Provincial Change Monitoring Inventory (CMI) and Young Stand Monitoring (YSM) Sampling Framework

May 2018
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Ministry of Forests, Lands, Natural Resource Operations and Rural Development

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Acronyms

BCLCCS: British Columbia Land Cover Classification System

BEC: Biogeoclimatic Ecosystem Classification

CMI: Change Monitoring Inventory

DBH: diameter at breast height of 1.3 m outside bark

FAIB: Forest Analysis and Inventory Branch

GY: Growth and Yield

MFLNRORD: Ministry of Forestry, Lands, Natural Resource Operations and Rural Development

NFI: National Forest Inventory

PPSWR: Probability proportional to size with replacement

TSA: Timber Supply Area

THLB: Timber Harvest Land Base

USFS-FIA: United States Forest Service, Forest Inventory and Analysis

VRI: Vegetation Resources Inventory

YSM: Young Stand Monitoring

Glossary

Bias: Systematic error introduced into sampling, measurement, or estimation by selecting or encouraging, possibly unintentionally, one outcome or answer over others

BC-NFI: FAIB specific data collection protocol that applies to the 268 NFI plots in British Columbia

VRI: Current provincial standard for management unit-level inventories, based on the traditional Canadian timber inventory model

VRI Phase 1: Refers to the Provincial Vegetation Resources Inventory process involving aerial photo estimation of detailed land cover attributes, generally conducted by TSA

VRI Phase 2: Temporary ground plots selected by PPSWR intended to improve volume estimates at the stand-level (VRI’s statistical adjustment process) or for other purposes

1. Background

To maintain a spatial inventory of the province, the Forest Analysis and Inventory Branch (FAIB) measures, estimates and predicts forest attributes. In a review of FAIB programs, Moss (2011) noted that predicting forest attributes is useful for many purposes (climate change, harvesting scenarios, fire impacts, etc.), however monitoring actual change in forest attributes is equally important for promoting sustainable forest management and economic sustainability of forest resources. In 2013, the Ministry of Forests Lands, Natural Resource Operations and Rural Development (MFLNRORD) published the 10-Year Forest Inventory Strategic Plan that established program goals and targets to address issues such as the Mountain Pine Beetle epidemic, changing technology, inventory update status, and program reviews. Goal 6 of the Strategic Plan states that MFLNRORD will "monitor stand growth and change throughout the province". FAIB's 2016/17 Business Plan, states that its key function is to monitor "the growth of stands and provide models to project stand development and future yield" (FAIB 2016a, p.8). FAIB's monitoring efforts strengthen MFLNRORD's commitment towards sustainable forest management while supporting economic opportunities in rural economies which depend on the forest resources.

To monitor average change in vegetation over the province, FAIB has implemented Provincial Monitoring Programs including the Provincial Change Monitoring Inventory (CMI) and Provincial Young Stand Monitoring (YSM) programs. These *Provincial* programs are distinguished from location specific CMI and YSM plots established by forest companies. The sampling framework, forest attributes, and estimates of change provided by these initiatives are based on traditional, well-known, reputable concepts in forest inventory (Schreuder et al. 1993). These initiatives are based on ground-based sampling surveys implemented on a systematic grid to provide the basis for statistically-sound, point-in-time and change estimates of forest attributes. Provincial change monitoring data could also be to (1) develop and validate growth-and-yield models; (2) validate VRI photo interpretation; (3) support LiDAR approaches to estimate forest attributes; (4) estimate forest carbon; (5) support wildlife habitat modeling; and (6) track forest health issues.

The goal of this document is to provide a sampling framework for the collection and analysis of Provincial CMI and YSM survey data, thereby increasing efficiency in meeting MFLNRORD's strategic vision. This framework is a living document that can, and should be, updated over time in response to changing information needs. Sampling frameworks are useful for 1) standardizing terminology and methods to promote clear, transparent communication with internal and external stakeholders; 2) clearly defining the target population; 3) clarifying the estimators required for analysis; and, 4) streamlining data collection and analysis to promote efficiency, accuracy, and confidence in the information generated.

2. Overview of programs

Data collection for the Provincial Change Monitoring Inventory (CMI) program began in 2013 and includes plots on all intersections of the National Forest Inventory (NFI) 20km by 20 km grid. The Provincial CMI project is a large-landscape-level initiative aimed to estimate forest and land cover attributes over large areas. The goal of the Provincial CMI program is to provide land cover and forest attribute information relevant to needs for natural resources decision making and monitoring change at a broad, landscape scale and at regular time intervals by using well known and understood survey sampling methods. Specific objectives for the Provincial CMI program include:

1) Calculate point-in-time statistics of land cover and forest attributes for the most current inventory.
2) Calculate change in broad land cover/land use classes where change is calculated over one time period from the most current inventory and the last inventory.
3) Calculate net change, components of change, and average annual change statistics of forest attributes, where change is calculated over one time period from the most current inventory and the last inventory.
4) Assess the accuracy of forest attribute estimates from various inventory datasets.
5) Validate growth model projections with an independent dataset.

