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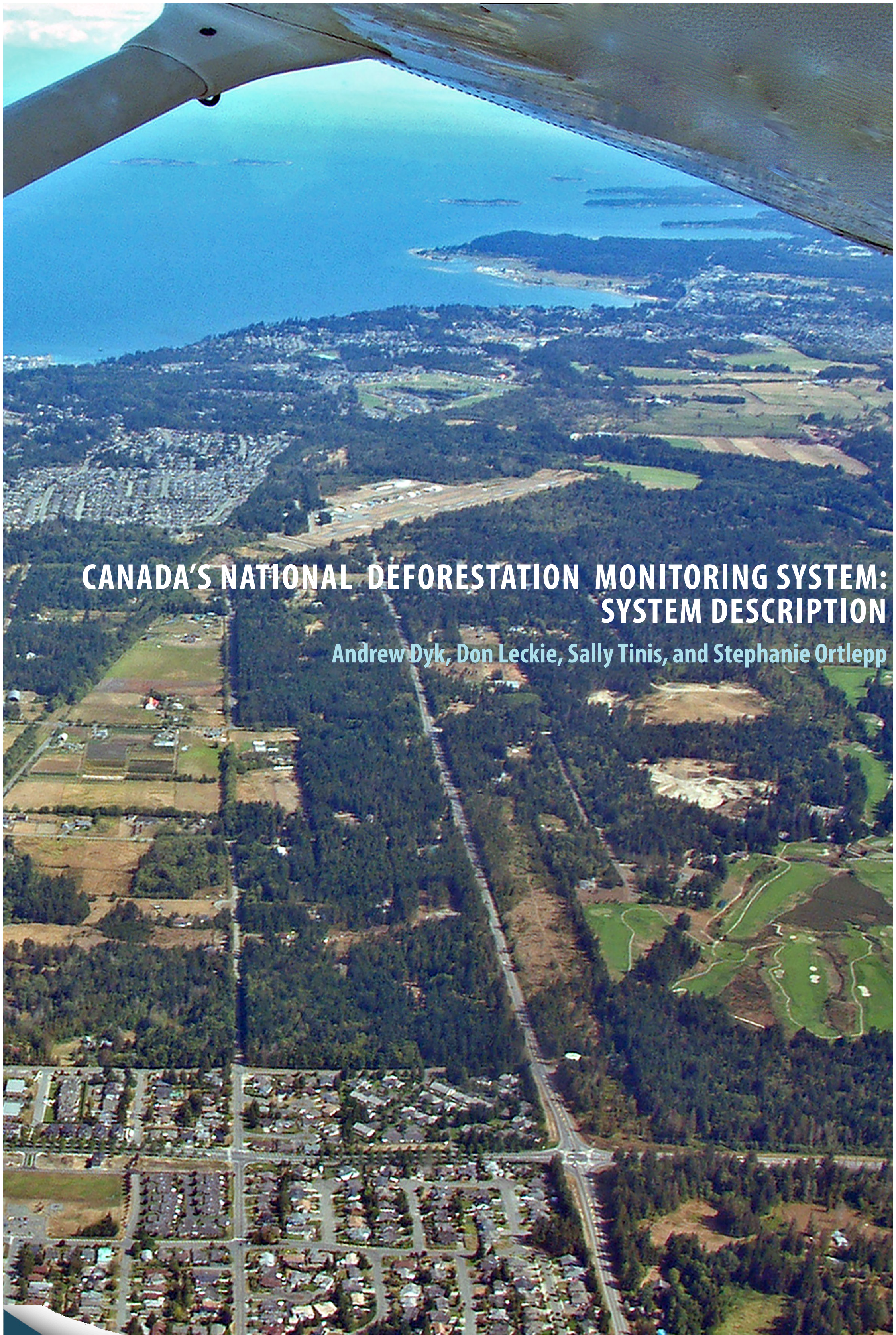
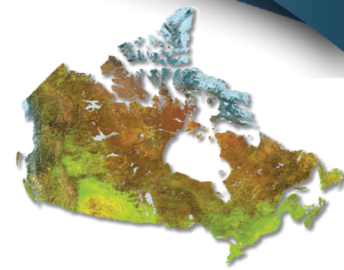


CANADA'S NATIONAL DEFORESTATION MONITORING SYSTEM: SYSTEM DESCRIPTION

Andrew Dyk, Don Leckie, Sally Tinis, and Stephanie Ortlepp



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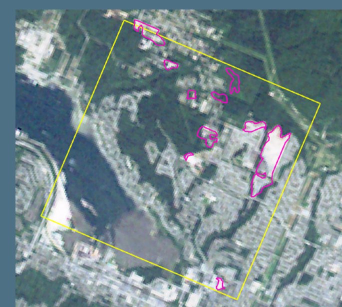

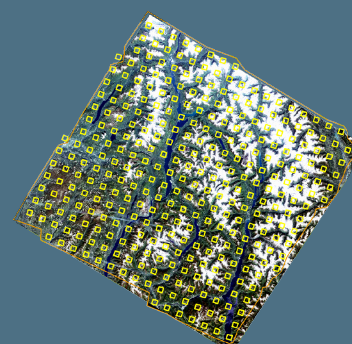

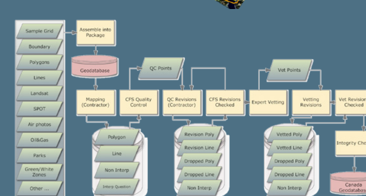

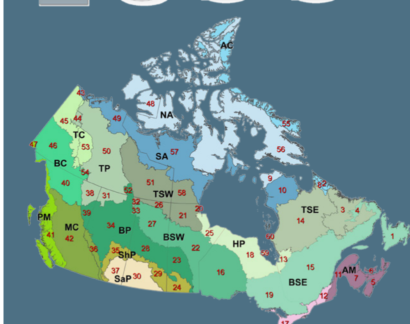

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Canada's National Deforestation Monitoring System: System Description

Andrew Dyk, Don Leckie, Sally Tinis, and Stephanie Ortlepp

Deforestation Monitoring Group

Digital Remote Sensing

Natural Resources Canada
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List of Acronyms

CBM-CFS3: Carbon Budget Model of the Canadian Forest Service version 3
GHG: greenhouse gas
GPG: Good Practice Guidance
IPCC: Intergovernmental Panel on Climate Change
NDMS: National Deforestation Monitoring System
RU: Reconciliation Unit
RZ: Reporting Zone
UNFCCC: United Nations Framework Convention on Climate Change

Abstract

Deforestation is the direct human-induced conversion of forested land to non-forested land use. Canada's National Deforestation Monitoring System (NDMS) was designed and implemented to provide information needed by Canada to meet its obligation under the United Nations Framework Convention on Climate Change (UNFCCC) to report the areas affected annually by deforestation. It also provides important information for the public, government policy makers, and scientists. To provide information about the amount of deforestation and why, where, and when it occurred in Canada, the NDMS uses deforestation mapped on a system of sample areas. The mapping is based on visual interpretation of satellite imagery supported by available ancillary information, such as high resolution imagery, forest inventory, and industrial databases, and informed by records-based information and expert knowledge. Accurate detection and mapping of deforestation events involves manual interpretation of satellite remote sensing imagery by specialized analysts. A key factor in the mapping is to distinguish deforestation from other forest cover losses that occur in Canada. This report describes the methods used to monitor and report on deforestation, including stratification and sampling, data sources, mapping and interpretation, estimation procedures, and quality control through all stages of the process. The NDMS was designed to make use of all available lines of evidence and be flexible to accommodate variable resourcing levels. This system has been producing national deforestation monitoring results annually since 2006. The flexibility of the NDMS's design makes it possible to adapt to future changes in data and resource availability, and positions the program well for sustained operational delivery into the future.

Keywords: deforestation, National Deforestation Monitoring System, NDMS, mapping and interpretation, land use change, data sources, quality control

Résumé

Le déboisement est la conversion anthropique directe de terres forestières en terres non forestières. Le Système national de surveillance du déboisement (SNSD) du Canada a été conçu et mis en œuvre afin de fournir l'information dont le Canada a besoin pour s'acquitter de son obligation, aux termes de la Convention-cadre des Nations Unies sur les changements climatiques (CCNUCC), de produire annuellement un rapport sur les régions touchées par le déboisement. Il fournit également d'importants renseignements au public, aux responsables des politiques gouvernementales et aux scientifiques. Afin d'offrir de l'information sur l'ampleur du déboisement, ainsi que pour expliquer pourquoi, où et quand il a eu lieu au Canada, le SNSD effectue une cartographie du déboisement en fonction d'un réseau de zones d'échantillonnage. La cartographie repose sur une interprétation visuelle de l'imagerie satellite, appuyée par les données accessoires disponibles — notamment l'imagerie à haute résolution, l'inventaire forestier et les bases de données fournies par l'industrie — et éclairée par l'information provenant de dossiers existants et des connaissances des experts. L'interprétation manuelle des images de télédétection par satellite, par des analystes spécialisés, est essentielle pour assurer l'exactitude de la détection et de la cartographie des activités de déboisement. Pour la cartographie, l'un des facteurs clés consiste à faire la distinction entre le déboisement et toute autre perte de couvert forestier qui se produit au Canada. Dans le présent rapport, nous décrivons les méthodes utilisées pour surveiller le déboisement et en faire un compte rendu, y compris la stratification et l'échantillonnage, les sources de données, la cartographie et l'interprétation, les procédures d'estimation et le contrôle de la qualité à toutes les étapes du processus. Le SNSD a été conçu pour tirer parti de toutes les sources de données à sa disposition et pour être suffisamment souple pour faire usage de ressources dont les niveaux sont variables. Ce système a permis de produire les résultats nationaux de la surveillance du déboisement tous les ans depuis 2006. La souplesse de la conception du SNSD permet de s'adapter aux futurs changements dans la disponibilité des données et des ressources, et place le programme dans une bonne position pour assurer une prestation opérationnelle soutenue dans les années à venir.

Mots-clés: déboisement, Système national de surveillance du déboisement, SNSD, cartographie et interprétation, changement d'affectation des terres, sources de données, contrôle de la qualité

1. Introduction

Forest cover in Canada is estimated to be 3.5 million km^2. Canada's forests have long been managed to provide goods and services valued by society. This management has included the temporary clearing for forest products and sometimes the permanent clearing of land for cultivation, settlement, or other uses. Deforestation is defined as "the direct human-induced conversion of forested land to non-forested land" (United Nations Framework Convention on Climate Change 2002).

Knowing the amount of deforestation and where, when, and why it occurs is important for several reasons. Forests around the world are coming under increasing pressure as human populations grow and the footprint of human civilization expands. This pressure is relatively modest in Canada but nevertheless must be taken into consideration.

The need to rigorously monitor and report on deforestation in Canada increased when Canada became party to the United Nations Framework Convention on Climate Change (UNFCCC). Deforestation releases carbon stored in forest vegetation as CO_2 and other greenhouse gases (GHG) and is a globally significant source of greenhouse gas emissions, especially in the tropics (Pan et al. 2011; Le Quéré et al. 2014). The UNFCCC obliges countries to report their emissions on an annual basis. The Montreal Process, an international agreement on criteria and indicators for conservation and sustainability of forests, also highlights the maintenance of forest area as an important criterion of sustainable forest management (Montreal Process 2009).

The Canadian Forest Service is the national and international voice for the Canadian forest sector. The organization provides science and policy expertise and advice on national forest sector issues, working in close collaboration with the provinces and territories. As a part of this role, the Canadian Forest Service develops information and knowledge of Canada's forest resources. Thus, in 2000, work began on the design of a National Deforestation Monitoring System (NDMS) with pilot projects starting in 2002. At the same time, a new plot-based National Forest Inventory (Gillis et al. 2005) was being implemented. It uses a systematic grid of sample cells, and an approach similar to this was desirable for the NDMS. The first national deforestation monitoring results were produced in 2005 and the NDMS has been producing updated results on an annual basis ever since. These results are published annually in Canada's national greenhouse gas inventory reports to the UNFCCC (Environment Canada 2006; 2014), are summarized in Canada's State of the Forest Reports, and have also contributed to reports published in the scientific literature (e.g., Masek et al. 2011; Kurz et al. 2013).

Although the NDMS is used to conduct Canada's estimation process and maintain the national deforestation database, other national and provincial-level initiatives have an interest in deforestation estimates (e.g., the National Forest Inventory, the Canadian Forest Service Carbon Accounting Team, Agriculture and Agri-Food Canada, and Environment Canada). The NDMS has close links with these programs.

This report provides an overview and description of the NDMS. The system is described as it has been implemented for calculations of deforestation up to the annual report of 2015. The report also includes the original system requirements, the overall system design, and details of the system implementation.

2. System Requirements and Definitions

The NDMS exists to serve information needs beyond national greenhouse gas inventory reporting, but the strict reporting requirements of the UNFCCC guided the system's design and implementation. The UNFCCC requirements are set by good practice guidance (GPG) provided by the Intergovernmental Panel on Climate Change (IPCC) (Intergovernmental Panel on Climate Change 2003), which helps countries meet forest monitoring and reporting challenges presented by the UNFCCC.

2.1 Definitions

Several basic terms were given precise definitions following the general guidelines provided by the UNFCCC, including "forest," "deforestation," and "land use categories."

2.1.1 Forest

Forest is defined for the purposes of national monitoring in Canada as a minimum area of land of 1 ha with tree crown cover of more than 25%, and with trees having the potential to reach a minimum height of 5 m at maturity in situ. Young natural stands and all plantations that have yet to reach a crown density of 25% or tree height of 5 m are included, as are areas that normally form part of the forest area which are temporarily un-stocked as a result of human intervention such as harvesting or natural causes but that are expected to revert to forest (United Nations Framework Convention on Climate Change 2002; Environment Canada 2006).

