Using Line Intersect Sampling for Coarse Woody Debris

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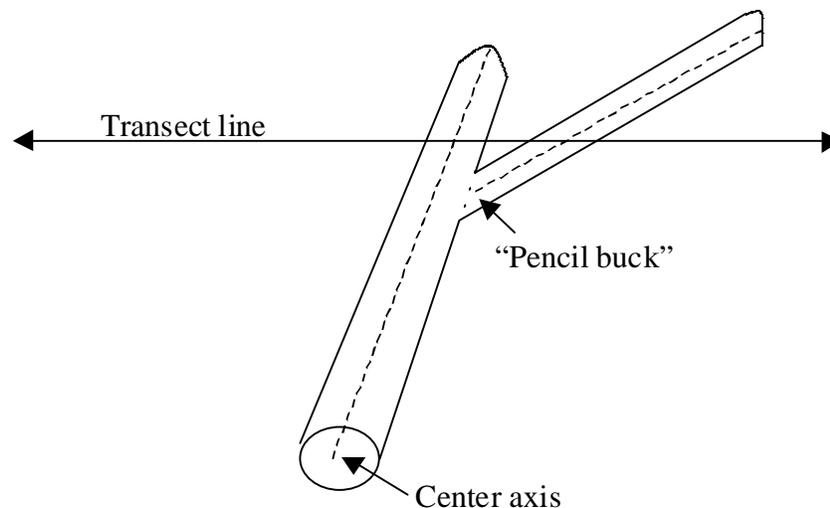
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CONTENTS

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ABSTRACT

Coarse woody debris (CWD), i.e., downed dead wood, is an important structural component of forest and stream ecosystems, and is linked to both biodiversity and ecosystem processes. In response to the growing recognition of the ecological importance of CWD, and to the need for quantitative data to guide forest management practices, there is increasing interest in sampling methods. Various methods exist for sampling CWD; however, line intersect sampling (LIS) is probably the most common technique currently in use.

Much of the published literature on LIS falls under the topic areas of field procedures or research. While LIS theory and the background to commonly used formulas are formally covered in certain statistical textbooks, it is difficult and time consuming for the field practitioner to review, integrate, and apply published information about LIS to new and existing projects. The purpose of this Technical Report is to provide an integrated overview of information on LIS for field practitioners who are in the initial stages of designing a sampling program, or who are interested in the theory from a compilation perspective. This report is not intended as a field procedures manual, but it does answer some of the more commonly asked field-related questions.

This report:

1. Briefly describes the field-sampling requirements for LIS.

2. Explains the theory underlying LIS for round pieces, semi-round pieces, and odd-shaped pieces and accumulations of CWD.

3. Provides basic formulas for estimating various CWD parameters.

4. Relates field-sampling requirements and commonly asked field questions to the underlying sampling theories for round pieces, semi-round pieces, and odd-shaped pieces and accumulations of CWD.

KEYWORDS

line intersect sampling, LIS, coarse woody debris, CWD, forest ecology, sampling methods

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1 INTRODUCTION

• Coarse woody debris (CWD) is an important structural component of forest and stream ecosystems, and is linked to both biodiversity and ecosystem processes. In BC, CWD is most often defined as downed dead wood, which includes sound and rotting logs and uprooted stumps.

Coarse woody debris (CWD) is an important structural component of forest and stream ecosystems, and is linked to both biodiversity and ecosystem processes. Specifically, CWD provides habitat for a broad range of organisms, it plays a key role in energy flow and nutrient cycling, and it can influence soil and sediment transport and storage in streams. While CWD management in British Columbia (BC) is a legislative requirement under the Forest Practices Code, little quantitative data have been gathered, from either managed or unmanaged BC forests. In response to the increasing recognition of the ecological importance of CWD, and to the need for quantitative data to guide forest management practices, there is growing interest in sampling methods.

In BC, CWD is most often defined as downed dead wood, which includes sound and rotting logs and uprooted stumps. It is usually described as dead, non-self-supporting, woody material in various stages of decomposition, located above the soil.[1] While a minimum diameter of 10 cm is commonly used to separate CWD from fine woody debris, this parameter may vary with study objectives. In some cases CWD is defined based on minimum piece diameter and length (e.g., >10 cm and >1.5 m).

• Various methods exist for sampling CWD; however, line intersect sampling (LIS) is probably the most common technique. LIS designs vary widely in some key aspects, depending on the study objectives; however, there is a common set of field measurements and analyses based on a shared underlying theory.

Various methods exist for sampling CWD; however, line intersect sampling (LIS) is probably the most common technique. LIS involves measuring specific attributes of CWD pieces that are crossed by line transects established on an area. LIS designs vary widely in some key aspects, depending on the study objectives; however, there is a common set of field measurements and analyses based on a shared underlying theory. In BC, LIS is the sampling method used to measure CWD within the BC Ministry of Forests' Vegetation Resources Inventory (VRI) (see BC Ministry of Forests 1999) and fire protection programs.

• The purpose of this Technical Report is to provide an integrated overview of information on LIS for field practitioners who are in the initial stages of designing a sampling program, or who are interested in the theory from a compilation perspective.