YSM data collection originally began on a subset of TFL’s in 2000; with the provincial expansion of YSM data collection to TSA’s in 2011 (FAIB 2016 b and c). The Provincial YSM program is also a landscape-level initiative with the goal of providing information on young stand growth, as relevant to needs for natural resources decision making at regular time intervals by using well known and understood survey sampling methods. Specific objectives for the YSM program include:

1) Calculate point-in-time forest attributes of young stands.
2) Calculate net change, components of change, and average annual change statistics of forest attributes between the most current inventory and the last inventory.
3) Report incidence and severity of forest health issues in young stands.
4) Help evaluate if young stands will meet future timber supply expectations.

3. Sampling framework

3.1 Target population

Provincial CMI target population is the entire area (land and inland waters) of British Columbia. The boundaries to be used for defining the entire area will be assessed as needed.

Provincial YSM target population is 15 – 50 year old stands[1] based on the year of ground sampling as delineated on VRI Rank 1, Phase 1 polygons[2], within management units on Crown Land. Stands may originate from natural disturbance or from harvesting.

3.2 Sample selection

Provincial CMI plot locations are based on Canada's National Forest Inventory (NFI) 20 km grid across the entire province. Therefore, some of the ground sample CMI plots coincide with NFI plots that FAIB is now responsible for managing. Sample selection for the Provincial CMI plots is based on an equal-probability systematic sample design. Either a photo plot or ground plot is established at every grid intersection. Since the target population is all land cover types over the entire province it is possible to estimate proportions of land cover, and land cover change.

Ground samples will be established on all grid points that are considered to be *productive* forest. The decision about whether a sample meets this criterion is determined based on a visual inspection of the sample location using the most recent imagery. If the sample is located in a marginally productive forested stand, then further assessment will be done using variables such as elevation, timber volume, amount of non-treed area, proximity to operable areas, road access and THLB. Ground samples will only be established in parks if they have road access. Ground samples will not be established on private land. Photo samples will be established on all the grid points that are not ground samples. High resolution DCS photos will be taken at all these points.

Provincial YSM plot locations are based on an intensification of the 20 km grid, generally 10 km easting by 5 km northing that fall within the defined population, but can be further intensified as needed. Occasionally, Provincial YSM plot locations coincide with the Provincial CMI plot locations on the 20 km grid. All three plot types (CMI, YSM and NFI) do coincide at some 20 km grid intersections, though this is a rare occurrence. Sample selection for the Provincial YSM plots is based on an equal-probability systematic sample design. Because the sample design depends on estimated stand age, Provincial YSM ground plots may enter and exit the target population when the VRI Phase 1 polygons are updated. This issue will not affect how point-in-time estimates are calculated. However, at each successive re-measurement, recruitment sample points entering the minimum age need to be added, and older sample points exceeding the maximum age may need to be dropped from the target population. This issue will affect how change estimates are calculated (Section 3.3).

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[1] The age is taken from the attribute "PROJ_AGE_1" with is the age of the leading species at the specified projection year.

[2] The spatial coverage originates from the posted Online version of the VRI VEGCOMP Poly Rank1 layer.

3.3 Sampling frequency

Provincial CMI and YSM are Periodic Continuous Forest Inventories (defined and discussed in Appendix 1). The planned remeasurement cycle for Provincial CMI plots is every 10-12 years and for Provincial YSM plots is every 5-7 years. With a total of 1594 ground sample Provincial CMI plots provincially, the implementation of this program is extremely realistic with approximately 160 ground plots to be measured annually.

3.4 Data collection

For both Provincial CMI and YSM, there is one nested circular plot per grid intersection (FAIB 2016d). Ground plot data collection protocol for both Provincial CMI and YSM are documented in FAIB 2016d. Photo plot data collection within Provincial CMI is based on VRI data collection standards (FAIB 2016e) and these standards will be updated for modifications that include photo interpretation at the Provincial CMI plot level.

Briefly,

- Parameter estimates include: total, total per hectare, average per tree, and proportion of area. Standard errors will be calculated for each.
- Forest attributes include: land cover (CMI), tree height, stand age, basal area, stems, gross volume, and net merchantable volume.
- Post-stratification classes (e.g., domains of interest) may include stand age classes, stand size classes, diameter classes, species, and forest type.
- Components of change include: survivor growth, ingrowth, cut, and mortality.

3.5 Precision requirements

The sampling error associated with a survey sample, such as a forest inventory, is the random error associated with an estimate and this error is due to sampling (Schreuder et al. 1993). Sampling error is also commonly known as the precision of the estimate or the standard error (Schreuder et al. 1993). Maximum allowable sampling error is commonly established as a precision requirement. In British Columbia, forest inventory precision requirements for timber sales are often set at 8% for cruise-based sales or at 15% for scale-based sales (Marshall and LeMay 2013). For VRI, precision requirements are not specified for individual strata; however they may be specified for combined strata at the 95% probability level (FAIB 2011).

For Provincial CMI and YSM, sampling errors and confidence intervals are calculated with a 95% probability level to maintain consistency with other FAIB programs (i.e., VRI).

