to "Agriculture", 13 to another post-class most often "Rural Residential", and an additional 15 to a finer Open Field post-class modifier. In the initial mapping, there was a known and accepted tendency to call cleared sites of somewhat uncertain post class "Open Field undifferentiated" as opposed to assigning a more specific class and this is evident in the results presented here. The current practice is to be more aggressive in calling specific classes, which means that most of the open field cases changed to agriculture would likely now be initially assigned to an Agriculture class. Eight rural residential sites were changed to open field because one of the new open field post-class modifiers was more appropriate. These eight and the other changes involving the open field class were mostly made possible by the availability of high-resolution imagery. There were two changes to "farm yard." The passage of time improved the interpretation of pasture versus crop using Landsat imagery only. The use of several Landsat images through the years sometimes helped identify crop sites by the different growth stages or harvest condition. High-resolution imagery also helped greatly. However, there can still be confusion, particularly related to the farming practice in the region of using hay or forage crop fields for pasture. Over the 200 attribute changes made, it was estimated that 35 changes resulted from the introduction of new post-class or post-class modifier categories and 30 from the overuse of "Open Field undifferentiated." Thus, about two-thirds of the changes were related to interpretation improvements mostly due to the availability of high-resolution imagery and (or) the passage of time. Fifty of these were changes between agriculture crop and pasture.

Attribution of road events was also improved. The initial mapping assigned roads to classes and gave each class a standard width (Eichel and Leckie 2006). The subsequent review process deliberately assigned actual widths to each road, using high-resolution imagery or Landsat. Approximately 50 of the 544 road events changed class, most of these to a lesser road class and many from secondary forestry to tertiary forestry roads less than 20 m wide.

Forest Harvest – The mapping of forest harvest was very effective. For events 1 ha or larger, only five events were omitted, accounting for 6% of the harvest events and 4% of the area of harvest in the test area. One was a large 14 ha clearcut and was missed due to time 1 forest being low density hardwood. Another two polygons, amounting to 40% of the omitted area, were the same event separated into two polygons by a stream and were likely detected by the interpretation but overlooked as they were partial cuts with few trees removed. For the remaining two omitted events, harvest was detected and well delineated but was labelled as deforestation (agriculture pasture). There were two omissions for the events between 0.5 and 1 ha in size. Regardless of size class, there were no commission errors (i.e., harvest candidate events that were not harvest). In total within the test cells, the harvest area mapped was only 1% higher than that of the truth data.

Harvest events were categorized into three classes: (1) clearcut (CC), (2) partial cut (PC), or (3) clearcut with residual (CL). When "clearcut with residual" was considered an acceptable interpretation for either "clearcut" or "partial cut," 68% of events matched in post-class and 24% were acceptable, whereas 8% were wrong; these incorrect attributions were fairly equally distributed between "clearcuts" called "partial cuts," and "partial cuts" called "clearcuts." "Clearcut with residual" can essentially be considered a post-class modifier since clearcuts can have residual trees and a gradation in the number of remaining trees exists between clearcuts and partial cuts. Of those events incorrectly attributed at the post-class modifier level (i.e., not ascribing the residual label correctly), 60% were cases in which the interpreter missed residual trees on a clearcut (i.e., clearcut with residual called a clearcut), 30% were cases in which the amount of residual was overestimated (i.e., clearcut with residual called a partial cut), and only a few cases where clearcuts were classed as clearcut with residual. Underestimating the presence of residual trees is to be expected when using 30 m resolution Landsat data.

5. Summary and Discussion

This pilot study developed and tested an integrated approach to forest disturbance mapping that combined automated change classification of Landsat imagery, forest inventory, and manual image interpretation supported by ancillary data. The pilot served to provide insights into the pros and cons of methods, their applicability for different landscape and forest disturbance types, possible improvements, and the overall effectiveness of the combined approach. Although undertaken in just one study area, the site represented several quite different landscapes and forest change drivers, including a commercial forest zone with harvest as the sole disturbance driver; agricultural regions similar to Canada's prairie fringe; zones of mixed agriculture, rural residential, and urban; a substantial city within a forest setting; and mixed activity within predominantly forest areas. Other studies have provided information on the manual interpretation process for deforestation mapping in other environments (see Leckie 2006). Stinson et al. (2005), using the harvest and deforestation mapping from this study, demonstrated how such data can be used in spatially explicit forest carbon stock change accounting. The landscape and activities in the Prince George study area are representative of quite a bit of the variety found across Canada. Mapping was over a nine-year period and the site is active in terms of forestry and land use change. The disturbance landscape was very simple in the commercial forest zone, but the agriculture and mixed areas were complex and difficult to map. Indeed, considering the practice of log-and-leave, the delay in urban and rural residential development after clearing, plus the mixed rural residential, agriculture, and forestry regions, the study area is one of the most difficult environments in which to detect, delineate and attribute forest disturbance.