The above definition was adopted by Canada for UNFCCC reporting purposes in 2003, working within the parameters agreed to in the Marrakesh Accords (UNFCCC Decision 11/CP.7). This definition is different from that used by the Food and Agriculture Organization of the United Nations: "Land spanning more than 0.5 hectares with trees higher than 5 meters and a canopy cover of more than 10 per cent or trees able to reach these thresholds in situ. It does not include land that is predominantly under agricultural or urban land use" (Food and Agriculture Organization 2001). The density parameter is the most important difference, and Canada reports areas with 10–25% tree cover as "other wooded land." The difference is most relevant in Canada's northern forest.

2.1.2 Deforestation

Deforestation is defined by the UNFCCC as "the direct human-induced conversion of forested land to non-forested land" (United Nations Framework Convention on Climate Change 2002). The term "deforestation" is sometimes used elsewhere to refer more broadly to forest cover loss, whether temporary or permanent, human-induced or natural. The NDMS tracks direct human-induced forest land use change. It provides clarity that is useful for policy analysis (e.g., Lemprière et al. 2013) by identifying permanent conversion of forest land, and distinguishing it from temporary forest cover loss related to forest management or natural forest cover dynamics such as wildfire or insect damage (Kurz 2010). Thus temporary change in land cover, such as tree harvesting, is not classified as deforestation. Non-anthropogenic land cover changes such as naturally occurring landslides are also not considered deforestation as these events are not caused by humans; they are relatively rare in any case.

Detailed specifications regarding shape, size, and configuration of forest and deforestation events used for deforestation mapping are found in the Deforestation Interpretation Guide (Leckie et al. 2012). For linear deforestation events (e.g., roads and right-of-ways), a minimum cleared width of 20 m is used. Therefore, narrow linear disturbances are not reported by the NDMS. Also, loss of areas having sparse tree cover is not reported because of the defined requirement of 25% tree crown cover.

2.1.3 Land Use Categories

The UNFCCC employs six land use categories defined under the IPCC's good practice guidance (Intergovernmental Panel on Climate Change 2003) to help report on and understand the dynamics of land use, land use change, and carbon emissions:

1. forest land
2. cropland
3. grassland
4. wetlands
5. settlements
6. other land

Although more detailed information on land transitions is needed for other applications, the NDMS must at a minimum be able to provide information on land use transitions from forest to the other five categories.

3. System Design

The NDMS uses a sampling approach with mapping and detection from satellite imagery, informed by records-based information and expert knowledge, to provide information about the amount of deforestation and why, where, and when it occurred in Canada. Land use changes are interpreted manually by expert interpreters who use all available evidence to support their interpretation. This design was adopted to provide the most detailed possible estimates of deforestation rates through time, given available resources.

A full-area annual detection and mapping of all deforestation events in Canada is neither practical nor necessary. It is not practical because the task of finding on the order of 500 km^2 of deforestation every year in a country with 3.5 million km^2 of forest and up to 10 000 km^2 of harvest per year would be prohibitively expensive, and manual interpretation is needed to reliably distinguish deforestation events from non-permanent forest cover change such as harvest. Spatial and temporal sampling strategies can be used to provide the necessary information. Practical implementation considerations associated with sampling were recognized early and factored into the NDMS.

In addition to the amount of deforestation, the NDMS was designed to provide three types of information:

1. where deforestation occurred (spatial location, shape, and topology);
2. when deforestation occurred (the year or years during which forest clearing occurred); and
3. why deforestation occurred (the classes of post-deforestation land use)

It also provides information on the type of forest being removed. The NDMS maintains a high level of detail in order to make its data as widely useful as possible.

3.1 Where Deforestation Has Occurred

The NDMS was designed to produce national and sub-national outputs. Sub-national reporting units were created in collaboration with scientists involved in the design and implementation of Canada's National Forest Carbon Monitoring Accounting and Reporting System (Kurz and Apps 2006), the Canadian Agricultural Greenhouse Gas Monitoring Accounting and Reporting System team of Agriculture and Agri-Food Canada, and Canada's national greenhouse gas inventory reporting system (Environment Canada 2006). This allows NDMS outputs to be integrated seamlessly by all of these systems.

Deforestation mapping is done within sample cells. The mapping data from all sample cells are compiled in an ArcGIS database and then input into an estimation process that produces data at the scale of reconciliation units and reporting zones (see Figure 1). The reconciliation units are common areas that are used by the teams listed above to summarize information. Environment Canada reports greenhouse gas emissions and removals in reporting zones. The reporting zone boundaries follow the boundaries of the Terrestrial Ecozones of Canada (Ecological Stratification Working Group 1996) with some additional stratification to distinguish eastern and western portions of the largest ecozones (Taiga Shield and Boreal Shield) and to distinguish two different portions of the Prairies ecozone (Subhumid Prairies and Semiarid Prairies) (McGovern 2008). The reconciliation unit boundaries follow the geographic intersection of the reporting zone boundaries with provincial and territorial borders. National estimates are calculated by summing reporting zone deforestation estimates.

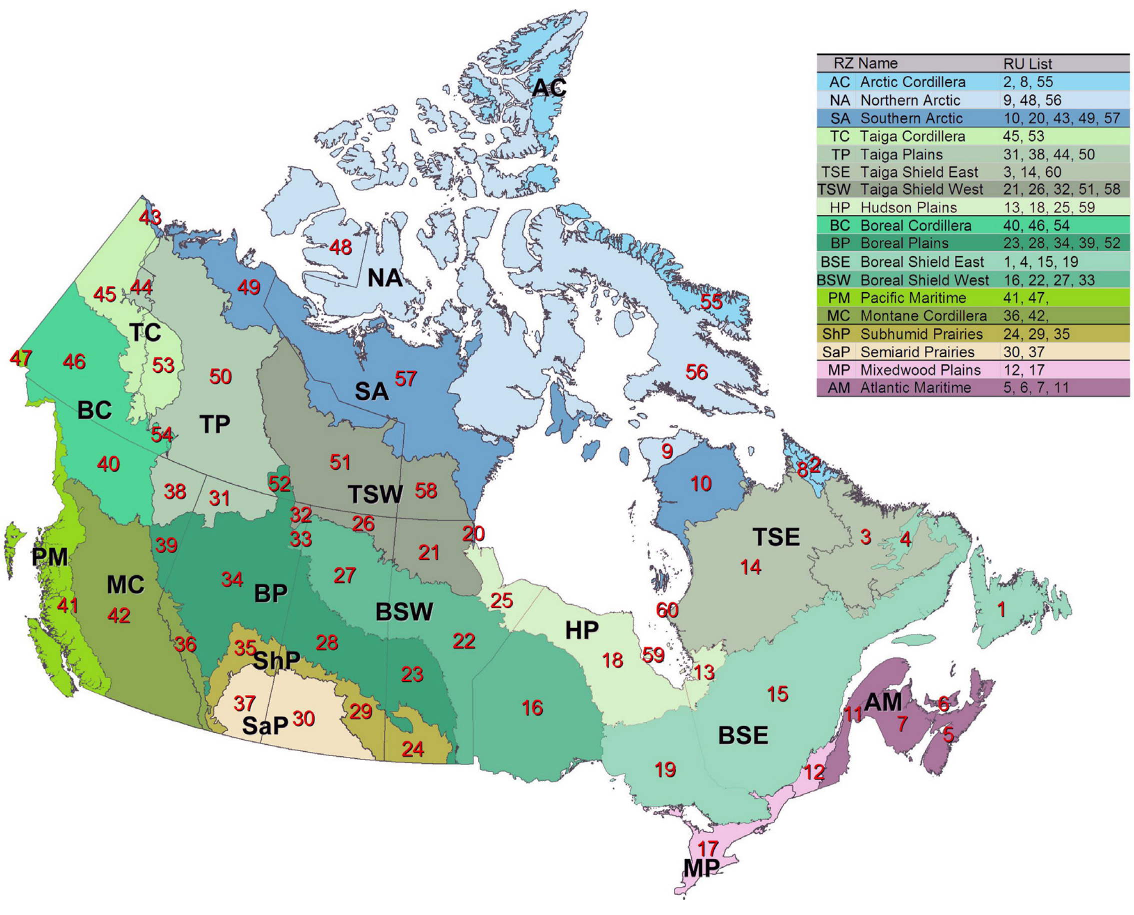

Figure 1. Deforestation reconciliation units and reporting zones in Canada. For international reporting purposes, Environment Canada compiles NDMS results for each reconciliation unit (RU; identified by number) and summarizes them for each reporting zone (RZ; identified by colour).

3.2 When Deforestation Has Occurred

The NDMS provides information about when deforestation occurred by establishing deforestation mapping periods. Image data for deforestation mapping are obtained as close to the time period bounding dates as possible. The dates of these images are considered "core dates." Deforestation events are detected and mapped by interpreting changes between these core date images. The mapped events are then used to compute deforestation rates for the period. These rates are interpolated and in some cases extrapolated to produce estimates of annual deforestation trends. When the timing of large deforestation events is known, these are processed separately and added to the trend results after interpolation.

The NDMS provides estimates of deforestation rates from 1970 onwards, in part to accommodate the needs of Canada's UNFCCC reporting. Although international UNFCCC reporting addresses greenhouse gas emissions and removals since 1990, deforestation events that occurred before 1990 contribute to emissions in 1990 and after. Deforestation causes both immediate and delayed residual greenhouse gas emissions. Immediate emissions are those that occur when forest cover is cleared, such as the burning of discarded biomass, and are accounted for in that year. Residual emissions, which can continue for up to 20 years after the deforestation event, are the result of long-term decay of discarded biomass and dead organic matter (Intergovernmental Panel on Climate Change 2003), and are estimated and incorporated in each year's emissions for 20 years as forest land converted to the post-conversion category.

3.3 Why Deforestation Has Occurred

The NDMS provides information about why deforestation occurred by recording the new land uses that are found where deforestation has been detected and mapped. For each mapped deforestation event, interpreters record both the type of forest that was present before the change (pretype) and the new land use that followed (post class). The pretype is described in terms of forest age class, density class, and cover type (see Appendix 1). It provides insight into the type of forest being converted and is input into the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3; Kurz et al. 2009) for calculating emissions. The post class, which identifies the new land use, is recorded using the categories shown in Table 1.

Table 1. Deforestation post-land use classes. During interpretation, deforestation events are attributed according to their post-deforestation land use type classes and subclasses (post classes and modifiers).

Post class	Post-class modifiers
Agriculture (AG)	Crop; pasture; farm yard
Artificial Lake (AL)	Agriculture pond; golf course related water body; recreational water body; pond in rural residential setting; pond/small lake in developed urban setting; agriculture effluent pond; industrial effluent pond/holding pond; mining tailing/waste pond; oil and gas related water body; hydroelectric flooding/reservoir (cleared forest); hydroelectric flooding/reservoir (standing forest)
Corridor (CR)	Hydro line (main/secondary/tertiary/other minor); pipeline (main/secondary/tertiary/other minor); cut line; railway; airstrip; undifferentiated corridor
Open Field (OF)	Agricultural setting; industrial setting; recreational setting; mine setting; mine facility setting; oil and gas facility setting; pit and quarry setting; oil sands setting; rural residential setting; urban/suburban setting; undifferentiated field
Industrial (IN)	Heavy industrial; light industrial; oil sands infrastructure; oil and gas infrastructure; mine heavy; mine light; well pad; hydro infrastructure
Recreational (RC)	Campground; golf course; ski areas; playing field; undifferentiated recreational
Road (RD)	General road (main/secondary/tertiary); forestry road (main/secondary/tertiary); oil and gas road (main/secondary/tertiary); mine related road (main/secondary/tertiary); hydroelectric related road (main/secondary/tertiary)
Soil Disturbance (SD)	Open pit mine; logging landing; landfill; oil sands extraction; peat extraction; gravel pit/quarry; rock slide scar (human induced); undifferentiated soil disturbance
Rural Residential (RR)	Many trees remaining (residual tree cover 25–75%); few trees remaining (residual tree cover < 25%)
Urban Residential (UR)	Many trees remaining (residual tree cover 25–75%); few trees remaining (residual tree cover < 25%)

These deforestation post classes can be aggregated in different ways according to user need. Table 2 provides an example of post class grouping into industrial categories and good practice guidance land use categories. For example, within the deforestation post class "corridor" (CR), the modifier code further distinguishes events such as hydroelectric lines (CRhm) from pipelines (CRpp), so that the former can be aggregated into the "hydro infrastructure" industrial category and the latter aggregated into the "oil and gas" industrial category. Both of these examples are classified as settlements (SL) under the good practice guidance land use categorization scheme. Appendix 2 provides a detailed listing of all post classes and modifier codes, and how they translate to good practice guidance land use categories.

Table 2. Deforestation post class aggregation. Post classes are cross-referenced to industrial and good practice guidance classes (Intergovernmental Panel on Climate Change 2006) by means of post-class modifiers. "X" indicates the presence of modifiers available within each post class.

Good practice guidance class →		Crop-land (CL)	Wetlands (WL)			Settlements (SL)							
Industrial categories →		**Agriculture**	**Flooded standing forest**	**Hydro reservoir**	**Peat mining**	**Forestry**	**Hydro infrastructure**	**Industry**	**Mining**	**Municipal**	**Oil and gas**	**Recreation**	**Transportation**
Deforestation post class													
Agriculture	AG	X											
Artificial Lake	AL	X	X	X				X	X	X	X	X	
Corridor	CR						X			X	X		X
Industrial	IN						X	X	X		X		
Open Field	OF	X						X	X	X	X	X	
Recreational	RC											X	
Road	RD					X							X
Rural Residential	RR									X			
Soil Disturbance	SD				X	X			X	X	X		
Urban Residential	UR									X			

The pretype and post class attributes are used for a range of applications, including the calculation of greenhouse gas emissions in the CBM-CFS3 (Kurz et al. 2009). Because of different type and carbon density of the forest being removed, and different treatment and fate of woody debris and soil carbon for deforestation to different land uses, some land use transitions result in differing amounts and rates of greenhouse gas emissions than others, even when removing similar forest. Therefore, it is important to have the pretype and post class information available for input into emissions estimation and analysis tools.