4. Analysis

There are three objectives in analysis of Provincial CMI and YSM data: (4.1) point-in-time estimation, (4.2) change estimation and (4.3) quality assurance. For point-in-time estimation and change estimation, estimators are defined as the equations used to make an estimate of the target population for specific attributes. Due to the systematic sampling design, finite population correction factors in these estimators are unnecessary. See Penner and Omule (2012) as an example of CMI data analysis.

4.1 Point-in-time estimation

Point-in-time estimation refers to making an estimate for one specific point in time by using sample data collected within a specific time period. Forest inventory data collected in one year or over several years (e.g., two to three consecutive years) is often used to make point-in-time estimates. Combining data collected over four years should be approached with caution, since the estimates may not accurately reflect the state of the forest attributes for a single point in time.

4.1.1 Tree Attributes

Estimation of Totals, Means, etc.

Let y_i be an attribute on tree i and N be the total number of trees in the population. The unknown population total is $Y = \sum_i^N y_i$, and most parameters of interest are functions of this total. These include the total per ha, the average per tree, the proportion of trees with some characteristic, the ratio of two totals, etc. For example, the total number of trees, gross volume, and net merchantable volume are generally reported on a per ha basis, whereas diameter and height are presented as averages per tree. The following estimators are based on estimators in Chapter 7 of Gregoire and Valentine (2007).

An estimate of the population total per plot based on the jth ground sampled plot is:

$$\hat{Y}_j = A \sum_i^{m_j} y_i \left(\frac{I_i(\mathscr{s})}{a_{\mathscr{s}}} + \frac{I_i(m)}{a_m} + \frac{I_i(\ell)}{a_\ell} \right) = A \left[\sum_i^{m_j(\mathscr{s})} \frac{y_i}{a_{\mathscr{s}}} + \sum_i^{m_j(m)} \frac{y_i}{a_m} + \sum_i^{m_j(\ell)} \frac{y_i}{a_\ell} \right] \quad (1)$$

where A is the known total area of the population in ha, m_j is the total number of trees in the plot, y_i is the attribute associated with tree i, $I_i(\cdot)$ are binary variables indicating whether the tree is in the small ($\mathscr{s}$), medium (m) or large (ℓ) diameter class, $a_{\mathscr{s}}$, a_m and a_ℓ are the areas of the small, medium and large tree plots in ha, and $m_j(\mathscr{s})$, $m_j(m)$, and $m_j(\ell)$ represent the number of trees within jth small, medium and large tree plots respectively. Note that the small tree plot includes trees less than 4cm DBH and these trees are not part of the standard compilation. However, we include them here for completeness, as some data is collected on them, and they can easily be omitted if inference is focused on a subset of the population that excludes them; see upcoming section on post-stratification and domain estimation.

For photo-plots, $\hat{Y}_j$ is provided directly by the photo-interpreter based on the large tree plot only, and tree-level characteristics will rarely be available. Attributes provided as totals per ha (or means per tree, if applicable) need to first be converted to estimated totals before plugging into (2) below. For example, if the number (m) and mean height ($\bar{y}$) of trees in the photo-plot is provided, then an estimate of the population total per plot based on the jth photo sampled plot is:

$$\hat{Y}_j = \left(\frac{A}{a_\ell} m\right) \bar{y} \qquad (2)$$

Combining photo- and ground-plots, an overall estimate of the population total is:

$$\hat{Y} = \frac{1}{n} \sum_{j}^{n} \hat{Y}_j \quad (3)$$

where n is the total number of ground and photo plots. The variance of $\hat{Y}$ can be approximated conservatively with:

$$var\left(\hat{Y}\right) = \frac{\sum_j^n \left(\hat{Y}_j - \hat{Y}\right)^2}{n(n-1)} \qquad (4)$$

An estimate of the total per ha is:

$$\hat{y} = \frac{\hat{Y}}{A} \quad (5)$$

The variance of $\hat{y}$ can be approximated with:

$$var(\hat{y}) = \frac{var\left(\hat{Y}\right)}{A^2} \quad (6)$$

An estimate of the average per tree is:

$$\bar{y} = \frac{\hat{Y}}{\hat{N}} \quad (7)$$

where $\hat{N}$ is estimated from (1) and (2) using a value of "1" for each y_i amongst the n plots.

The variance of $\bar{y}$ can be approximated with:

$$var(\bar{y}) = \frac{1}{\hat{N}^2} \cdot \frac{\sum_j^n \left(\hat{Y}_j - \bar{y} \cdot \hat{N}_J\right)^2}{n(n-1)} \qquad (8)$$

Other ratios along with their variance, can be estimated analogous to (7) and (8).

For some parameters/attributes, the above estimators will reduce to familiar "textbook" equations.