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[2] See Google Earth and Google Street View web site: https://www.google.com/maps/; and Microsoft® Bing Maps web site: http://www.microsoft.com/maps/

5.1 Usefulness of Ancillary Data

Ancillary data is useful for forest harvest mapping but very important for deforestation interpretation. The data available for this study was typical of what might be available for much of Canada. There will be various layers of national and provincial base map information of variable vintage. Forest inventory will also often be readily available, as will one (perhaps more) aerial photograph or high-resolution image coverage within or near a 10-year time interval. In this study, we had a photo set two years before (1988) and in the middle of the mapping period (1996). Currently and into the future, deforestation mapping, especially in developed regions, can expect to have more high-resolution data available from sources such as Google Earth™ and Bing™ Maps[2]. If the mapping process is taking place several years after the T2 date, there may commonly be high-resolution imagery available near or after T2.

The aerial photography was very useful. The 1996 photography was digital and coregistered so it was very helpful in calibrating the interpreter for different disturbances on the Landsat imagery, understanding the land use and forestry practices, and confirming the type of disturbance for specific events between 1990 and 1996. The photography was used heavily and made the mapping faster, increased the interpreters' confidence and resulted in a better product. The 1996 photography was also useful for checking the nature of smaller and complex changes, especially their post class, either by examining the change if before 1996 or through association with adjacent or nearby land uses. Moreover, it aided in delineating rural residential events or smaller events with convoluted shapes or mixed with existing open or partly forested sites.

In contrast, the 1988 photography was used in moderation. This was partly because of the awkwardness of the hardcopy format, which made interpreters reluctant to go to the effort of searching for the site of interest unless the information was badly needed. The 1988 photography was used primarily to confirm the presence of forest at T1, but most sites were dense mature conifer with some dense hardwood, which were easy to interpret on the Landsat imagery without the photographs. The photographs, however, were effective for determining cases of low-density hardwood, shrub, and young or regenerating hardwoods. The 1988 photographs were also useful for more precise delineation of deforestation events that were adjacent to sites cleared before 1990 but left vacant until later development. Greater use of the 1988 photography would have reduced the error resulting from these types of deforestation.

The base map layers were of moderate use. Features such as roads, transmission lines, urban areas, and other infrastructure were generally easy to interpret from the Landsat imagery or aerial photographs and therefore, the base map information was not needed. The wooded area layer was also infrequently used since forest cover was generally easy to determine on the imagery and definitions of wooded area were different than what was needed in this study. The wetland layer was useful to confirm some false alarms, but the level of detail and consistency of the wetland boundaries was insufficient to use as a hard mask to eliminate these areas automatically as candidates for forest disturbance. Experience has shown this is also true in other areas of the country.

The forest inventory was not often needed to confirm the presence of T1 forest as this was generally easy to determine from the Landsat imagery. Time 1 forest was sometimes difficult to interpret when hardwoods, shrubs, or low-density forest were present in the suburban rural residential areas or in mixed agriculture rural residential forest areas. However, the inventory was often not useful in these cases because inventories often lump non-forest cover types into general classes, such as exposed land, herb, and shrub, and have a minimum map unit size of 2 ha. Thus, in these mixed used regions, the small stand size, fine-scale mixing of cover types, and presence of pre-existing open areas meant the sites of interest were often combined in the inventory map and not at the needed detail. On the other hand, in the mixed agriculture forestry zone, the forest inventory did occasionally help to differentiate harvest cuts from agriculture conversions by looking at the attribute of the cleared area. Even if the cleared area was not yet mapped on the inventory, the forest type of the area prior to clearing gave some clues about the possible type of clearing. For example, a clearing of a young or immature site is not likely to be a forest harvest.