4. Implementation

Deforestation monitoring begins with visual interpretation of satellite imagery. Data are collected from relevant sources to support the work of expert interpreters, who use all available lines of evidence to map and attribute deforestation events. Mapped deforestation events in sample cells within a stratified sampling approach are compiled in a GIS database and used to estimate deforestation rates by scaling from sample to national estimates.

A systematic sequence of operational steps is followed, whereby mapping work is broken up into work or project packages for completion by in-house Canadian Forest Service technical staff, provincial partners, or contractors, and then passed through a series of quality control checks before being included in the compilation and estimation procedures (see Section 5.1 for more details).

4.1 Stratification and Sampling

Deforestation mapping is guided by the stratification of the Canadian landscape into units of land having similar patterns and rates of deforestation (Figure 2). This stratification is done so that sampling effort can be directed where it is most needed. Sampling rates are set for each stratum according to intelligence about deforestation activity.

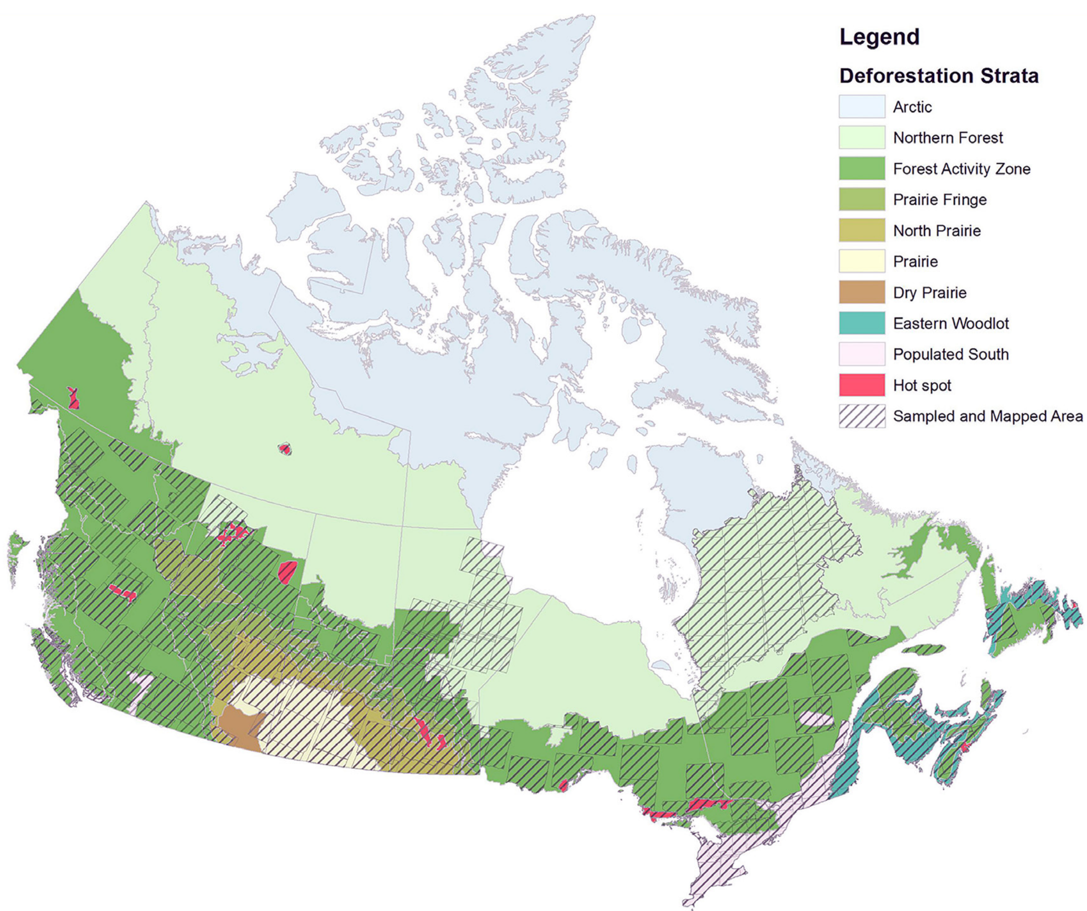

Figure 2. Deforestation strata units and sampling framework. Canada is stratified into types of land that have distinct patterns and rates of deforestation. Deforestation mapping has been completed in the areas indicated by shading.

The deforestation strata were created incorporating information from ecozone locations, forest tenure boundaries, known and interpreted land use and landscape patterns, and provincial and territorial boundaries. The strata are further refined into "deforestation strata units," which are generally the deforestation strata within a single reconciliation unit but sometimes within several adjacent reconciliation units. Appendix 3 lists the deforestation strata units and gives their size and spatial relationship with reconciliation units. More detailed discussion of the stratification process is provided by Leckie et al. (2006a and 2006b). Hotspots are areas (strata units) of localized high deforestation activity, such as rapidly expanding urban areas. Hotspots are delineated to exclude high-activity areas from the larger deforestation strata. The deforestation rates in hotspots can be far greater than the levels observed in the larger strata, and these areas should therefore be treated separately.

The sampling density within each stratum varies depending on a number of factors, including the level of deforestation activity and resource constraints. A sampling rate of approximately 12% is obtained by establishing 3.5 × 3.5 km sample units (termed "cells") at the intersections of a regular 10 × 10 km grid. This grid is aligned with the National Forest Inventory's 20 × 20 km grid. A sampling rate of 6% is obtained by excluding every second cell, as shown on the left side of red line in Figure 3. Higher sampling densities are used in strata where more precise estimates are needed. When resources permit, full-area mapping is conducted in some strata, such as hotspots. Leckie et al. (in review) provide details on sample design considerations.

The actual mapping is done on a scene basis, and therefore gaps between scenes exist in some strata, which reduces the sampling rate somewhat from the target rate. These gaps are more common in some early mapping due to the fact that Landsat scenes were not free at that time. In addition, to focus efforts on regions of high deforestation, a subset of some low-deforestation strata (e.g., forest activity strata of Quebec and Ontario (Figure 2)) was identified based on a systematic pattern of Landsat scene coverages, and deforestation was then mapped in sample cells within the sub-area (e.g., for a 6% sample).

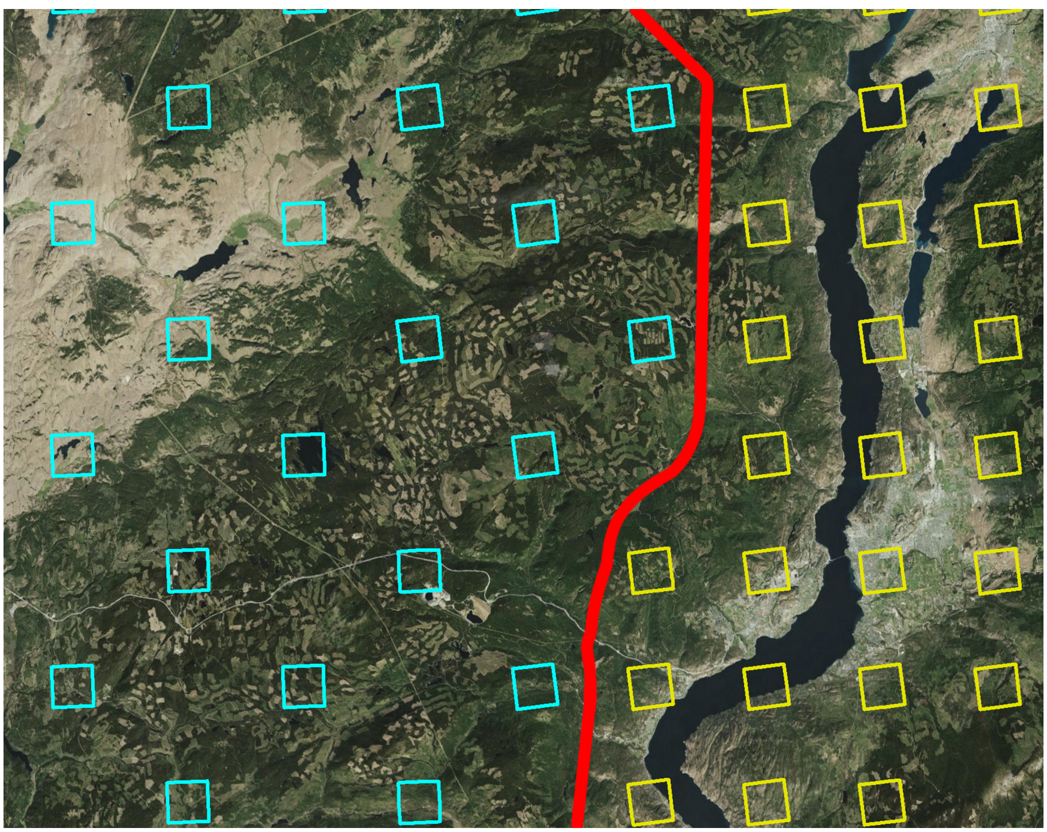

Figure 3. Sampling intensity in two different deforestation strata. The sample cells in a stratum are collectively referred to as a sample "grid." This example illustrates 6% sampling in the left stratum (blue grid) and 12% sampling in the right stratum (yellow grid).

The sampling rate for a stratum is the proportion of the total area examined divided by the total area of the stratum. Total area examined is the area of the sample cells reduced by any area within them deemed non-interpretable owing to cloud, shadow, or lack of imagery, which is generally less than 2% of the total area mapped.

The sample coverage has been improving, with more coverage in recent mapping periods in most deforestation strata (see Figures 4–6). The sample area is larger for mapping period P2 (1990–2000) and P3 (2000–2008) than for mapping period P1 (1975–1990). The P2 period has several large areas with full-area mapping. The sample coverage for periods P1, P2, and P3 has likely stabilized at that shown in Figures 4, 5, and 6, respectively. This coverage was built up over time; early national reporting of deforestation was derived from smaller sample coverages, and indeed the P3 sample estimate was not introduced to the national deforestation report until 2010.

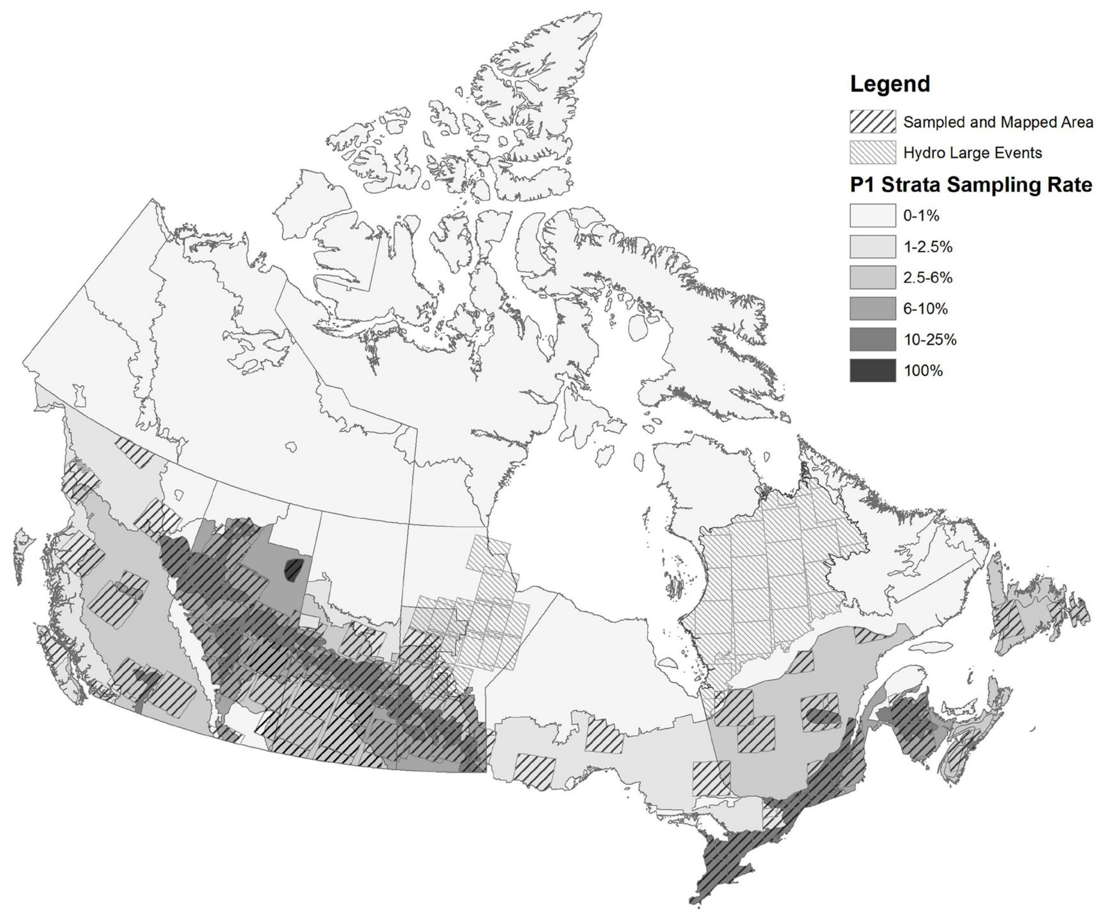

Figure 4. Deforestation strata sampling rates for mapping period P1 (1975–1990).