For reporting purposes, one of two uncertainty estimates generally accompanies the estimate of the total or mean. First, an estimate of precision is the *standard error* which is calculated by:

$$\sqrt{var(\hat{Y})} \quad (9)$$

Eq. 9 demonstrates the standard error based on Eq. 4, but Eq. 9 can also be based on Eq. 6 ($var(\hat{y})$) or Eq. 8 ($var(\bar{y})$). Second, the *confidence interval* is an interval around the estimate of the total or mean that will include the true population parameter $100(1-\alpha)\%$ of the time (e.g. upon repeated samples of the population using the same sampling design). For the purposes of Provincial CMI and YSM, we set the level of significance $\alpha = 0.05$ and use $100(1-\alpha)\% = 95\%$ as our level of confidence. The confidence interval for the overall estimate of a population total is calculated by:

$$\hat{Y} \pm t_{n-1,\alpha/2}\sqrt{var(\hat{Y})} \qquad (10)$$

where $\alpha = 0.05$and $t_{n-1,\alpha/2}$ is taken from a table of critical values from Student's t distribution.

Standard errors and confidence intervals for the total per ha, the average per tree, and domain estimation are constructed in the same manner as in Eq. 9 and Eq. 10.

Post-stratification and domain estimation

In what follows, post-stratification is described by way of domain estimation. Domains are subsets of the population that were not targeted through the original sampling design. Further definition of a domain is found in Gregoire and Valentine (2007, p. 238). Domains can be defined at the tree-level (e.g. tree species), stand-level (e.g. leading species) or landscape-level (e.g. BEC zone).

For tree-level domains, such as tree species or a specific diameter class, an estimate of the domain total per plot based on the jth ground sampled plot is:

$$\begin{aligned}\hat{Y}_{dj} &= A\sum_{i}^{m_j} y_i \cdot I_i(d)\left(\frac{I_i(\mathscr{s})}{a_{\mathscr{s}}} + \frac{I_i(\mathscr{m})}{a_m} + \frac{I_i(\ell)}{a_\ell}\right) \\ &= A\left[\sum_{i}^{m_j(d,\mathscr{s})}\frac{y_i}{a_{\mathscr{s}}} + \sum_{i}^{m_j(d,\mathscr{m})}\frac{y_i}{a_m} + \sum_{i}^{m_j(d,\ell)}\frac{y_i}{a_\ell}\right] \qquad (11)\end{aligned}$$

where $I_i(d)$ is a binary indicator variable describing whether each tree is in d, and $m_j(d,\mathscr{s})$, $m_j(d,\mathscr{m})$, and $m_j(d,\ell)$ represent the number of trees in the domain within jth small, medium and large plots respectively.

Each domain d is estimated individually, and the total per domain is:

$$\hat{Y}_d = \frac{1}{n}\sum_{j}^{n} \hat{Y}_{dj} \quad (12)$$

For stand-level and landscape-level domains, all the trees in each nested plot are either inside or outside of the domain, so $\hat{Y}_{dj} = \hat{Y}_j \cdot I_j(d)$, where $I_j(d)$ indicates whether the plot is in d, and (9) still applies.

The variance of $\hat{Y}_d$ can be approximated with:

$$var(\hat{Y}_d) = \frac{\sum_j^n (\hat{Y}_{dj} - \hat{Y}_d)^2}{n(n-1)} \quad (13)$$

Note that some $\hat{Y}_{dj}$ could be zero in the above estimator. These zeros account for the random sample size in the domain by contributing added variation.

To put the estimated total on a per ha basis, we must know or be able to accurately estimate the horizontal area of the domain, say A_d. Note that this area could be identical to A for a domain such as a specific diameter class, or it could be a subregion of A, such as the horizontal area of a BGC zone. Provided with A_d an estimate of the domain total per ha is:

$$\hat{y}_d = \frac{\hat{Y}_d}{A_d} \qquad (14)$$

and its variance is estimated as:

$$var(\hat{y}_d) = \frac{var(\hat{Y}_d)}{A_d^2} \qquad (15)$$

In general, A_d will be unknown but can be estimated by pro-rating A by the proportion of trees or plots in the domain.

For the rare case where a domain is defined at the tree-level (e.g., soil type), this means using:

$$\hat{A}_d = \frac{1}{n}\sum_{j}^{n} \hat{A}_{dj} \qquad (16)$$

where

$$\hat{A}_{dj} = A\left(\frac{\frac{m_j(d,s)}{a_s} + \frac{m_j(d,m)}{a_m} + \frac{m_j(d,\ell)}{a_\ell}}{\frac{m_j(s)}{a_s} + \frac{m_j(m)}{a_m} + \frac{m_j(\ell)}{a_\ell}}\right) \quad (17)$$

For stand- or landscape-defined domains, this simplifies to:

$$\hat{A}_d = \frac{1}{n}\sum_{j}^{n} A \cdot I_j(d) = \frac{1}{n}\sum_{j}^{n} \hat{A}_{dj} = A\ \frac{n(d)}{n} \qquad (18)$$

where $n(d)$ is the number of plots in the domain.