5.2 Site Familiarization and Local Data

The first step of the mapping procedure is interpreter calibration, including gathering knowledge of local land management practices and searching for useful local data sets and records. The site visit and contacts with local officials early in the project were useful. Particularly important was being warned about the pre-clearing of some developments and log-and-leave practices, and the realization that differentiating harvest from agriculture was difficult.

Local records or databases were not used. As in much of Canada, these data are of mixed quality, type, and utility. Even when effective and desirable, making arrangements to access them can often be time consuming. The City of Prince George had some data types and GIS coverages that looked effective. The rural municipality's data, conversely, did not look as effective and were not in digital format, but the local land use planners and managers had very valuable information, both on general land use changes and specific details on actual sites. The difficulty is in efficiently accessing the local data and expertise. This will be typical of much of Canada (Leckie et al. 2000). The effort in acquiring, then understanding and applying data sets to a specific issue must be weighed against the benefit. Note that local and regional data sets are not designed for forest clearing or deforestation purposes and therefore these data will rarely be directly useful in mapping. Their most likely use will be to provide clues about where land use change may have occurred and its nature. For nationwide surveys, such as Canada's deforestation monitoring program, it is not generally practical to pursue local records as a standard practice. Nevertheless in some cases where data is appropriate and readily available, the cost versus benefit will be worthwhile.

Accessing local knowledge before and during the interpretation, or later for quality control or validation would be very helpful; although, a willing collaborator with sufficient time and interest is needed. Such collaborators take time to find, develop, and train. Moreover, the process has to be made streamlined and simple for the collaborator. In this study, the vetting of a near final map by local experts would likely have been worthwhile. In subsequent operational deforestation mapping in British Columbia, the use of local experts to check sites was implemented through a collaboration with the B.C. Ministry of Agriculture. Uncertain sites, mainly agriculture related, were identified and regional staff used local knowledge and site visits to check them.

5.3 Interpretation Environment

The manual interpretation process was conducted with the Landsat imagery and ancillary data. Overall, the process was effective. Having an image analysis component available on one screen was useful for displaying and enhancing different band combinations. While this component was not always needed or used, it was very helpful for difficult-to-interpret events, especially deforestation. The panchromatic 15 m 1999 spectral band was not very informative and seldom examined. The suite of band combinations and the change enhancements displayed were usually good enough to show the needed features. A key issue for interpretation was having enough screen real estate to effectively display the various information, including imagery, GIS layers, aerial photography, oblique photographs, and data entry dialogue. A two-screen system was essential and indeed, for part of the process, a four-screen system was used. Viewing back and forth and finding the same site on both systems (GIS and image analysis) was an annoyance. Since the completion of this study, a tool ("Live Link") has been developed to alleviate this issue. It displays the cursor position on both the PCI image analysis system on one screen and the Arc/GIS environment on the other screen (Leckie et al. 2004). Current deforestation practice does not often include an image analysis system component. Instead Arc/GIS is used for display of the main imagery and, although awkward and not as effective, it is also used for image enhancements. The Arc/GIS with drop-down menus to assist data entry was also efficient for delineating and attributing events.

Interpreter fatigue was an issue. The mapping in the mixed use area could be onerous and detailed work demanding many decisions that incorporated a variety of information and logic. For example, the mixed agriculture, rural residential, and forest areas typically contained 40–90 event triggers per 10 × 10 km interpretation cell. Breaks were important, as was communication between the interpreters to share ideas, confirm events, and provide mutual support. Regardless, fatigue or boredom was an issue and a cause of some of the errors in the final product.

5.4 Interpretation Process

The interpretation approach required identification of candidate forest clearing events through triggers on the images. Triggers are the red areas on the change enhancement image usually associated with changes from vegetation to non-vegetated, or changes identified by toggling between the two Landsat scenes. A key component of the mapping procedure is sorting out false alarms from other forest clearings. The number of these triggers changed depending on the landscape. Wetland changes and agriculture field changes were the most common types of false alarms, with disturbance of ground vegetation on existing clearcuts or misregistration also being error sources. Outside the forestry-only zone, there was on average 250 triggers per interpretation grid cell, typically varying from 200 to 400. Within the forestry-only zone, triggers usually varied from 80 to 220 per cell. The number of actual forest clearings represented by these triggers (i.e., the event–trigger ratio) was typically 10–20% in the forestry-only region and 15–30% in the other regions. Despite the number of triggers, false alarms were generally easily resolved, either by examining the change enhancement or the Landsat images of T1 or T2. This was not a time consuming issue. It was also considered better to produce a change enhancement that would tend to create many false alarms rather than miss some events.