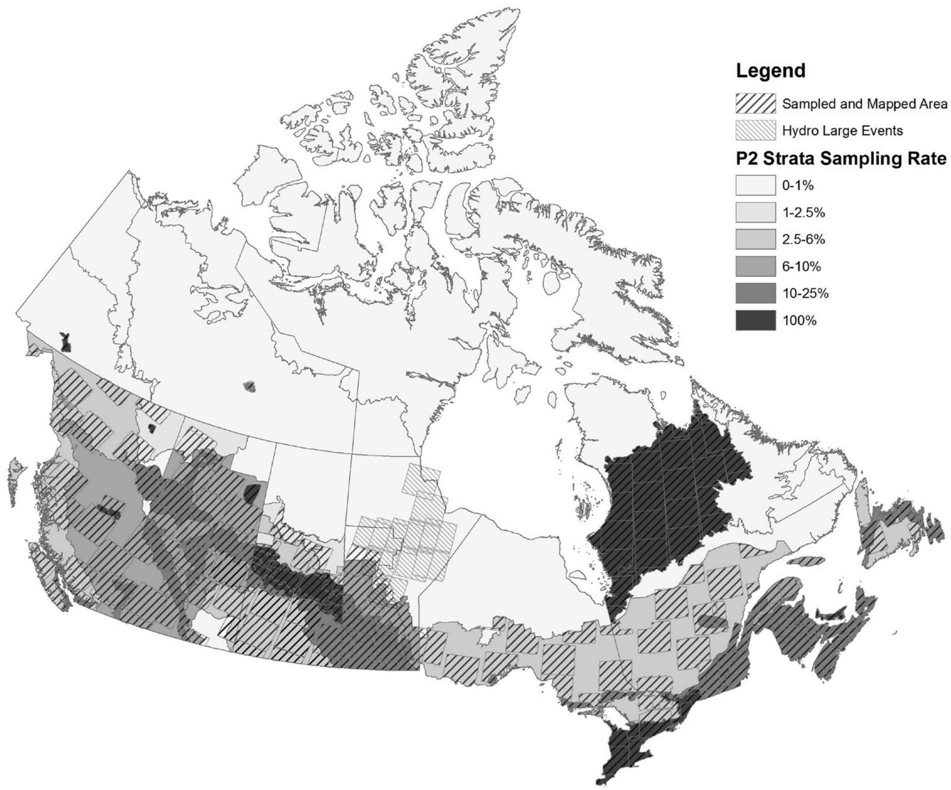

Figure 5. Deforestation strata sampling rates for mapping period P2 (1990–2000).

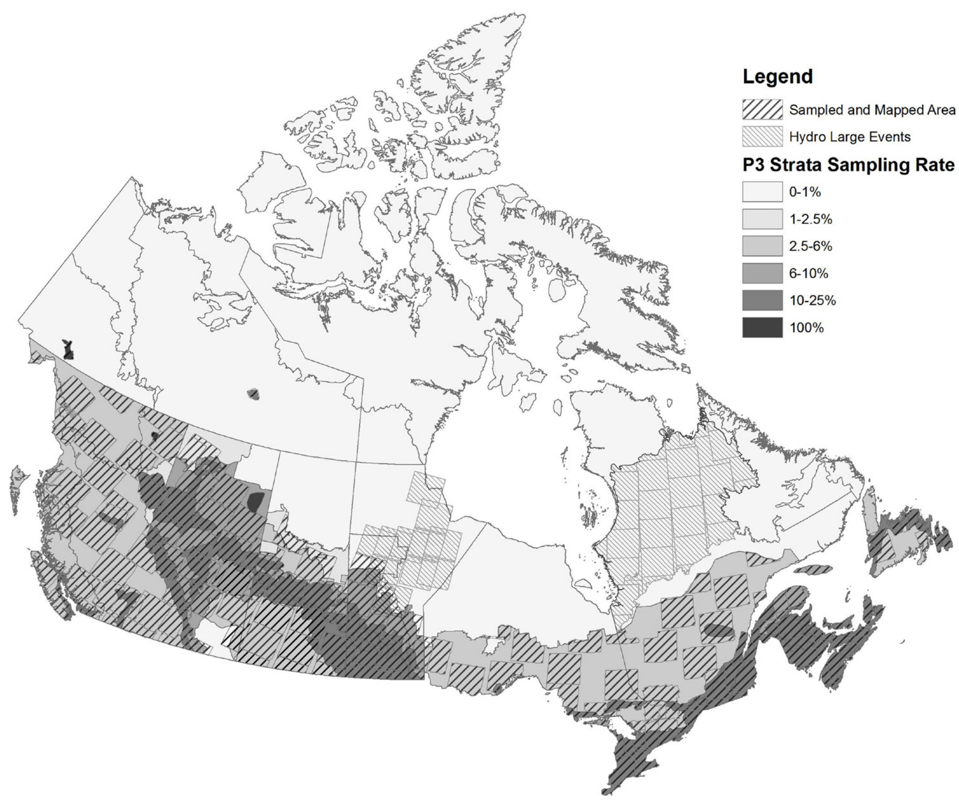

Figure 6. Deforestation strata sampling rates for mapping period P3 (2000–2008).

The total area of Canada covered by the sampled regions (i.e., the shaded area in Figure 2), in one or more time periods, is 3.46 × 106 km^2. This includes full-area mapping for 5.6 × 105 km^2 of hydro survey areas in northern Quebec and another 2.5 × 105 km^2 in northern Manitoba, in which only hydroelectric development deforestation was mapped. Excluding hydro survey areas, the area of the sample cells interpreted was 1.65 × 105 km^2 in P1, 4.09 × 105 km^2 in P2, and 2.18 × 105 km^2 in P3. The large sample area for P2 reflects the greater amount of full-area mapping.

4.2 Data Sources and Information Collection

Remote sensing imagery is the most critical input to the process of deforestation monitoring. In the NDMS, image data are used to identify the location, size, and timing of events. These data are also used to determine pre-existing forest types and subsequent post classes. The NDMS employs medium-resolution satellite imagery in combination with high-resolution satellite and air photo data wherever available. Ancillary sources, in the form of spatial data and non-spatial records, are used to support the mapping process and act as supplementary sources for estimation and quality control.

4.2.1 Core Image Data

Landsat is the primary data source for deforestation mapping. Landsat series satellites have been acquiring data since the early 1970s and provide a consistent data stream for all NDMS mapping periods with a spatial and spectral detail suitable for deforestation mapping. The current Landsat instruments are medium-resolution sensors with 30 × 30 m pixels and a large image footprint (170 × 185 km). Each satellite has a return period of 16 days, with continual image acquisition and scene sidelap that increases at higher latitudes.

Landsat imagery, formerly available for purchase, was made freely available by the United States Geological Survey, starting in January 2009 (Wulder et al. 2012). For mapping done before 2009, data had to be purchased and thus image acquisition focussed on the basic summer data for core dates (circa 1975, 1990, 2000, and 2008) and winter imagery in more difficult-to-interpret regions. For mapping done after 2009, more imagery was used and additional dates were added to help identify with more precision when deforestation events occurred and also help increase mapping confidence. This new imagery was also used to review any previous mapping.

4.2.2 Additional Image Data

Delineating deforestation boundaries can benefit from use of high-resolution imagery. Higher-resolution data are also very useful in supporting the interpretation of pre-existing conditions and forest types, and in confirming deforestation and better identifying the post class and post-class modifier. High-resolution imagery is therefore used to supplement core Landsat data wherever possible.

Data are continuously being sought out by NDMS staff; for example, a 2.5 m resolution SPOT 5 panchromatic mosaic of the Prairies (circa 2006) was provided by Agriculture and Agri-Foods Canada, and a 10 m SPOT 4/5 national coverage called GeoBase[1] was obtained from the Centre for Topographic Information of Natural Resources Canada. The SPOT 4/5 satellites offer a higher spatial resolution but provide fewer spectral bands than Landsat. Various aerial photo data sets have been assembled through partnerships with provincial governments and other agencies, including National Air Photo Library imagery, provincial aerial photography, and high-resolution satellite image data sets.

Google Earth™ and Bing Maps™ are a valuable resource with an ever-expanding selection of recent high-resolution imagery over population centres and many other regions of the country. In some cases, archives of older imagery (e.g., circa 2002) are also available and can be accessed through the Time Slider tool available in Google Earth. Even current high-resolution imagery can help with the identification of events that occurred in an earlier time period.

4.2.3 Ancillary Spatial Data

Ancillary data are also incorporated to support the interpretation process. These data may be used to validate or confirm deforestation occurrence or to support the interpretation of prior forest type or post-change land use. Some data types are available nationally, whereas others are present only within limited extents. Such data include GIS data sets of road networks, hydrology, wetlands, wooded areas from provincial base maps, pit and quarry licence areas, forest inventories, forest management tenure areas, specialized oil and gas pipeline and well pad databases, field oblique photos, and other data.

In addition to the satellite and aerial photo data described above, Google Earth™ offers further ancillary spatial data in the form of terrain display, crowd-sourced Panoramio™ photographs, ground-based StreetView™ photography, and other useful layers.

[1] See: http://www.geobase.ca/geobase/en/data/imagery/imr/index.html

4.2.4 Records Data

Spatial and non-spatial records and activity data may also be incorporated into the estimation or quality control processes. In early deforestation reports, records and activity data were sometimes used to provide estimates of deforestation associated with a particular sector and area. As more mapping was completed, estimates from records were replaced by mapping-based information. Records data used in the past have included hydroelectric clearing areas, forestry road records and standard road class widths, and oil and gas pipeline records.

4.3 Mapping

Deforestation event mapping is done using core date imagery and multi-band image products. Mapping is broken up into units of mapping work, called "project packages," to be completed by internal staff, provincial partners, or qualified private sector contractors. All relevant images and supporting data are assembled as a package for mapping in a particular area. Detection, interpretation, digitization, and attribution of individual deforestation events is done manually by trained interpreters according to the established NDMS methods in a standardized ArcGIS geodatabase (Leckie et al. 2012).

4.3.1 Data Handling

Interpretation of deforestation events requires the detection of change between pairs of images acquired at two "core dates" chosen to best represent the mapping time period start and end year (i.e., 1975, 1990, 2000, and 2008). Forest cover changes, or potential events, are highlighted using a multi-temporal display or "change enhancement" image created using the visible red band from two core dates of imagery. When the mapping period end date image is displayed using the red image colour gun and the mapping period start image is displayed using green and blue, the resulting image shows areas of vegetation loss as red. In addition, possible deforestation events can be detected by comparing the two core images directly. Many changes besides deforestation can cause a difference between the images (e.g., forest harvest, forest fires, beaver dam flooding, wind blowdown, agricultural field changes, and avalanches), so it is critical that a change event be confirmed as deforestation before it is mapped.

Individual deforestation events are manually interpreted and identified, delineated, and attributed. Figures 7 and 8 illustrate some of the data that are used in this process: Landsat multiple band combinations at both core dates, change enhancement, higher-resolution imagery, and field oblique aerial photographs.

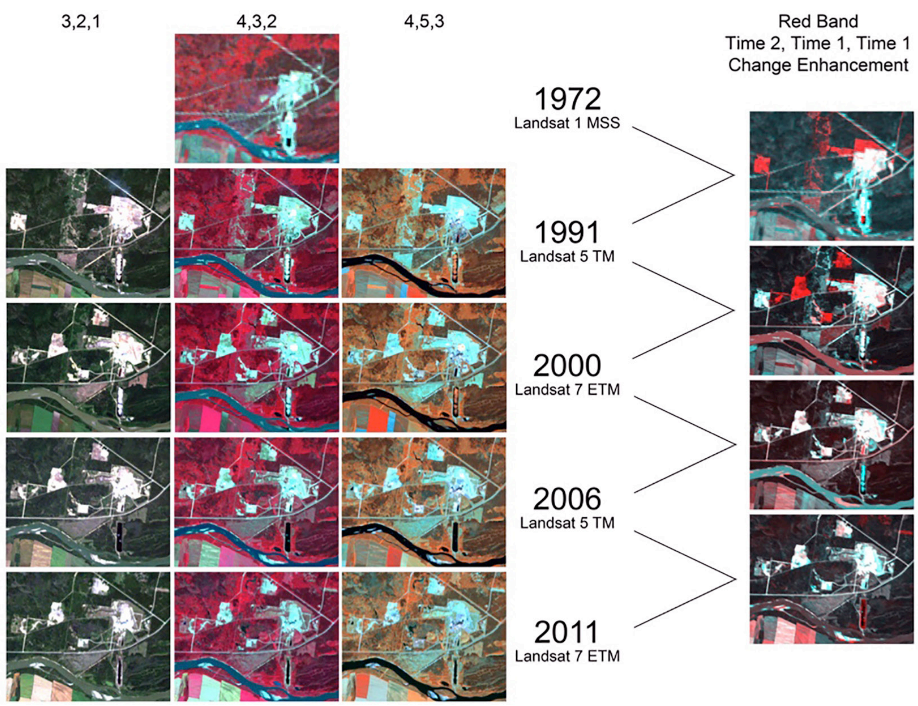

Figure 7. Examples of various Landsat satellite band combinations and change enhancements that may be used in the mapping process. Note the change enhancement at right shows red triggers where vegetation loss or change has occurred. Band combinations shown are normal colour rendition on left, with colour infrared in the middle. The right-hand column shows Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper (ETM) bands 4,5,3 (i.e., the two near infrared bands and a red band) displayed as red, green, blue.