Because $\hat{y}_d = \frac{\hat{Y}_d}{\hat{A}_d}$ is akin to a ratio estimator, its approximate variance is:

$$var(\hat{y}_d) = \frac{1}{\hat{A}_d^2} \cdot \frac{\sum_j^n \left(\hat{Y}_{dj} - \hat{y}_d \cdot \hat{A}_{dj}\right)^2}{n(n-1)} \qquad (19)$$

Per tree estimates $\bar{y}_d = \frac{\hat{Y}_d}{N_d}$ require N which will almost never be known. It can be estimated for tree-defined domains with:

$$\hat{N}_d = \frac{1}{n}\sum_{j}^{n} \hat{N}_{dj} = \frac{1}{n}\sum_{j}^{n} A\left(\frac{m_j(d,\mathscr{s})}{a_{\mathscr{s}}} + \frac{m_j(d,\mathscr{m})}{a_{\mathscr{m}}} + \frac{m_j(d,\ell)}{a_{\ell}}\right) \qquad (20)$$

and for stand- and landscape- defined domains:

$$\hat{N}_d = \frac{1}{n}\sum_{j}^{n} \hat{N}_{dj} = \frac{1}{n}\sum_{j}^{n} A \cdot I_j(d)\left(\frac{m_j(\mathscr{s})}{a_{\mathscr{s}}} + \frac{m_j(\mathscr{m})}{a_{\mathscr{m}}} + \frac{m_j(\ell)}{a_{\ell}}\right) \qquad (21)$$

Being a ratio, the approximate variance of $\bar{y}_d = \frac{\hat{Y}_d}{\hat{N}_d}$ is:

$$var(\bar{y}_d) = \frac{1}{\hat{N}_d^2} \cdot \frac{\sum_j^n \left(\hat{Y}_{dj} - \bar{y}_d \cdot \hat{N}_{dj}\right)^2}{n(n-1)} \qquad (22)$$

The above stand- and landscape-level domain ratio estimators and their variances often take familiar form. For example, say we are interested in net volume per ha $\hat{y}_d$, and define v_j as the estimated combined volume per ha for the jth nested plot. Of the original n plots, a subset of $n(d)$ plots are in the domain, and for this domain define the mean volume per ha as $\bar{v}_d = \frac{1}{n(d)}\sum_j^{n(d)} v_j$ and the squared standard deviation as $s_d^2 = \frac{\sum_j^{n(d)}\left(v_j - \bar{v}_d\right)^2}{n(d)-1}$. It's straightforward to show that $\hat{y}_d = \bar{v}_d$ and $(\hat{y}_d) = \left(\frac{n}{n(d)}\frac{n(d)-1}{n-1}\right)\frac{s_d^2}{n(d)} \cong \frac{s_d^2}{n(d)}$.

Likewise, define h_j as the estimated combined total height per ha and x_j as the estimated number of stems per ha respectively for the jth nested plot, with domain means $\bar{h}_d = \frac{1}{n(d)}\sum_j^{n(d)} h_j$ and $\bar{x}_d = \frac{1}{n(d)}\sum_j^{n(d)} x_j$. The natural estimate of the mean height per tree is

$\hat{r}_d = \frac{\bar{h}_d}{\bar{x}_d} = \frac{\sum_j^{n(d)} h_j}{\sum_j^{n(d)} x_j}$ and the squared standard deviation is $s_d^2 = \frac{\sum_j^{n(d)}\left(h_j - \hat{r}_d \cdot x_j\right)^2}{n(d)-1}$. It's straightforward to show that $\bar{y}_d = \hat{r}_d$ and $(\bar{y}_d) = \left(\frac{n}{n(d)}\frac{n(d)-1}{n-1}\right)\frac{s_d^2}{n(d)\cdot\bar{x}_d^2} \cong \frac{s_d^2}{n(d)\cdot\bar{x}_d^2}$.

4.1.2 Area Attributes: Estimation of Proportions

We may also be interested in estimating the proportion of the population's area falling into certain domains or post-strata. For example, situations may arise where VRI polygon data does not cover the entire target population or only coarse strata (i.e., BCLCCS level one or level two) are available for the target population. In these cases, there is still a need to provide estimates for the proportion of land cover at a more refined level (i.e., BCLCCS level four or level five). Further, the estimates of proportions at the refined level are needed per strata or domain (i.e., BEC zone, management unit, BCLCCS level one, etc.). The resultant proportion is a ratio of two totals: the estimated total area in in the refined domain (e.g. BCLCCS level one in the IDF zone) to the estimated total area in the broader domain (e.g. the IDF zone).

For purposes of this sampling framework, land cover class is associated with each large tree plot only, and the smaller tree plots are not considered. Let $\hat{A}_{dj}$ be the estimated area in domain d based on the jth plot:

$$\hat{A}_{dj} = A\frac{a_j(d)}{a_\ell}, \qquad (23)$$

where $a_j(d)$ is the area associated with the intersection of the domain(s) area and the large tree plot. If the domain is defined such that the entire plot must be inside or outside the domain, $\hat{A}_{dj} = A \cdot I_j(d)$. Likewise, let $\hat{A}_{dkj}$ be the estimated area in both class k and domain d based on the jth plot:

$$\hat{A}_{dkj} = A\frac{a_j(d,k)}{a_\ell}, \qquad (24)$$

or when the entire plot must be either inside or outside both k and d, $\hat{A}_{dkj} = A \cdot I_j(d,k)$. The proportion of area of class k within d is then:

$$\hat{p}_{dk} = \frac{\hat{A}_{dk}}{\hat{A}_d} = \frac{\frac{1}{n}\sum_j^n \hat{A}_{dkj}}{\frac{1}{n}\sum_j^n \hat{A}_{dj}} = \frac{\sum_j^n a_j(d,k)}{\sum_j^n a_j(d)} \qquad (25)$$

with approximate variance:

$$var(\hat{p}_{dk}) = \frac{1}{\hat{A}_d^2} \cdot \frac{\sum_j^n\left(\hat{A}_{dkj} - \hat{p}_{dk} \cdot \hat{A}_{dj}\right)^2}{n(n-1)} \qquad (26)$$