A precise wetland map would be useful. Issues in the use of such maps would be the relevance of the definitions of wetlands to deforestation, especially for treed wetlands, and also the ephemeral nature of the boundaries of wetlands, which depend on moisture conditions. Equally useful would be a detailed map of agriculture fields compatible with specifications appropriate for deforestation mapping. If accurate, reliable, and appropriate for the time period, such maps could even be used as a solid mask under which one would not have to look for deforestation. Another factor that reduces false alarms is very good image registration, although there will always be some registration issues and resultant false alarms. An additional registration step to automatically identify and correct for local misregistration would help eliminate misregistration and related false alarms, although overall, dealing with misregistration issues was not time consuming or difficult.

5.5 Field Verification

The mapping and interpretation process consists of initial interpretation, quality control, field verification, and revision. They need to be considered as one process. Field verification was very important in this study, because of the complexity of the land use landscape and difficulty in differentiating harvest from agriculture clearing. Almost 1000 sites were assessed from field observations or oblique aerial photographs, accounting for approximately 20% of all forest clearing events, and because the fieldwork was focused on the agriculture and mixed use zones, 35% of the sites in these landscapes were assessed. The efficiency of the field observations benefitted from the relatively compact nature of the agriculture and mixed areas, which were concentrated in three regions covering about one-third of the study area. A field campaign for a pilot project in the Saskatchewan prairie fringe (Leckie 2006) covered 51% of all deforestation sites over a 71 000 km2 area showing field observations of large areas is possible. However, these densities of field observations may not always be achievable.

Several factors were considered when determining which sites to visit. These included the preliminary site visit and interviews with local experts, the identification of certain land use practices as potential problems, and general interpretation issues flagged during mapping and quality control. Another important factor and a prime driver in prioritizing sites was the interpreters' requests for field visits. Interpreter confidence, although not always a good reflection of potential error, was of some value. In practice, the sites assessed also depend on the aerial observation flight planning, which takes into account optimizing the route to visit priority sites, plane fuel capacity, locations of landing strips, and local weather conditions at the time of the flight. Although the flights cannot generally confirm that a site was previously forested, they can usually help determine whether it is still forest, or a harvest or deforestation event, and what post-class and post-class modifier it is. Given the value of the "in-the-field" site confirmation of deforestation and post-class type, and of oblique photos, both are recommended. The photographs were essential in some cases where the landscape was too complex to identify and call sites effectively from the aircraft. With increasing amounts of publicly available high-resolution imagery and tools such as Google Street View, the number of uncertain sites that require, or would benefit from fieldwork has diminished, but the latter remains an important option.

Field verification indicated that the interpretation was identifying non-forest areas well, but many of the sites originally interpreted as forest clearing sites needed to be changed from deforestation to clearcut or partial cut. Most sites requiring change had been labelled as "agriculture deforestation." This reflects both the difficulty in differentiating some harvest from agriculture clearing in this landscape and also that the original interpretation was designed to err on the side of calling events "deforestation." Conversely, only 33 of approximately 2650 original harvest events required a change to deforestation. Twenty-eight percent of the agricultural deforestation sites were assigned moderate or low confidence and 75% of the low or moderate confidence sites were labelled "agriculture", which also highlights the uncertainty surrounding the interpretation of agriculture clearings and the tendency to err on the side of calling sites deforestation. As part of the field verification and quality control procedure, clues on the imagery, in terms of spectral content and texture as well as context, shape and pattern, were derived that helped interpret and change the attribute of some events. Despite this additional knowledge, it was still difficult to categorize some sites without the aerial and ground field observations. Indeed, even with observations from the air or ground it remained difficult to differentiate some sites between harvest and pasture. This was due to the practice of cutting a site, then running cattle for several years and sometimes letting it regenerate while at other times converting it to pasture. In some cases the farmer may change or not even know his/her intentions.