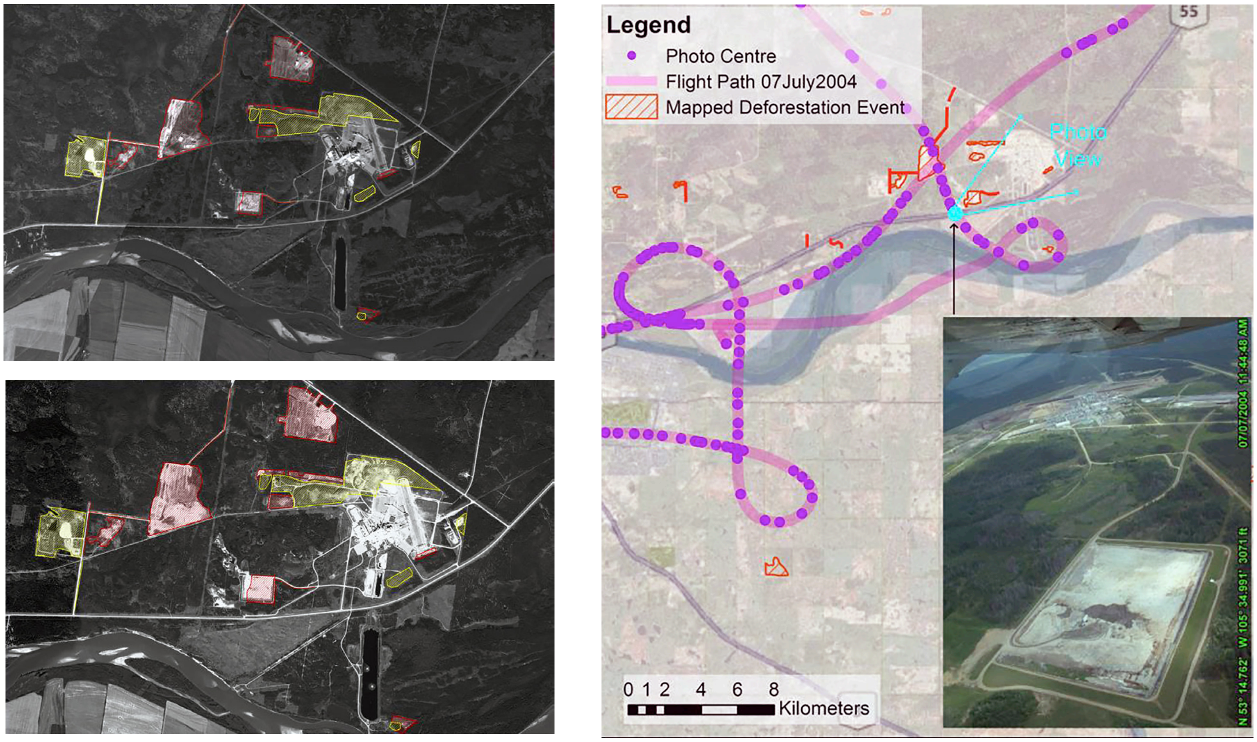

Figure 8. Examples of supplemental data use. Left: Example of confirmed and interpreted events (red and yellow lines) shown as polygons on the SPOT imagery (2.5 m resolution SPOT 5, top left, and 10 m SPOT 4, bottom left). Right: Example of flight path and oblique aerial photograph from a deforestation field verification campaign.

Typically, the interpretation process is conducted in a GIS environment, where change enhancement and single-date images can be layered and compared by blinking or using the swipe tool. Georeferenced ancillary imagery can be simultaneously displayed, and a link between ArcGIS and Google Earth allows the synchronization of spatial display extents in both programs.

4.3.2 Project Packages

Project packages are units of mapping work. They include specification of the mapping area, time period to be mapped, and the sample cells to be used. Each project package contains: a standardized geodatabase with pre-defined sets of values for some of the attribute fields; core date and change enhancement imagery; other imagery, including winter and overlapping scenes from east and west of the scene being mapped; additional SPOT and aerial photographs (if available); and ancillary data sets.

Once the mapping has been completed for a project and passed successfully through quality control, the data are added to the national geodatabase, which carries all deforestation mapping data for the country, including all time periods. The structure of the project geodatabases mirrors the structure of the national geodatabase.

4.3.3 Interpretation

Image interpretation is done manually on a cell-by-cell basis. Typically, the change enhancement is used first to identify change events. These are then confirmed or refuted as deforestation by the interpreter using the individual core date images supported by other image and ancillary data. The supporting data are used to assess whether an event area was forested before the change, and whether the event meets the deforestation definition. Supporting data are also used to help interpret pretype and post class.

The boundary of a deforestation event is identified in the Landsat images, but higher-resolution imagery is used in a supporting role to improve event boundary delineation. Interpreters follow specific digitizing guidelines provided in the Deforestation Interpretation Guide (Leckie et al. 2012) that dictate how events shall be mapped (e.g., digitize smooth lines rather than following pixel boundaries, avoid gaps and overlaps between adjacent events, keep the mapping topology clean, etc.).

Deforestation events may be linear in form (e.g., roads, hydro lines) or polygonal. They are digitized accordingly as lines or polygons in the project geodatabase. Specific guidelines apply for each type of feature. Delineation follows clearly defined situational rules (e.g., for composite/mixed use polygons, roads in cutblocks, tertiary versus more significant roads, episodic clearing, etc.), all of which are addressed in detail in the Deforestation Interpretation Guide. When events extend beyond the boundaries of a sample cell, they are delineated to the full extent of the event but only the portion inside the cell is included in the estimation.

Event attributes are interpreted and recorded, using attribute values defined in the NDMS data dictionary. Pretype attributes include forest type, density, and maturity (see Appendix 1 for details). Post class attributes are listed in Table 2 (see Appendix 2 for details). Interpreters also record their level of confidence about each deforestation event (i.e., how confident they are that it was forest before the change and that it is indeed a new land use). Comment fields are used extensively to record details specific to each event. These may indicate uncertainty in an event, a request by the interpreter for specific review by the quality control person, or the need for checking the event in a later time period. The widths for linear events (such as roads or corridors) are also recorded, as it is more efficient to map these as lines and later convert to polygons using the width data during a subsequent processing stage.

If mapping already exists for an earlier time period in the area, the interpreter reviews it in the context of recent imagery, either to confirm the previous interpretations or to note whether corrections are required. Points are used to flag areas for revision or later review by analysts, such as where older mapping may require updating.

In some cases, imagery available for a core date is contaminated by clouds, shadows, or missing data at image edges. In such cases, the interpreter digitizes the contaminated area within the sample cells and saves the polygon into a special geodatabase layer for "non-interpretable area" polygons, and notes the affected date. The areas saved into this layer are removed from the sample during later processing to create what is termed the "interpretable grid." The opening of the Landsat archive through free access to geocorrected imagery has substantially reduced the amount of non-interpretable area entering the estimate calculations. For example, sometimes images outside the core date can be used to infer deforestation in the non-interpretable area. In fact, recently non-interpretable areas have been almost eliminated from the process.

A series of quality checks has been built into the mapping process; these are completed in every mapping project. Canadian Forest Service analysts conduct quality control checks of the mapped data (see Section 5) and return a set of quality control points to the interpreters, indicating where more work and specific changes are needed before the mapping can be loaded into the national geodatabase.

4.4 Deforestation Estimation

The mapping data from deforestation sample cells are used to estimate the area of deforestation in each RU by scaling up from sample to population in each deforestation stratum, and then summing the deforestation estimate for each stratum in an RU. Scaling up is done for each land use type (post-class modifier) in each time period. Temporal interpolation is used to compute annual deforestation rates. Lastly, large event mapping, records and activity data, and intelligence are used to refine the estimates when appropriate.

4.4.1 GIS processing

The national deforestation geodatabase contains all the mapped areas representing deforestation events sampled within each time period as lines and polygons. The geodatabase also contains layers required for the estimation calculations, including the sample grids, the non-interpretable areas, the Landsat image boundaries (which define the core dates and areas sampled), the deforestation strata boundaries, and the RU boundaries.

The spatial data are first processed to prepare them for the scaling up analysis, which is conducted later in a non-spatial database program (Section 4.4.4). Figure 9 provides a schematic of the tasks involved in the GIS processing (Burt et al. 2006). The two main calculated outputs produced are the event and grid tables, shaded in red in Figure 9. The processing of the mapped GIS data for the national summary is performed for each time period.

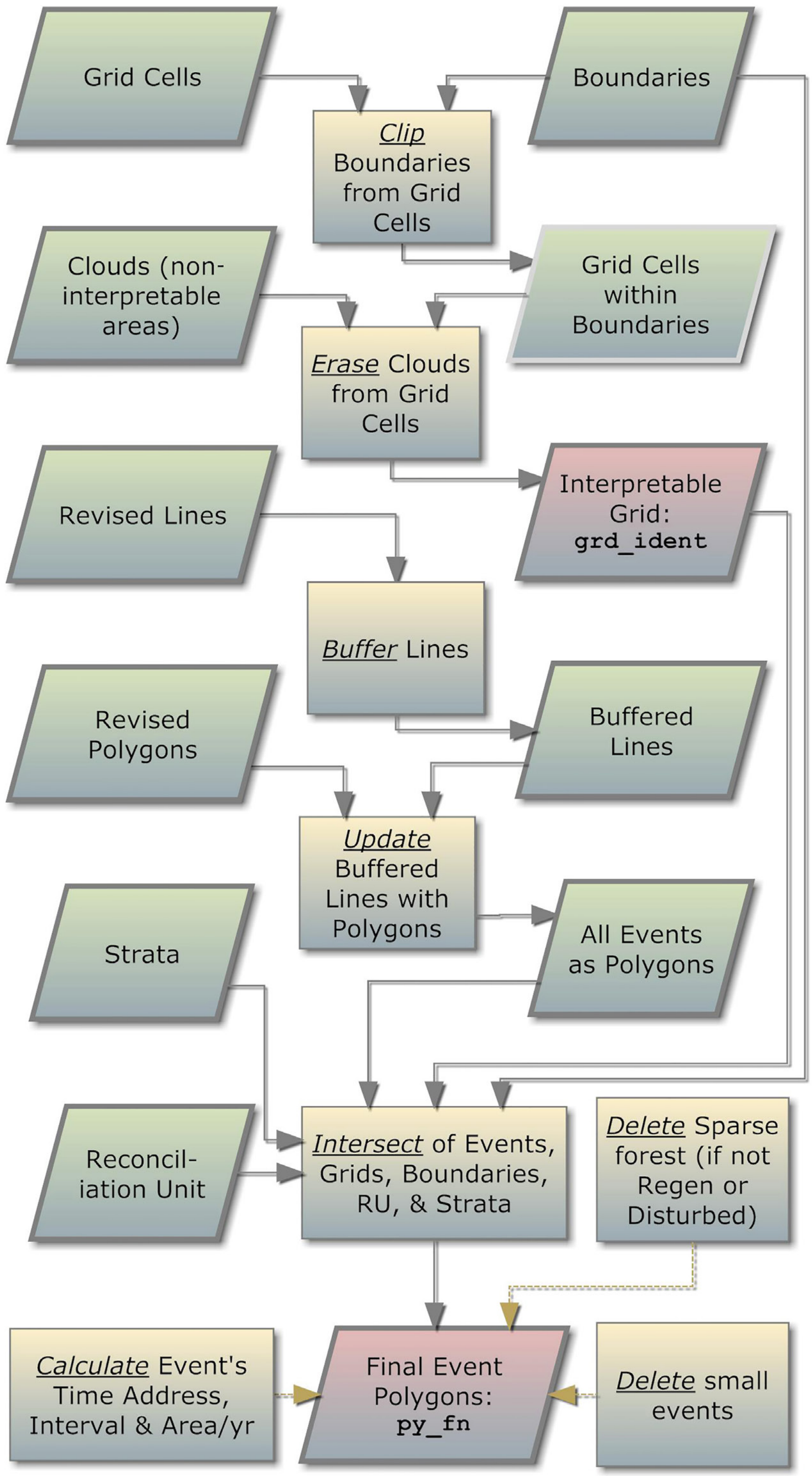

Figure 9. Simplified deforestation GIS processing flow. Input tables are in green, processes in yellow, and output tables in red. Gold arrows denote updates to a table. The term "lines" refers to linear deforestation events; ArcGIS commands are *underlined*.

The first of the output tables, the "interpretable grid" (labelled grd_ident in Figure 9), defines the actual area for which mapping was done. As a result, the full set of sample cells is clipped by the extent of the Landsat imagery (thus removing portions of the cells that fall outside the Landsat image boundary), and has the non-interpretable areas (e.g., clouds) removed.

The second table, the "Final Event Polygons" (labelled py_fn), is created from the intersection of many input layers. The post-class modifier code for each event is carried through in these deforestation calculations. The linear deforestation events are converted to polygons by applying a buffer according to the width attribute associated with each line, then combined with the other deforestation polygon events to create a complete polygonal coverage of all deforestation events mapped. The events are then intersected with the interpretable grid layer. Further intersections are applied to the boundary, RU, and deforestation strata layers to identify which strata and RU are associated with each event. In the end, the data for each event include attributes drawn from all the intersected layers, including the deforestation stratum and RU of each event. As well, small slivers created during the GIS processing steps are removed.

At this stage, it is possible to calculate the rate of deforestation for each time period. All events are assigned to the time period in which they occur (i.e., P1 [1975–1990], P2 [1990–2000], or P3 [2000–2008]) based on the core dates of imagery used for mapping. For each event, an effective annual rate of deforestation (hectares per year) is calculated by dividing the deforested area by the number of years between the core dates. Later in the process, the resulting per-event annual rates are summed for each stratum and divided by the area of grid cells interpreted to determine the average annual rate for each time period and post-class modifier (Section 4.4.4).

To provide flexibility, the mapping activity captures forest clearings that meet a more inclusive definition of deforestation than strictly required. Land conversion of sparse forest does not constitute deforestation (unless it is conversion of a recently disturbed or regenerating area) but is mapped for completeness unless otherwise specified. The GIS processing steps are used to exclude such mapped events with sparse forest density.

4.4.2 Large Events and Records Data

Certain types of events that are large, uncommon, and isolated (e.g., hydroelectric reservoirs, new surface mines, long and major hydroelectric lines, etc.) are better represented by complete mapping and census rather than sampling (Leckie et al. [in review]). Such events, termed "large events," are mapped separately and completely using either core date imagery or imagery captured as close to the actual event dates as possible. When large events fall within sample cells, and thus are also captured by the sampling, these are excluded from the processing of sample data to avoid double-counting.