The estimated variance (26) simplifies to:

$$var(\hat{p}_{dk}) = \frac{s_d^2}{n \cdot \bar{a}_d^2} \qquad (27)$$

where $s_d^2 = \frac{\sum_j^n \left(a_j(d,k) - \hat{p}_{dk} \cdot a_j(d)\right)^2}{n-1}$ and $\bar{a}_d = \frac{1}{n}\sum_j^n a_j(d)$.

For domains with coarser resolution, $\hat{A}_{dj} = A \cdot I_j(d)$ and $\hat{A}_{dkj} = A \cdot I_j(d,k)$, so

$$\hat{p}_{dk} = \frac{\hat{A}_{dk}}{\hat{A}_d} = \frac{n(d,k)}{n(d)} \qquad (28)$$

and the approximate variance (26) simplifies to:

$$var(\hat{p}_{dk}) = \frac{\hat{p}_{dk}(1 - \hat{p}_{dk})}{n(d) - 1}\left(\frac{n}{n(d)} \frac{n(d) - 1}{n - 1}\right) \cong \frac{\hat{p}_{dk}(1 - \hat{p}_{dk})}{n(d) - 1} \qquad (29)$$

4.1.3 Linkage

To clarify the usage of estimators, Table 1 specifies the population or domain estimator to use for each combination of population parameter and attribute of interest.

Table 1. Point-in-time estimators to use for specific attributes of interest.

Population parameter	**Attribute of interest**	**Population estimator**	**Domain estimator**
Total	Gross volume, net merchantable volume, stems	Eq. 3	Eq. 12
Total per ha	Basal area, gross volume, net merchantable volume, stems	Eq. 5	Eq. 14
Average per tree	Height	Eq. 7	Eq. 16
Proportion	Land cover	Not estimated	Eq. 24

4.2 Change estimation

Estimation of changes in attributes (i.e., land cover, volume, etc.) will account for changes between the most current inventory and the previous inventory (e.g., one time period). It may be that either one or both inventories are spread over several years (i.e., 2003-2005 and 2013-2015). In this case, the estimate of change reflects the overall change between the two periods and not the specific years. However, it is assumed that the specific plots would be remeasured and that the changes are computed directly from tree-level or plot-level changes.

4.2.1 Net change

The net change between time 1 and time 2 is:

$$\hat{\Delta}_{Y_{net}} = \hat{Y}_2 - \hat{Y}_1 \qquad (30)$$

where $\hat{Y}_2$ is the estimate of an attribute at time 2, $\hat{Y}_1$ is the estimate of an attribute at time 1 (Gregoire 1993). $\hat{Y}_2$ and $\hat{Y}_1$ can be calculated using the appropriate population or domain estimators in Table 1. Net change of area attributes should focus on broad classes only (e.g., BCLCCS Level 2). When net change for gross volume, net merchantable volume, and stems (and biomass, if applicable) for the overall population is required, then it is necessary to use both photo and ground plots with Eq. 30. However, when net change can be estimated for specific domains of interest where tree-level remeasurements are available, net change will be calculated from the components of change (next section).

When all photo- and/or ground-plots are remeasured, an estimate of the variance for $\hat{\Delta}_{Y_{net}}$ is:

$$var\left(\hat{\Delta}_{Y_{net}}\right) = var\left(\hat{Y}_2\right) + var\left(\hat{Y}_1\right) - 2cov\left(\hat{Y}_2, \hat{Y}_1\right) = \frac{\sum_j^n \left(\hat{\Delta}_{Y_{net\,j}} - \hat{\Delta}_{Y_{net}}\right)^2}{n(n-1)} \qquad (31)$$

where $cov\left(\hat{Y}_2, \hat{Y}_1\right)$ is the estimated covariance between the two estimators and $\hat{\Delta}_{Y_{net}} = \frac{1}{n}\sum_j^n \hat{\Delta}_{Y_{net\,j}}$.

Eq. 31 is readily modified for domain estimation by including the subscript. Standard errors and confidence intervals for net change can be calculated using Eq. 9 and Eq. 10.