5.6 Use of Automated Classification and Forest Inventory Data

The mapping procedure was a combined approach using interpretation, forest inventory, and the automated change classification. Inventory polygons were not effective for direct use as deforestation polygons, except for large agriculture events. Even when just the agriculture deforestation events were considered, only 10% of final agriculture deforestation polygons were derived from inventory polygons, and only slightly more had acceptable boundaries. Almost no inventory polygons were directly used for other deforestation types. This was largely due to the minimum mapping unit size, a lack of specificity in the non-forest open types, and the amalgamation of areas of mixed land cover into combined inventory polygons in the complex fine-scale landscapes. For forest harvest mapping, 25% of the inventory polygons were used and 37% were acceptable. The main reason for not using forest inventory polygons for forest harvest mapping was that the harvest had not been updated on the inventory (94% of unacceptable events). Unacceptable boundaries were the other reason for not using an inventory polygon. Currency of inventories is an issue across Canada. Although provinces have programs to keep inventories up to date, this is not always achieved. The uncertainty of how recently and thoroughly the latest maps have been updated is an important issue in using the data. Nevertheless, the inventory was useful in providing some polygons and other information to confirm harvest or T1 forest. Therefore, forest inventories are not essential but should be used where practical.

The automated change classification is a main component of the integrated approach to mapping. The two-date unsupervised classification approach was effective in identifying cleared areas and also gave information on the cover type of stable areas and nature of cover type changes. In terms of extracting forest clearings, the classification method allowed the analyst to rapidly focus on areas related to forest clearing. The K-means clustering produced 74 initial clusters related to land cover change. From these, it was easy to identify the 21 clusters related to forest clearing versus other changes, which were mostly associated with ground vegetation changes on previously clearcut areas. The classification in this study was particularly complicated as 17 clusters were associated with vegetation senescence, which would normally not be present in the imagery. Nevertheless, senescence was handled well and efficiently. Regardless of how good or thorough methods are, there will always be some cases of mixed classes including stable forest, change, and (or) other spurious features such as misregistration and senescence. The classification itself was effective for the clearcuts in the forest harvest region, with pixel-based accuracies approaching 100% for clearcuts in conifers. Older clearcuts in mixedwood or broadleaf stands were less accurate as they had time to develop moderate or dense ground vegetation or shrub cover by 1999.

Pixel classifiers do not necessarily produce spatial units of the shapes, boundary smoothness, and minimum size necessary for some applications or of a quality achievable by visual interpretation. Thus in the case of change classification, spatial aggregation methods are often needed (Walsworth and Leckie 2004). Several spatial aggregation techniques were applied and it was determined that it is useful to have these adaptable to different forest change types or landscapes. Sieving, followed by vectorization of units, and a spline smoothing were conducted. This procedure was effective for most forest clearing polygons, but for small units, especially those that were narrow or convoluted in shape, the resulting shape was sometimes corrupted (e.g., corners cut, boundaries too smooth, events split, or small sections eliminated). Thus, in the rural residential and mixed agriculture, urban, rural residential zones, good boundary delineation was not necessarily achieved and the process sometimes made the polygons worse. A better method or adaptive methods dependent on landscape and change type could be beneficial. An adaptive spatial aggregation concept was partially applied in this study. In the region where the overwhelming forest clearing type was regularly shaped medium to large clearcuts, an erosion and dilation morphological operation was applied to forest clearing polygons greater than 1 ha in size. This compensated for the general underestimation of the original polygon area and eliminated narrow protrusions related to new roads extending off clearcuts.

In terms of the final map product, the automated two-date classification was effective in identifying and outlining forest clearing polygons in the simple environment of the forestry-only zone. However, manual intervention was needed to eliminate wetland areas that were misclassified as forest clearing due to their spectral changes. Improved or specialized classification to account for this tendency may help, but a visual quality control step will still be necessary. The boundaries were well captured, with 98% acceptable, and with 91% having very good delineations. Wetlands adjacent to the new cuts were the main source of boundary discrepancy. In the end, within the forestry-only zone, the 9% of events that did not have very good delineations were modified manually and the automated polygons were used unmodified for the rest. In the remainder of the test site (mixed land use region), 42% of the automated polygons that represented clearcuts or partial cuts had their boundary captured acceptably. Only 26% of the automated polygons representing deforestation events had acceptable boundaries; these were mainly agriculture and sites with high spectral change, such as gravel pits and industrial areas. Automated classification of deforestation events was made difficult by their small size, often convoluted shape, and the fact that they were often mixed with adjacent open or partially forested sites. Therefore, the automated classification used in this study or similar approaches are not effective for precise mapping of deforestation in mixed and complex landscapes. It is likely not worth the effort to conduct classifications for deforestation mapping alone in such complex environments. However, if a classification is done for forest harvest in surrounding simpler landscapes or for other purposes, it would add useful information as triggers for candidate deforestation events and will provide some polygons for direct use or manual modification.