Records and activity data, when used for a given type of deforestation in a region (e.g., stratum), are added to the database and removed from the processing of sample data, similar to large events (see Section 4.2.4).

4.4.3 Expert Intervention

After the mapping and GIS processing steps have been completed, the initial estimation results are analyzed to identify potential problems. With the nature of deforestation in Canada and intensity of the sample, occasionally spurious estimates may occur.

Canadian Forest Service deforestation monitoring experts have accumulated familiarity with land use change patterns and activities in Canada over many years. These experts scrutinize NDMS estimation process outputs and investigate questionable outputs that may be then modified if a change is justified.

When suspicious estimation outputs are encountered, experts intervene by evaluating available records information and reconnaissance data. For example, when a particular event type is rare and sampling produces estimates that are unexpectedly high or low, expert reviewers may scan available imagery to see what is occurring outside the sample cell boundaries (i.e., in the non-sampled area), and use this to inform expert intervention. Estimation outputs may be deemed suspicious when they contradict previous estimates or other available lines of evidence. All expert interventions are documented for transparency, and in case they need to be reassessed as new evidence emerges (e.g., Leckie et al. 2009; Leckie et al. 2010).

4.4.4 Database Processing

Annualized national deforestation estimates are produced for each industrial sector and RU by combining the GIS data and any large event or records/activity data, and incorporating expert interventions. These data are loaded into a non-spatial database environment (Paradine 2007). The resulting estimates are used to produce customized reports for NDMS data users such as provincial government agencies, Canada's National Forest Carbon Monitoring Accounting and Reporting System for input to greenhouse gas emission estimation, and others.

The non-spatial part of the processing follows the work flow shown in Figure 10. The ratio of the area sampled (the "interpretable grid") to the area of the stratum is calculated (labelled "1" in Figure 10). The area of deforestation in the sample is then scaled up by this proportion (labelled "2" in Figure 10) to produce the deforestation estimate for the stratum. This process is repeated for all strata, time periods, and post classes (including post-class modifiers) using the mapped sample data only.

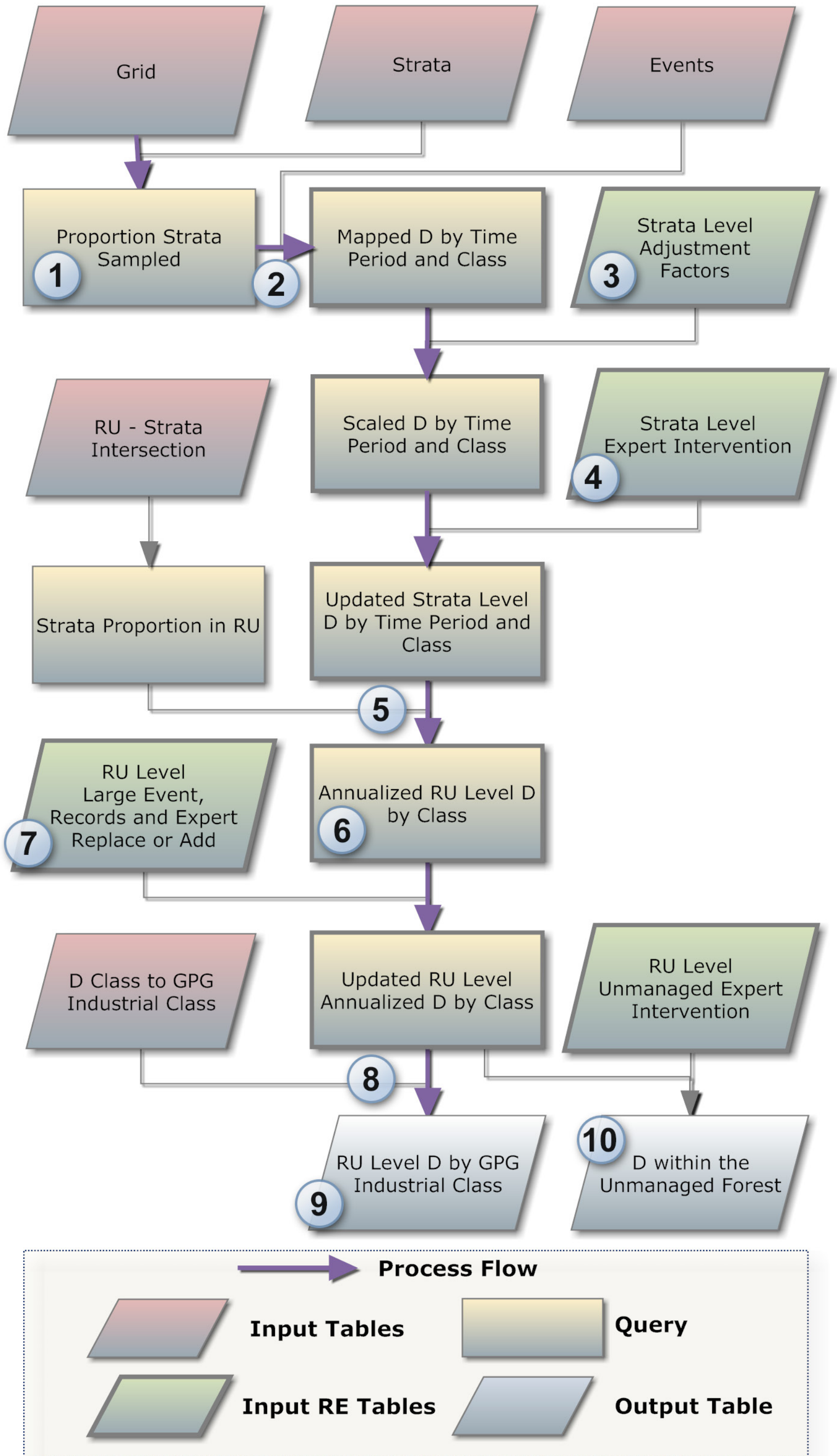

Figure 10. Schematic of the deforestation database process used to produce estimates.

The expert intervention can be added at the strata level for a particular time period as an adjustment factor (labelled "3" in Figure 10) or as replacements or additions (labelled "4" in Figure 10) to existing data. It can also be applied at the RU level (labelled "7" in Figure 10). Early national deforestation reporting had more expert interventions because of lower sample rates, less availability of high-resolution imagery, and more use of records data over the remote sensing sample. Currently, few expert interventions occur, with most occurring for the 1975–1990 time period, which has a smaller sample.

At the strata level, the updated deforestation estimates by time period and post-class modifier are proportioned (labelled "5" in Figure 10) into their respective RUs (see Appendix 3).

The data are then annualized. The deforestation estimates for each time period (by post class and RU) are assigned to the middle year of the time period (i.e., 1983 for 1975–1990, 1995 for 1990–2000 and 2004 for 2000–2008). Annual trends are produced by applying linear interpolation between midpoints and extrapolation from endpoints (labelled "6" in Figure 10). Figure 11 provides one example.

Large event mapping data, records and activity data, and expert interventions are applied as shown by the various green boxes in Figure 10. Large event data have the year of the event attached to them and are added to the mapping data at the RU level (labelled "7" in Figure 10). Records data also generally have a date attached and are added to the annualized data in a similar fashion to large event data.

Figure 12 shows the trend line calculated in Figure 11, and the large event data (purple) representing hydro reservoir flooding, facility construction, and associated transportation and hydro line corridors.

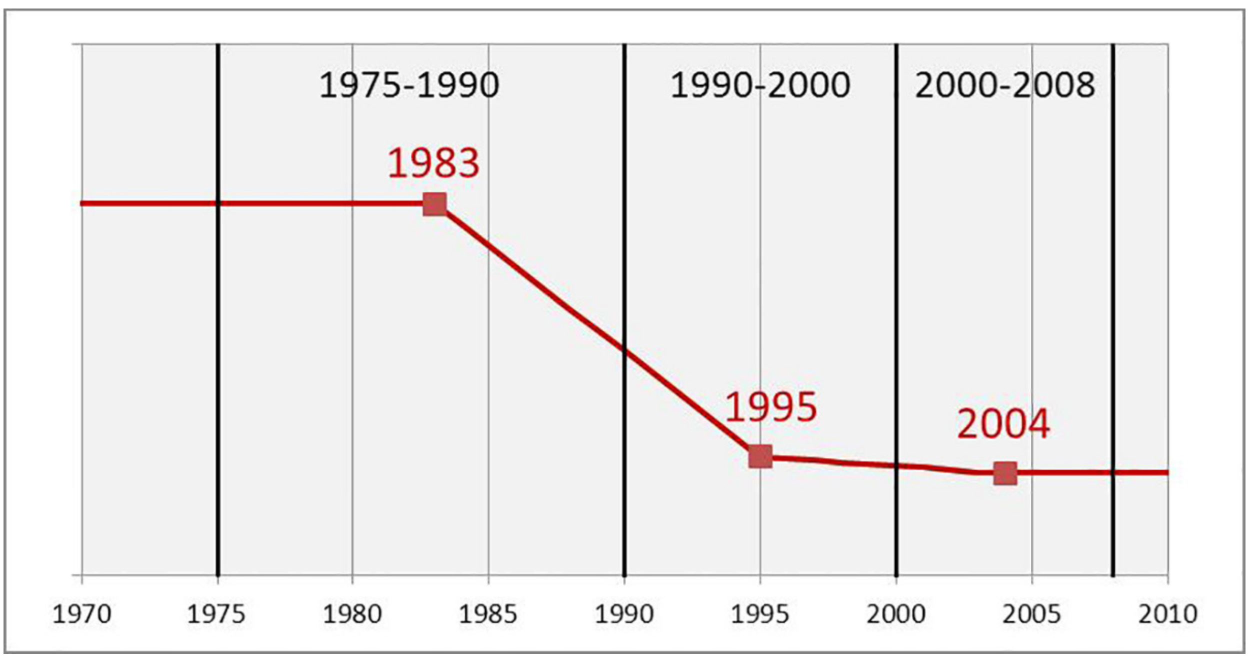

Figure 11. Example deforestation trend produced using data from three mapping periods.

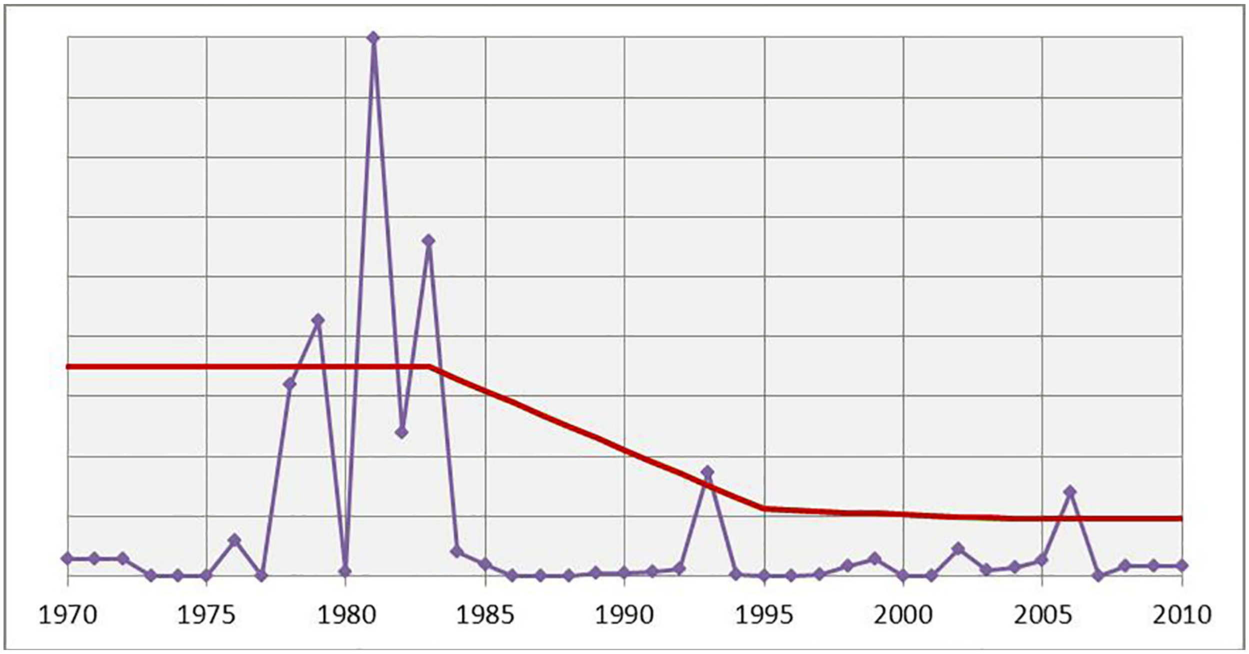

Figure 12. Example of a deforestation area trend from sample mapping (red) and large events data (purple).

The post-class modifier classes (Table 1 and Table A2.1 in Appendix 2) are aggregated (labelled "8" in Figure 10) to the appropriate industrial category and good practice guidance class using a lookup table. The various modifiers within each deforestation post class provide flexibility to summarize to different industrial categories based on user requirements (e.g., the categories used by the National Forest Carbon Monitoring Accounting and Reporting System and shown in Tables A2.1 and A2.2).

The result of the processing is a series of database tables. A major product among these is the list of annual deforestation area per RU, per industrial class (labelled "9" in Figure 10). Another product is the breakdown of forest pretype percentages by RU; this is done by calculating the percentage area of each pretype mapped in the RU. Reporting for the UNFCCC requires separate estimates of deforestation and greenhouse gas emissions for managed and unmanaged forest, thus a separate table is produced for unmanaged forest (labelled "10" in Figure 10).

5. Quality Control

Three major quality control stages are applied during the deforestation mapping process:

1. initial mapping quality control;
2. revision quality checks; and
3. overall quality assurance or vetting, where a check on the final mapping data is performed.