4.2.2 Components of change

Components of change are equivalent to estimating change within specific domains, defined by sub-groups of trees. Components of change will only be applied to ground plots measured at both time 1 and time 2. This will generally coincide with ground plots on the THLB. There are many variations on the components of change (i.e., Therien 1999, Scott et al. 2005). However, Provincial CMI and YSM change analysis will focus on the following four basic components of change between time 1 and time 2:

> S = survivor growth, volume growth on individual trees that are at or above minimum DBH and measured at time 1 and survive to time 2.
>
> I = ingrowth, volume growth on individual trees from the minimum DBH threshold (for the relevant nested ground plot size) to time 2 when they are above the minimum DBH threshold.
>
> C = cut, the volume of individual trees that are at or above minimum DBH and measured at time 1, and cut by remeasurement at time 2. It is assumed that C trees were cut immediately after the time 1 measurement.

M = mortality, the volume of individual trees that are at or above minimum DBH and measured at time 1, and die from natural causes by remeasurement at time 2. It is assumed that M trees died immediately after the time 1 measurement.

Each component (S, I, C, M) is treated as a domain where each remeasured tree in the inventory is classified per the relevant component. As such, estimators listed in Table 3 also apply to the components. The variance for the components cannot be calculated by Eq. 31 because not all trees are remeasured (e.g., I, C, M); therefore, the variance of each component can be calculated from variance estimators relevant to domain estimation (e.g., Eq. 13). Change in stems is calculated for I, C and M but not S. In all cases where a tree grows across a DBH threshold, the sampling weight (e.g., plot size) associated with time 1 is used to streamline analysis. This is referred to as the Beers-Miller estimator (Scott et al. 2005, p.63).

The net change between time 1 and time 2 is calculated from the components of change by:

$$\Delta_{Y_{comp}} = S + I - C - M \qquad (32)$$

One desirable characteristic of change estimation is achieved if $\Delta_{Y_{comp}} = \Delta_{Y_{net}}$ (Gregoire 1993). When $\Delta_{Y_{comp}} = \Delta_{Y_{net}}$, then $\Delta_{Y_{comp}}$ is said to be additive. However, the Beers-Miller estimator for $\Delta_{Y_{comp}}$ is not necessarily additive because sampling weights at the tree-level stay the same for time 1 and time 2. The need to achieve additivity depends on the information desired, complexity of the inventory, and the types of change possible. If additivity is required, then other tree-level information may be needed (e.g., distance and azimuth to each tree from the ground plot center).

4.2.3 Issues with components of change

1. For Provincial YSM, there are issues in ground plots that enter and exit the target population at time 2 due to the target population definition in 3.1. In this case, it is necessary to use a subset of Provincial YSM data.
2. It is possible that ground plots measured in the THLB at time 1 could be converted to other land uses outside the THLB at time 2 (e.g., road construction, urbanization or suburbanization, etc.). This is generally known as diversion. In the case of diversion, ground plots will be removed from analysis for the components of change because the focus is on changes within the THLB, not the component changes between THLB and other classes.
3. It is possible that individual trees characterized as net merchantable volume at time 1 may be characterized as gross volume at time 2 per the ground plot data (e.g., onset of forest health incidence). In this case, the tree will remain as net merchantable volume at time 2 for analysis purposes. The statistical properties of the estimator will remain unbiased, but this will have the effect of reducing the S component of growth.

4.3 Quality assurance

Currently, there are precisely defined standards for contractors collecting data for both aerial photo interpretation and ground sampling. In some cases, information needs may require improved precision when too few samples are available. For example, some strata may have too few Provincial CMI plots for an acceptable estimate. If other data are available, it is possible to combine data across inventories for improving precision. To combine data from separate inventories, refer to estimators and methods in Halperin and LeMay 2016.

5. Conclusion

This sampling framework is intended to help guide FAIB and other stakeholders involved in analysis and use of forest inventory information in BC. This framework facilitates discussions around forest inventory as a means to providing information for sound natural resource decision making. The purpose of this sampling framework is to provide context for the statistical background in collecting and analysing Provincial CMI and YSM data. Further, this framework targets a set of core forest attributes for analysis and reporting that are normally assessed in forest inventory and monitoring. This framework forms a living document that can and should be updated over time in response to changing information needs. For example, refinements to the estimators may be needed given new strata information, or additional estimators may need to be included. Inclusion of new auxiliary data (e.g., LiDAR) could be integrated into the inventory and could require additional estimators. We hope to make this framework transparent, robust, and flexible in its ability to respond to future changes.

In the future, it could be interesting to conduct a double sampling approach where a photo is collected at every 20 km grid intersection for the purpose of estimating land cover/land use class, according to the BC Land Cover Classification Scheme (which is also used in the VRI Phase 1 photo interpretation). Then, Provincial CMI ground-based plots are established to provide field measurements at all vegetated, treed (classification scheme level 2) plots located on Crown Land, but not in Provincial Parks.

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Appendix 1

Sampling frequency is the time period between measurements of sample plots. Three types of inventories can be defined according to sampling frequency (Scott 1998). The first type of inventory is comprised of temporary, independent samples. The second type is a Continuous Forest Inventory (CFI) of permanent sample plots. The third type is labeled as Sampling with Partial Replacement (SPR). An inventory of temporary, independent samples is not efficient (i.e., high variance; Schreuder et al. 1993) and does not apply to either Provincial CMI or YSM; therefore, this type of inventory is not further considered.