5.7 Summary of Accuracy

High accuracy is achievable in the final map product for forest harvest with the integration of the three information sources and quality control steps. Forest harvest, both clearcut and partial cut, for example, were mapped well. In the simple forestry-only zone there were no omissions or commissions and boundaries were outlined very effectively. The roads were also well captured and delineated. In the rest of the study area, which included mixed land use regions, harvest mapping accuracy as assessed from the results in the accuracy test area, was also very good. There were no commissions and for events of 1 ha or greater in size, there were only five omissions representing 6% of the harvest events. These errors were due to low-density hardwoods at T1 or low levels of partial cut that were not considered significant enough during the mapping. In total, the area of harvest mapped in the test area was within 1% of the area of the truth harvest events. The type of harvest--partial or clearcut--was also accurately attributed at 92%.

The accuracy of the deforestation component of the final product map was more complex. Accuracy was based on assessment within the accuracy test area. For truth events 1 ha and greater in size, 69% were captured acceptably and 16% omitted, whereas 80% of the deforestation candidates matched truth events acceptably and 6% were commissions. Both omissions and commissions were higher for the smaller events. Despite representing 16% by number of events, omissions only represented about 8% of the area of deforestation truth events. Omission rates for events between 0.5 and 1 ha were much higher at 42% of the truth events.

Even after careful quality control and field observations, confusion between agriculture (mostly pasture) and harvest remained an issue. Approximately one-half of the deforestation omissions and 64% of the deforestation commissions were not due to misinterpretation of forest clearing but rather to mislabelling them between forest harvest and deforestation. Commission errors were mostly partial cuts being identified as pasture or rural residential. Of the commissions that were not related to harvest events, the main source of error was misinterpreting as forest at T1 areas that were already cleared at T1, but had shrub and dense ground vegetation. The main cause of omission of deforestation events, other than confusion with harvest, was misinterpreting T1 cover, usually misidentifying low-density or young broadleaf forest as shrub or ground vegetation. Narrow sites at the edge of existing clearings were sometimes confused due to misregistration. Errors were also related to interpreter fatigue and lack of attention to detail in regions with a lot of activity and small events.

The interpretation of post-deforestation class was good, with 84% of sites matching perfectly and another 9% having an acceptable match. Confusion among agriculture, open field, and rural residential classes was the most common error. Thus, it is possible, even in a difficult setting, to categorize post-class reasonably well. However, confusion at the post-class modifier level was high for agriculture (crop vs. pasture) and rural residential (few trees remaining vs. many trees remaining).

Once identified as an event, delineation was generally good, with 81% of the events captured having very good or good delineations and only 4% having very poor outlines. Urban and rural residential were the least well delineated, with few very good delineations. Rural residential events were often difficult to delineate as they were commonly small, irregularly shaped, and mixed with other small vegetated open sites and partially treed areas, or they were patchy with varying amounts and widths of treed areas between them. As well, a judgement call was often needed about how to outline and define sites. For example, one can either delineate a larger area that includes patches of treed or partially treed areas, or try to delineate the areas between the patches. The first case might be considered as an event of "rural residential–many trees remaining", whereas the second would be smaller events of "rural residential–few trees remaining." There are defined rules concerning the interpretation of such cases (Paradine et al. 2003a), but situations can be complex and the interpreters may be inconsistent in their application of these rules.

Candidate events generally tended to be larger than the true event size, likely reflecting the resolution of the imagery used. For the captured truth events, the total area delineated for corresponding candidates over the whole accuracy test area was 8% higher. The events outlined with very poor boundaries were also all much larger than the truth event. Omissions were larger in total area than commissions but did not totally compensate for the over-delineations. Total mapped deforestation for the accuracy test area was 5% greater than the truth area.