This multi-stage approach reduces the likelihood of errors and increases consistency of and confidence in the final product. The data processing stage has further checks for data integrity. After the data are calculated in the estimate process, the final numbers and trends are assessed for changes from previous year estimates. Deforestation estimates are also scrutinized by external users before they incorporate the data into their applications. For an overview of quality control practices, see Dyk et al. (2011).

5.1 Quality Control at the Mapping Stage

The mapping process flow is illustrated in Figure 13, including the quality control steps. Typical errors caught through quality control at the mapping stage include: incorrect event interpretations or delineations; event omissions or commissions; missing field values; typographical errors; and topology problems. During the quality control phase, an internal Canadian Forest Service reviewer performs detailed checks to ensure consistency with mapping and interpretation rules, and returns a set of points to flag and describe the problem areas to the interpreter or contractor. These quality control points are stored in the mapping geodatabase as a permanent layer.

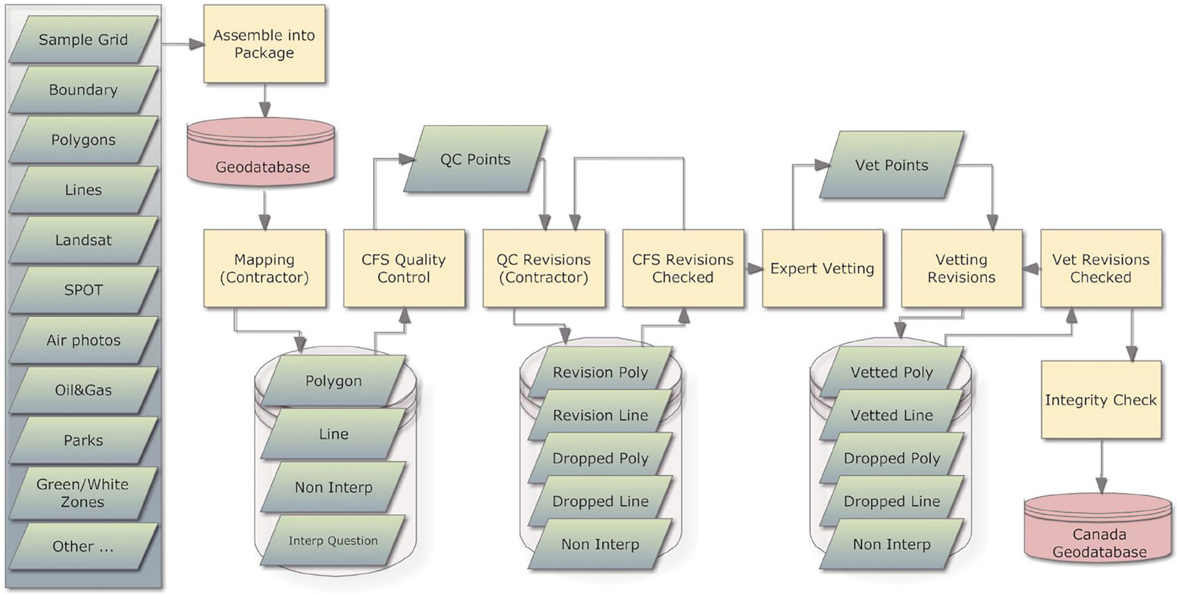

Figure 13. The deforestation mapping and quality control process flow.

The mapping interpreter reviews these points and applies the recommended corrections to the working database. The quality control points are sent to the interpreter early and frequently in the project timeline to reduce or avoid propagation of persistent errors or misunderstandings through the duration of the project.

The original line and polygon mapping is preserved and revisions are performed in separate "revised line" and "revised polygon" layers in the project geodatabase. Information about the changes, including what was done, by whom, and the date, is added for every revised event. Any deleted events are also retained in what are termed the "drop layers," to mark the area as a non-deforestation event, which is reviewed during future mapping.

When the revised data are resubmitted to the Canadian Forest Service, the data layers make clear what changes were requested and what changes were made. The reviewer uses these layers to verify that appropriate revisions were properly applied at all quality control points. Any further errors or misunderstandings are communicated to the interpreter immediately for resolution. At this stage, the interpreter can also open a dialogue regarding specific events using additional comment fields in the quality control point layer or personal communication.

The next level of quality control is the final vetting. This audit step is conducted internally by senior Canadian Forest Service interpreters to ensure consistency of mapping across all projects. All aspects of the new data are reviewed during this stage: omission and commission errors, delineation, and attribution. In addition, the older mapping data are scanned to ensure newer imagery confirms the original interpretation. A set of "vet revision" points is created to mark all adjustments required in the database. An analyst works through these point by point to make the necessary changes, noting any complex or uncertain events, and communicating directly with the vetting interpreter when necessary.

Field validation is a desirable aspect of the revision process but is not included during the mapping stage. In general, field campaigns are conducted on an ongoing basis when resources permit. Areas where local knowledge or ground truth information are needed to clarify the interpretation are identified from the interpreter confidence records or the revision point data. Dedicated field programs schedule air or ground visits to high-impact and low- to moderate-confidence events. Local experts sometimes provide information about ground conditions that can be used to verify and update the database.

Throughout the entire mapping and revision process, an internal "project story" is maintained by the Canadian Forest Service. This document summarizes activity on a given project, including staff and contractors involved, dates, and actions completed. It also includes detailed explanation of any complex situations or vet revisions, as well as notes on any issues raised by the quality control or vetting interpreters. To maintain consistency, analysts who are involved in revisions or who vet revisions read this project story before starting work.

5.2 Quality Control at the Data Processing Stage

Once revisions are vetted, final data integrity checks are conducted on the project database to find and correct any technical errors, such as missing attributes, mismatched post classes and modifiers, incorrect or reversed event dates, inappropriate line widths, topology errors, overlaps and duplicates, and typos. This stage is partially automated. The final mapping layers can be loaded into the national database only after the integrity checks have been completed.

Data quality checks are built into the script that automates the data processing stages. The script both delivers reports to the screen while running, and dumps to log files, which are reviewed by Canadian Forest Service staff to ensure the runs were successful.

Transfer of the final GIS tables into the non-spatial deforestation database is also automated. The grid and event tables for each time period are checked before loading, and the number of records loaded is recorded and compared with previous runs to highlight any potential discrepancies.

The database queries and tables used to create the annual estimates by industrial category and RU are controlled by Microsoft Access macros to ensure consistency between the runs.

5.3 Quality Control at the Output Analysis Stage

Following generation of the estimate tables, the main outputs (annualized deforestation by industrial class and RU, pretype table, and unmanaged forest table) are evaluated closely by Canadian Forest Service experts to ensure that estimates have been calculated properly and that discrepancies from previously calculated values can be explained. To aid in this effort, a comparison spreadsheet is created for each RU showing the deforestation estimates by industrial class for the current and previous year's national run, together with illustrations and statistics. The experts scrutinize the data for changes and ensure the new estimates are consistent with the input mapping data. Any specific issues and special adjustments required are documented in a report that becomes part of the record for each year's estimate.

5.4 External Quality Control

Users of the deforestation estimates conduct their own reviews of the data prior to use in their systems, and communicate any issues before incorporating the data into their own business processes. When new issues arise, these are dealt with and the NDMS quality control processes are updated to catch similar issues in the future.

6. Conclusions

Deforestation is the direct human-induced conversion of forested land to non-forested land use. The NDMS was designed and implemented to provide information needed by Canada to meet its obligation under the UN Framework Convention on Climate Change to report the areas affected annually by deforestation. Also considered was the need to provide information useful for policy analysis, land management, and forest stewardship applications. Understanding why, where, and when deforestation occurs is a prerequisite to the development of appropriate policy instruments to optimize land use, develop mitigation strategies, and address cumulative impacts on forest resources.

The NDMS uses manual mapping from a satellite remote sensing sampling system, informed by records-based information and expert knowledge, to provide information about deforestation in Canada. The remote sensing mapping is supported by available ancillary information such as high-resolution imagery, forest inventory, road networks, and other industrial databases. Certain types of events that are large and isolated (e.g., mine and hydroelectric developments) are mapped and incorporated separately in the overall deforestation estimates. Occasionally, records and activity data on land use changes are incorporated when they are deemed more appropriate than the sampling estimate. The mapping results from the sample are scaled up to regional levels. In the data processing stage, these data are merged and annualized to produce national deforestation estimates.

The system has been used and improved over the last 10 years. The flexibility of the NDMS's design makes it possible to adapt to future changes in image sources, ancillary data, resource availability, and user needs, and positions the program well for long-term maintenance and improvement.

7. References

Burt, W.; Paradine, D.; Leckie, D. 2006. Geographic Information system processing of deforestation mapping data for estimating deforested area of Canada. Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Victoria, B.C. Report DRS-P-001.

Dyk, A.; Tinis, S.; Leckie, D. 2011. National Inventory Report, 2011: Deforestation area estimation for Canada: Quality control overview. Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Victoria, B.C. Report DRS-N-031.

Ecological Stratification Working Group. 1996. A national ecological framework for Canada. Agriculture and Agri-Foods Canada, Research Branch, Centre for land and Biological Resources Research and Environment Canada, State of the Environment Directorate, Ottawa, Ont.

Environment Canada. 2006. National Inventory Report, 1990–2004: Greenhouse gas sources and sinks in Canada. Government of Canada Submission to the UN Framework Convention on Climate Change.
http://unfccc.int/national_reports/annex_i_ghg_inventories/national_inventories_submissions/items/3734.php (Accessed August 2014).

Environment Canada. 2014. National Inventory Report, 1990–2012: Greenhouse gas sources and sinks in Canada. Government of Canada Submission to the UN Framework Convention on Climate Change. Report issued by Pollutant Inventories and Reporting Division, Environment Canada, Ottawa, Ont.
http://unfccc.int/national_reports/annex_i_ghg_inventories/national_inventories_submissions/items/8108.php (Accessed August 2014)

Food and Agriculture Organization. 2006. 2001. Global forest resources assessment 2000, main report. United Nations Food and Agriculture Organization, Rome, Italy. FAO Forestry Paper 140.

Gillis, M.; Omule, A.; Brierley, T. 2005 Monitoring Canada's forests: The National Forest Inventory. Forestry Chronicle 81(2):214–221.

Intergovernmental Panel on Climate Change. 2003. Good practice guidance for land use, land-use change and forestry. Penman, J.; Gytarsky, M.; Hiraishiet, T., et al. (eds.). Institute for Global Environmental Strategies, Hayama, Japan.

Intergovernmental Panel on Climate Change. 2006. 2006 IPCC guidelines for national greenhouse gas inventories. Eggleston, H.S.; Buendia, L.; Miwa, K.; Ngara, T.; Tanabe, K. (eds.). Intergovernmental Panel on Climate Change National Greenhouse Gas Inventories Programme, Institute for Global Environmental Strategies, Hayama, Japan.
http://www.ipcc-nggip.iges.or.jp/public/2006gl (Accessed January 2015).

Kurz, W. 2010. An ecosystem context for global forest cover loss estimates. Proceedings, National Academy of Sciences 107(20):9025–9026.

Kurz, W.; Apps, M. 2006. Developing Canada's national forest carbon monitoring, accounting and reporting system to meet the reporting requirements of the Kyoto Protocol. Mitigation and Adaptation Strategies for Global Change 11(1):33–43.

Kurz, W.; Dymond, C.; White, T.; Stinson, G.; Shaw, C.; Rampley, G.; Smyth, C.; Simpson, B.; Neilson, E.; Trofymow, J.; Metsaranta, J.; Apps, M. 2009. CBM-CFS3: A model of carbon-dynamics in forestry and land-use change implementing IPCC standards. Ecological Modelling 220(4):480–504.

Kurz, W.; Shaw, C.; Boisvenue, C.; Stinson, G.; Metsaranta, J.; Leckie, D.; Dyk, A.; Smyth, C.; Neilson, E. 2013. Carbon in Canada's boreal forest: A synthesis. Environmental Reviews 21:260–292.

Leckie, D.; Dyk, A.; Ortlepp, S.; Tinis, S. 2010. Records of decision for Canada's national deforestation estimate 2011. Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Victoria, B.C. Report DRS-N-029.

Leckie, D.; Dyk, A.; Paradine, D.; Tammadge, D.; Tinis, S. 2012. Deforestation interpretation guide. Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Victoria, B.C. Report DRS-M-030.

Leckie, D.; Dyk, A.; Tinis, S. 12009. Records of decision for Canada's national deforestation estimate. Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Victoria, B.C. Report DRS-N-026.

Leckie, D.; Paradine, D.; Burt, W. 2006a. Mapping sample coverage for Canada's national deforestation estimate 2006. Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Victoria, B.C. Report DRS-N-002.

Leckie, D.; Paradine, D.; Tinis, S. 2006b. Geographic strata for Canada's national deforestation estimates report. Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Victoria, B.C. Report DRS-Q-003.

Leckie, D.; Paradine, D.; Kurz, W.; Magnussen, S. [2015]. Deforestation mapping sampling designs for Canadian landscapes. Natural Resources Canada, Canadian Forest Service, Victoria, B.C. In review.

Lemprière, T.; Kurz, W.; Hogg, E.; Schmoll, C.; Rampley, G.; Yemshanov, D.; et al. 2013. Canadian boreal forests and climate change mitigation. Environmental Reviews 21(4):293–321.

Le Quéré, C.; Peters, G.; Andres, R.; Andrew, R.; Boden, T.; et al. 2014. Global carbon budget 2013. Earth System Science Data 6:689–760.

Masek, J.; Cohen, W.; Leckie, D.; Wulder, M.; Vargas, R.; de Jong, B.; Healey, S.; Law, B.; Birdsey, R.; Houghton, R.; Mildrexler, D.; Goward, S.; Smith, W. 2011. Recent rates of forest harvest and conversion in North America. Journal of Geophysical Research 116:G00K03.