A CFI utilizes permanent sample plots where all sample locations are remeasured at subsequent visits and there are two versions of a CFI (Scott 1998). The first version is known as a <u>periodic inventory</u> that collects measurements over specific, discrete geographic areas (i.e., TSA) within the target population and at certain points in time (Scott et al. 1999). Even if a periodic inventory may take two or possibly three years to complete measurements over the geographic area, it is still considered as a certain point in time. After a regular interval (five or ten years are common choices), the periodic inventory then returns to the same geographic area to conduct remeasurements. The second version of a CFI is known as an <u>annual inventory</u> that collects measurements over a percentage (i.e., 10% or 20%) of the samples from the entire target population every year (Scott et al. 1999).

SPR combines remeasurements from permanent sample plots with measurements from temporary sample plots (Scott 1998). The permanent sample plots facilitate estimation of change, while the temporary sample plots help to maintain a representative sample of the target population at the current inventory. SPR can be a useful framework for forest inventory because it provides efficient estimates of current attributes and change (Scott 1998).

There are advantages and disadvantages that apply to the periodic CFI, the annual CFI, and SPR, and these are thoroughly documented in Scott (1998), Scott et al. (1999), and Bechtold and Patterson (2005, chapter 5). In a periodic CFI, travel costs are minimized when compared to an annual inventory. SPR does not apply to Provincial CMI since it does not intend to measure temporary plots. Because of these factors, Provincial CMI is currently intended to be implemented as a periodic CFI.

In the Provincial YSM program, not all sample locations are remeasured at subsequent visits due to the specific goal, objectives, and definition of the target population. The target population is based on VRI Phase 1 polygon stand ages which may/will change at each remeasurement period; therefore, samples may/will be selected and dropped as well. Sampling with Partial Replacement (SPR) does not apply to this scenario even though temporary samples are included with permanent samples. SPR does not apply to Provincial YSM because SPR assumes that the target population does not change from one measurement to the next, which is the case for Provincial YSM. The annual CFI does not apply to Provincial YSM since samples will not be measured each year. The periodic CFI also does not apply, at least directly, since it assumes that all samples are remeasured at each time period.

However, the targeted sampling frequency for Provincial YSM is five years (Omule 2013). There is a possible, simple solution in which to consider Provincial YSM as a periodic inventory. First, the sample selection from the changing target population can continue as planned, where analysis of the data as described in Omule (2013) is still the primary goal. Second, point-in-time estimates of forest attributes can use all of the samples at the current measurement period. Third, change estimates of forest attributes can utilize only those samples measured at both the current and most previous times. Under this scenario, proper determination of the sample weights will be crucial for avoiding bias. The sampling weights can correctly be determined by calculating the area of the polygon intersections between the two measurement times.

Two assumptions are needed to facilitate this scenario of estimating change utilizing Provincial YSM data. First, it is assumed that proper handling of the spatial polygon data in a GIS will be taken into consideration. Second, it is assumed that the information needs pertain to change within stand ages between 15 and 50 years old, and not change for stands that became at least 15 years old at the time of remeasurement or became older than 50 years old. The change being estimated is the change for stands between 15 and 50 years old at both measurement times (Table A1).

Table A1. Provincial YSM plots used for point-in-time estimates at time 1 and/or time 2, and change between time 1 and time 2. Stand age based on VRI Rank 1 Phase 1 polygon stand age. This table assumes that there is an updating of VRI Rank 1 Phase 1 polygons by time 2. The updating could be reassessment of all polygons or accounting of depletions.

		Time 2		
	Stand age	< 15	15 – 50	> 50
Time 1	< 15	**Not in target population[1]**	**Point-in-time estimate for time 2 (not measured at time 1)**	**Not in target population[4]**
	15 - 50	**Point-in-time estimate for time 1 (not measured at time 2)[2]**	**Point-in-time estimate for time 1** **Point-in-time estimate for time 2** **Estimate of change between time 1 and time 2**	**Point-in-time estimate for time 1 (Possible point-in-time estimate for time 2 and change)**
	> 50	**Not in target population[2]**	**Point-in-time estimate for time 2 (not measured at time 1)[3]**	**Not in target population[5]**

1. Stand age too young
2. Harvested or disturbed at time 2
3. Error correction of VRI Rank 1 Phase 1 polygon stand age estimate from time 1; or, harvested or disturbed between time 1 and time 2, then estimated VRI Rank 1 Phase 1 polygon stand age of 15-50
4. This can probably only happen if a VRI Rank 1 Phase 1 polygon stand age error at Time 1 is corrected by Time 2
5. Stand age too old

🟥	Not used for Provincial YSM estimates (but could be measured for other purposes)
🟩	Measured and used for Provincial YSM estimates at time 1 and time 2, and YSM change
🟨	Measured and used for point-in-time Provincial YSM estimates at time 1 or time 2
🟧	Measured and used for point-in-time Provincial YSM estimates at time 1; if measured at time 2, could also be used for point-in-time Provincial YSM estimates at time 2 and for Provincial YSM change