6. Conclusion

When applied in an integrated mapping approach as in this study, each data source (automated classification, forest inventory, and manual interpretation) brings its own efficiency, value, and contribution to the final map product. Overall, the procedure used was effective at producing a good-quality map product over varied landscapes and forest disturbance activities, from simple commercial forestry activity to agriculture and various mixes of rural residential, urban–suburban–industrial, agriculture, and forestry. The mixed land use areas in this study are among the most difficult landscapes in Canada to map for deforestation. This pilot demonstrates that use of Landsat as the core information source is viable. However, for an event size limit of 0.5 ha or smaller, mapping is much more demanding and good mapping on an event basis is perhaps not possible. Nevertheless, many small events of 0.5–1.0 ha can be captured, and because of their small event size and contribution to total deforestation, estimation of total deforestation using a 0.5-ha limit may be possible.

Automated techniques are appropriate for harvest mapping in simple landscapes and forest operations. In mixed land use areas, automated techniques are less effective but useful for detecting cleared areas; however differentiation of harvest from deforestation such as agriculture pasture will be very difficult and likely not possible. The automated change procedure used in this pilot, and it is suspected other automated methods, will likely not be appropriate or worth the effort for identifying and delineating deforestation in mixed use areas involving rural residential, agriculture, forestry, and urban land uses. If conducted for other purposes, automated techniques do provide useful information, triggers, and some polygons to use or modify for deforestation. Use of dense Landsat time series of annual or better data will likely improve the effectiveness of automated techniques.

Forest inventories can provide information to help manual interpretation or can provide polygons for direct use in mapping. The usefulness of management forest inventories for supplying harvest polygons depends on how up to date they are compared to the time period being mapped (e.g., date of the T2 Landsat imagery). For deforestation mapping, most inventories will not provide enough detail to adequately determine event size or distinguish land type and land use within cleared areas. Nevertheless, forest inventory should be used when readily available as it can provide some harvest polygons, help confirm harvest versus deforestation, and sometimes assist in confirming the presence of forest at T1.

Local knowledge and data sources can be valuable but are often not easy to gather, understand, and apply. For deforestation mapping, it is very important to have ancillary data and to follow the various interpretation steps from intelligence gathering through interpretation, field checks, and vetting. High-resolution imagery improves results and efficiencies, and, fortunately, its availability is improving over time. A good interpretation environment with abundant screen real estate is also important, as are a collaborative team of interpreters that includes an experienced senior member, and mechanisms to reduce interpreter fatigue. The strategy to deliberately over-interpret deforestation in the initial interpretation stage was effective.

A comprehensive accuracy assessment procedure for change mapping was developed in this pilot. The procedure deals with diverse issues, such as timing of truth data versus the date interval of the mapping, omissions, commissions, too small or too narrow events, complicated overlap of multiple truth and candidate events, boundary delineation accuracy, and post-class attribution. Suggestions for improvements in mapping procedures and additional tools have been made. Applicability of methods for different environments and change types was determined. The methods were appropriate and effective, and an accurate product was produced. The lessons learned have been important to the development of forest change and deforestation mapping procedures.

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Appendix 1: Accuracy Assessment Definitions

Basic Definitions

Candidate Event – Areas interpreted and mapped as forest clearing polygons (e.g., clearcut, clearcut with residual, partial cut, or deforestation) or lines (e.g., road or corridor) during Landsat interpretation and mapping.

Truth Event – A true forest clearing event as detected, delineated, and attributed from the truth imagery or other truth sources.

Captured – It is evident that the forest clearing event was noticed and it was the forest clearing event that was being delineated. It is the boundary that is important. An error in pre- or post-type is not relevant in determining whether an event is captured.

Matched – It is evident that the candidate is associated with a forest clearing (i.e., the delineation is matched by a true forest clearing).