McGovern, M. 2008. Reporting zones: GHG spatial reporting structure for Canada 2008. Environment Canada, Greenhouse Gas Division, Ottawa, Ontario.

Montreal Process. 2009. Criteria and indicators for the conservation and sustainable management of temperate and boreal forests. Fourth edition. http://www.montrealprocess.org/documents/publications/general/2009p_4.pdf (Accessed January 2015).

Pan, Y.; Birdsey, R.A.; Fang, J.; et al. 2011. A large and persistent carbon sink in the World's forests. Science 333:988–993.

Paradine, D. 2007. National Inventory Report, 2008: ACCESS database description, GIS processing description and consolidated GIS database description. Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Victoria, B.C. Report DRS-N-019.

United Nations Framework Convention on Climate Change. 2002. Conference of the Parties–Report of the Conference of the Parties on its seventh session, held at Marrakesh from 29 October to 10 November 2001. United Nations Office, Geneva, Switzerland. http://unfccc.int/resource/docs/cop7/13.pdf (Accessed January 2015).

Wulder, M.; Masek, J.; Cohen W.; Loveland, T.; Woodcock, C. 2012. Opening the archive: How free data has enabled the science and monitoring promise of Landsat. Remote Sensing of Environment 122:2–10.

Appendix 1: Pretype Forest Conditions

The tables below list the approved forest type, density, and maturity values applied in deforestation mapping. Note not all combinations are valid, particularly those that include recent disturbance and regeneration terms. Table A1.1 lists the acceptable parameter combinations.

The most common pretype groupings found are the 36 combinations of three Type classes (B, C, and M), three Density classes (D, O, and S), and four Maturity classes (R, Y, I, and M). The two older Maturity classes (O and G) require additional verification to identify them. Several classes identify recently disturbed forests (K, X, and R).

Table A1.1. Pre-change forest type descriptors

TYPE		Definition	Restrictions of use
B	Broadleaf	> 75% of trees are broadleaf (Angiospermae)	
C	Conifer	> 75% of trees are conifer (Coniferae)	
M	Mixed	> 25% of both broadleaf and conifer present.	
K	Clearcut	Exposed ground and (or) ground vegetation. No visible regeneration.	Use only with S or N density, and Q maturity.
X	Burn	Exposed ground and (or) ground vegetation. No visible regeneration. May have live residual trees up to 25% crown closure.	Use only with S or N density, and Q maturity.
R	Regen	Regenerating areas with < 25% crown closure, where the forest composition (B, C, or M) is not identifiable.	

Table A1.2. Pre-change forest density descriptors

DENSITY		Definition	Restrictions of use
D	Dense	> 60% crown closure	
O	Open	25–60% crown closure	
S	Sparse	5–25% crown closure	
N	Nil	< 5% crown closure	Use only with K and X pretype.

Table A1.3. Pre-change forest maturity descriptors-

MATURITY		Definition	Restrictions of use
Q	Recent disturbance	No visible regeneration.	Use only with K and X pretype.
R	Regen	Forest stands 0–14 years old.	
Y	Young	Forest stands 15–25 years old.	
I	Immature	Forest stands 26–40 years old.	
M	Mature	Forest stands 41–80 years old.	
O	Old	Forest stands 81–200 years old.	
G	Old-growth	Forest stands over 200 years old	Restricted to British Columbia only

Table A1.4. Valid combinations of pretype attributes (Type–Density–Maturity)

	Regen	Broadleaf	Mixed	Coniferous
Dense	RDR	BDR	MDR	CDR
		BDY	MDY	CDY
		BDI	MDI	CDI
		BDM	MDM	CDM
		BDO	MDO	CDO
				CDG
Open	ROR	BOR	MOR	COR
		BOY	MOY	COY
		BOI	MOI	COI
		BOM	MOM	COM
		BOO	MOO	COO
				COG
Sparse	RSR	BSR	MSR	CSR
		BSY	MSY	CSY
		BSI	MSI	CSI
		BSM	MSM	CSM
		BSO	MSO	CSO
				CSG
		Burn	**Clearcut**	
	Regen	**Broadleaf**	**Mixed**	**Coniferous**
Disturbed		XSQ	KSQ	
		XNQ	KNQ	

Appendix 2: Post-class Modifiers by Industrial Category

Table A2.1 lists all land use post-class deforestation modifiers. They provide additional detail regarding what has occurred on the ground for each deforestation event. These classes can be assigned to various industrial classes (see Table A2.2). Detailed definitions are provided in the Deforestation Interpretation Guide (Leckie et al. 2012).

Table A2.1. Post class and post-class modifier codes and short descriptions grouped by industrial category/sector (in bold)

Post class		Post class modifier	
Agriculture			
AG	Agriculture	ab	bare
		cp	crop
		fy	farm yard
		pa	pasture
AL	Artificial Lake	aa	agriculture pond
		ea	agriculture effluent pond
OF	Open Field	fa	agriculture setting
Flooded Standing Forest			
AL	Artificial Lake	ff	flooded standing forest
Forestry			
RD	Road	mf	mainline forestry road
		sf	secondary forestry road
		xf	tertiary forestry road with width ≥ 20 m
SD	Soil Disturbance	ld	logging landing
		ss	rock slide scar
Hydro Infrastructure			
CR	Corridor	hm	hydro line–main
		hs	hydro line–secondary
		xy	hydro line–tertiary ≥ 20 m
IN	Industrial	ih	hydro infrastructure
Hydro Reservoir			
AL	Artificial Lake	hr	hydroelectric flooding
Industry			
AL	Artificial Lake	ei	industrial effluent pond
IN	Industrial	hi	heavy industrial
		li	light industrial
OF	Open Field	fi	industrial

Post class		Post class modifier	
Mining			
AL	Artificial Lake	em	waste ponds for mining
IN	Industrial	mh	mine heavy
		ml	mine light
OF	Open Field	fk	mine facility
		fm	mine
		fq	pit and quarry
SD	Soil Disturbance	mn	open pit mine
		pq	gravel pit/quarry
Municipal			
AL	Artificial Lake	ad	pond urban setting
		ar	pond rural residential
		ul	other human caused
CR	Corridor	cl	cut line
		cu	undifferentiated
OF	Open Field	fd	urban/suburban
		fr	rural residential
		uf	undifferentiated field
RR	Rural Residential	rf	few trees remaining
		rm	many trees remaining
SD	Soil Disturbance	lf	landfill
		su	undifferentiated
UR	Urban Residential	df	few trees remaining
		dm	many trees remaining
Oil and Gas			
CR	Corridor	pp	pipeline–main
		ps	pipeline–secondary
		xp	pipeline–tertiary ≥ 20 m
IN	Industrial	oi	oil sands industrial
		op	oil and gas industrial
		wp	well pad
OF	Open Field	fo	oil and gas facility
		fs	oil sands open field
SD	Soil Disturbance	os	oil sands
AL	Artificial Lake	eo	oil and gas related pond

Post class		Post class modifier	
Peat Mining			
SD	Soil Disturbance	pm	peat extraction
Recreation			
AL	Artificial Lake	af	golf course related
		ap	recreational water body
OF	Open Field	fc	recreational field
RC	Recreational	ca	campground
		go	golf course
		ru	other or undifferentiated
		sk	ski areas
Transportation			
CR	Corridor	as	airstrip
		ry	railway
RD	Road	mm	main road clearly for a mine
		mr	main road
		mo	main road clearly for oil and gas
		my	main road clearly for hydroelectric
		sm	secondary mining road
		so	secondary oil and gas road
		sr	secondary road
		sy	secondary hydroelectric road
		xm	tertiary mining road with width ≥ 20 m
		xo	tertiary oil and gas road with width ≥ 20 m
		xr	tertiary road with width ≥ 20 m
		xy	tertiary hydroelectric road with width ≥ 20 m

Table A2.2. Aggregation of deforestation mapping classes to good practice guidance and industrial categories

Good practice guidance class →		Crop-land (CL)	Wetlands (WL)			Settlements (SL)							
Deforestation post class / Industrial Categories →		Agriculture	Flooded standing forest	Hydro reservoir	Peat mining	Forestry	Hydro infrastructure	Industry	Mining	Municipal	Oil and gas	Recreation	Transportation
Agriculture	AG	ab cp pa fy											
Artificial Lake	AL	aa ea	ff	hr				ei	em	ad ar of ul	eo	af ap	
Corridor	CR						hm hs xy			cl cu	pp ps xp		as ry
Industrial	IN						ih	hi li	mh ml		oi op wp		
Open Field	OF	fa						fi	fk fm fq	fd fr uf	fo fs	fc	
Recreational	RC											ca go fu sk	
Road	RD					mf sf xf							mm mo mr my sm so sr sy xm xo xr xy
Rural Residential	RR									rf rm			
Soil Disturbance	SD				pm	ld ss			mn pq	lf su	os		
Urban Residential	UR									df dm			

Appendix 3: Deforestation Strata Units and Reconciliation Unit Inclusion

Table A3.1 shows the names of the deforestation strata, their area in kilohectares, and the percentage of that area contained in each reconciliation unit that they overlap (sorted by reconciliation unit identification number; see Figure 1 for unit location and name).

Table A3.1. Area of strata units and percent of strata unit area that is in each reconciliation unit

Deforestation strata unit name	Strata unit area (kilohectares)	Reconciliation unit (% inclusion)
Newfoundland Eastern Woodlot	4 477	1 (100)
Newfoundland Forest Activity Zone	6 512	1 (100)
Newfoundland St. Johns	55	1 (100)
Labrador Arctic	1 893	2 (100)
Labrador Northern Forest	23 238	3 (98), 4 (2)
Labrador Forest Activity Zone	4 620	4 (100)
Nova Scotia Eastern Woodlot	2 894	5 (100)
Nova Scotia Forest Activity Zone	2 396	5 (100)
Nova Scotia Halifax/Dartmouth	182	5 (100)
Prince Edward Island	577	6 (100)
New Brunswick Eastern Woodlot	4 121	7 (100)
New Brunswick Forest Activity Zone	3 174	7 (100)
Quebec Arctic	20 443	10 (75), 9 (18), 8 (7)
Quebec Eastern Townships	3 948	11 (100)
Quebec Gaspe Forest Activity Zone	2 740	11 (100)
Quebec Southern RU12	2 968	12 (100)
Quebec Northern Forest	72 759	14 (73),15 (22), 13(5)
Quebec Forest Activity Zone	44 717	15 (100)
Quebec Ile D'Anticosti	795	15 (100)
Quebec Lac St. Jean	964	15 (100)
Quebec Southern RU15	1 687	15 (100)
Ontario Thunder Bay	225	16(100)
Ontario Southern	8 198	17 (100)
Ontario Manitoulin Island	326	17 (100)
Ontario Northern Forest	46 468	18 (56), 16 (43), 19 (1)
Ontario Sudbury/North Bay	874	19 (100)
Ontario Forest Activity Zone	42 398	19 (56), 16 (43), 18 (1)
Ontario Sault Ste. Marie	536	19 (92), 17 (8)
Manitoba Forest Activity Zone RU22 East	2 405	22 (100)
Manitoba Forest Activity Zone RU22 North	6 109	22 (100)
Manitoba Prairie Fringe RU22	804	22 (100)
Manitoba Northern Forest	37 339	22 (43), 21 (35), 25 (19), 23 (3)
Manitoba Forest Activity Zone RU23	7 382	23 (100)
Manitoba Prairie Fringe RU23	3 970	23 (100)
Manitoba Hotspot	851	24 (100)
Manitoba North Prairie	6 117	24 (100)

Deforestation strata unit name	Strata unit area (kilohectares)	Reconciliation unit (% inclusion)
Saskatchewan Northern Forest	21 224	27 (75), 26 (22), 28 (3)
Saskatchewan Prairie Fringe	5 509	28 (100)
Saskatchewan Inactive Forest Activity Zone	6 196	28 (58), 27 (42)
Saskatchewan Forest Activity Zone	8 189	28 (99), 27 (1)
Saskatchewan North Prairie	8 167	29 (100)
Saskatchewan Prairie	15 921	30 (100)
Alberta Northern Forest	10 862	31 (58), 34 (28), 32 (8), 33 (6)
Alberta Forest Activity Zone	22 066	34 (100)
Alberta Fort McMurray	807	34 (100)
Alberta High Level	789	34 (100)
Alberta Northwest Fringe	5 436	34 (100)
Alberta Prairie Fringe	6 038	34 (100)
Alberta North Prairie	7 397	35 (100)
Alberta RU 36 Forest Activity Zone	4 764	36 (100)
Alberta Palliser Triangle	3 689	37 (100)
Alberta Prairie West	4 522	37 (100)
British Columbia RU 38	6 759	38 (100)
British Columbia Prairie Fringe	2 333	39 (100)
British Columbia RU 40	19 220	40 (100)
British Columbia Lower Mainland, East Vancouver Island	1 142	41 (100)
British Columbia RU 41 Forest Activity Zone	15 440	41 (100)
British Columbia VI QCI	3 813	41 (100)
British Columbia Okanagan	1 109	42 (100)
British Columbia Prince George	464	42 (100)
British Columbia RU 42 Forest Activity Zone	44 286	42 (96), 39 (4)
Yukon Arctic	496	43 (100)
Yukon Northern Forest	19 987	45 (91), 44 (9)
Yukon Whitehorse	417	46 (100)
Yukon Forest Activity Zone	27 440	46 (98), 47 (1)
Northwest Territories Arctic	42 788	48 (49), 49 (43), 50 (7)
Northwest Territories Northern Forest	91 972	50 (52), 51 (37), 53 (9), 52 (2)
Northwest Territories Yellowknife	176	51 (100)
Northwest Territories Forest Activity Zone	467	54 (100)
Nunavut Arctic	198 915	56 (64), 57 (25), 55 (11)
Nunavut Northern Forest	9 892	58 (100)

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