"Captured" and "Match" Categories

Captured: Boundary Acceptable (CBA) / Matched: Boundary Acceptable (MBA) – A truth event is considered Captured: Boundary Acceptable if the delineated boundary of the event essentially captures the correct boundary, accounting for the expected displacements, size biases, and boundary smoothing with Landsat interpretation. Boundary errors that miss or add units of less than 0.5 ha can occur; boundary deviations in the order of 50 m and, for smaller events, area differences of 15% and sometimes of 20% are considered acceptable. Both Truth Overlap and Forest Clearing Proportion are generally over 75%. A candidate event is considered Matched: Boundary Acceptable when the candidate matches the truth according to these specifications.

Captured: Boundary Poor (CBP) / Matched: Boundary Poor (MBP) – All other cases where there is an overlap of the truth event and candidate. Exceptions are where there is less than 25% overlap (i.e., < 25% of the true forest clearing event [truth event] is within the delineation, or < 25% of the delineation is true forest clearing), AND it is clear the candidate event outlined is not the truth event or related to the truth event. In such cases:

- the truth event is considered an omission and labelled Omission: Impure ("impure" means a candidate delineation intersects it)
- the candidate event is considered a commission and labelled Commission: Impure ("impure" means a true event intersects it).

Commissions and Omissions

Commission: Event Too Small (CS) – Candidate has forest clearing within it but the event is under the size limit that is considered a forest clearing (in this study 0.5 ha). The candidate itself is large enough.

Commission: Event To Narrow (CN) – Candidate has forest clearing within it but the clearing is under the width limit that is considered an event (in this study 20 m for linear events such as corridors; 30 m for other events). The candidate itself is large enough.

Commission: Impure (CI) – Candidate has some forest clearing within it but there is only a small overlap, and the event is essentially missed.

Commission: Pure (CP) – No forest clearing associated with delineation (false alarm).

Omission: Pure (OP) – No delineation associated with a forest clearing event (missing event)

Modifiers

There will be cases where there are multiple events or candidates associated with each other. In these cases a modifier is added to the above cases (labels) as follow.

Split – A forest clearing truth event is represented by several separate delineations (candidates). The overall match of associated delineations is assessed. For example, an event is labelled Captured: Boundary Acceptable–Split if the outside boundary of the multiple delineations is close to the actual event boundary and only small areas within the event are omitted. The group of candidates involved are also labelled with the modifier "Split" (e.g., Matched: Boundary Acceptable–Split).

Grouped – A candidate event that includes several forest clearing events. An example of a Matched: Boundary Acceptable–Grouped is several closely associated forest clearing events delineated as one candidate with the outside boundary good and only 30 m gaps between events. The group of truth events is labelled according to the above rules and will likely be Captured: Boundary Acceptable–Grouped.

Overall Delineation

Very Good (VG) – Delineation closely follows the true boundary; the shape is essentially the same with all convolutions mimicked. Both Truth Overlap and Forest Clearing Proportion are generally 90% or more.

Good (G) – Boundary closely follows the true boundary for at least one-half its length, with one or two deviations in shape (e.g., missing a protrusion); and there will generally be no more than 25% of the truth not being captured and (or) no more than 25% of the candidate not representing forest clearing.

Poor (P) – Events not meeting other categories. Missing or added sections represent more than 25% of the area or more than 1 ha for larger events.

Very Poor (VP) – The boundary attempts to capture the true event, but the shape is substantially dissimilar or there are several large additions or omissions. Truth Overlap or Forest Clearing Proportion are generally 50% or lower.

Correspondence

Correspondence – This refers to the correspondence of truth events and candidates (used for truth events > 1 ha.). Of those truth events captured (acceptable or poor) the correspondence between the truth event and candidates is given by the lower value of the Truth Overlap or Forest Clearing Proportion. This basically takes the area that corresponds to both the truth and candidate and divides it by the area of the larger of the two (i.e. the larger of either the candidate or truth polygon).

Comparison of Post-class and Post-class Modifier Attributes of Truth Versus Candidates

Matches – The interpreted class of a candidate event is the same as the "truth attribute."

Acceptable – In many cases, a class other than that of the truth event is almost as good. For example, in some areas pasture may be only occasionally used and is not treated/worked, so "open field" may be an acceptable call, whereas an open field in an urban setting labelled as pasture would be wrong. Another example of acceptable matches are classes that are transitional, with characteristics near the definitional boundary (e.g., the post-class modifiers for the rural residential class of few trees remaining versus many trees remaining).

Wrong – Attributes do not "match" and are not "acceptable."

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