Much of the published literature on LIS falls under the topic areas of field procedures or research. While LIS theory and the background to commonly used formulas are formally covered in certain statistical textbooks, it is difficult and time consuming for the field practitioner to review, integrate, and apply published information about LIS to new and existing projects. The purpose of this Technical Report is to provide an integrated overview of information on LIS for field practitioners who are in the initial stages of designing a sampling program, or who are interested in the theory from a compilation perspective. This report is not intended as a field procedures manual, but it does answer some of the more commonly asked field-related questions.

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3. Provides basic formulas for estimating various CWD parameters.
4. Relates field-sampling requirements and commonly asked field questions to the underlying sampling theories for round pieces, semi-round pieces, and odd-shaped pieces and accumulations of CWD.

While estimating volume/ha is the focus of the report, the application of LIS for estimating other parameters (e.g., number of pieces/ha) is also discussed.

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[1] CWD includes rotting wood under moss if the shape of the log is obvious.

The report is organized into seven sections. Section 2 briefly touches on study objectives. Section 3 discusses some of the practical aspects of implementing LIS in the field. Section 4 presents the theory underlying LIS, including developing general estimates, the special case of volume estimation, and formulas for estimating other CWD parameters. Section 5 describes the theory underlying field measures for odd-shaped pieces and accumulations. Section 6 contains formulas for combining the results from more than one transect on an area and for constructing confidence intervals for these combined estimates. Section 7 contains a list of additional reading.

Figure 1 is a flowchart of the various activities involved in conducting LIS, including references to appropriate sections in the text. A list of the abbreviations used in the equations appears in Appendix I. Appendix II is a worked example for volume, density, and projected area estimates. The bullets in the margins of the report highlight key issues discussed in each section.

2 Study Objectives

- Establishing clear study objectives is essential to developing an efficient design for sampling CWD. The sampling design should strike a balance between short-term study objectives and longer term goals related to inter-study comparisons.

Establishing clear study objectives is essential to developing an efficient design for sampling CWD. The study objectives determine the level of detail used in examining CWD at a given site. Further, they direct sample design issues related to: selecting site and stand types, within-site stratification, sampling intensity, shape and length of sampling unit, CWD classes, CWD measurements, and data analyses.

The sampling design should strike a balance between short-term study objectives and longer term goals related to inter-study comparisons. Data collected in a manner that permits inter-site and inter-study comparisons are most useful.

Many of the sampling design issues listed above are discussed in the following pages with respect to the underlying LIS theory. While alternative approaches to layout and measurement are legitimately used in the field as cost and/or time savers, adoption of these approaches must carry with it an understanding and acceptance of the potential errors within the context of the specific study objectives.

3 BASICS OF FIELD SAMPLING

This section provides a brief overview of many of the common issues related to field sampling using LIS. It is not intended to be all encompassing, nor to be used as a field manual. A few field manuals are listed in Section 7.

3.1 Determining Shape, Length, and Number of Transects

Transect Shape

- Each line transect, irrespective of shape or length, represents a single sampling unit. Line transect shape and length depend on the sampling protocol.

Each line transect, irrespective of shape, represents a single sampling unit comprised of a number of CWD pieces. This idea is similar to sampling the volume of standing trees using a fixed-area plot, where each plot provides a single sample comprised of a number of trees. The shape and length of a line transect will vary depending on the protocol employed. For example, a triangle with three 30-m lines (i.e., a 90-m transect) is often used for determining fuel loading prior to a prescribed burn, while an L-shaped transect with two 24-m lines (i.e., a 48-m transect) is used in the VRI.

The spatial distribution of CWD pieces on an area is usually clumped. This means that line transect shapes that sample a larger area from a given

PLANNING

```
                              Project Objectives (2.0)
                                       ↓
                     Shape, Length, & Number of Transects (3.1)
                                       ↓
                          Locating Line Transects (3.2)
                                       ↓
                             Classifying Pieces (3.3)
```

FIELD MEASURES

```
   Round, Semi-Round,                          Odd-Shaped Pieces,
   or Odd-Shaped Pieces                         & Accumulations

          ↓         ← Horizontal Transect Length (m) (3.1) →         ↓

   Diameter or                                   Height & Width
   Height/Width for    ← Cross-Sectional →           (cm)
   Semi-Round or          Area (3.4.2)
   Odd-Shaped
   Pieces (cm)

          ← ─ ─ ─ ─ Piece Angle (°) (3.4.1)
          ← ─ ─ ─ ─ Piece Length (m) (3.4.3)
          ← ─ ─ ─ ─ Other (species, density, etc.) (3.4.4) ─ ─ ─ →
          ↓                                                        ↓
```

COMPUTATIONS

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   Standard LIS                                  Theory Based on
   Theory (4.0)                               Rectangular Areas (5.0)
          ↓                                              ↓
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PARAMETERS

```
   Volume/ha: by diameter, length, decay class        Volume/ha
   Pieces/ha: by diameter, length, decay class        Biomass/ha
   Biomass/ha: by diameter, length, decay class    Projected area/ha
   Projected area/ha: by diameter class
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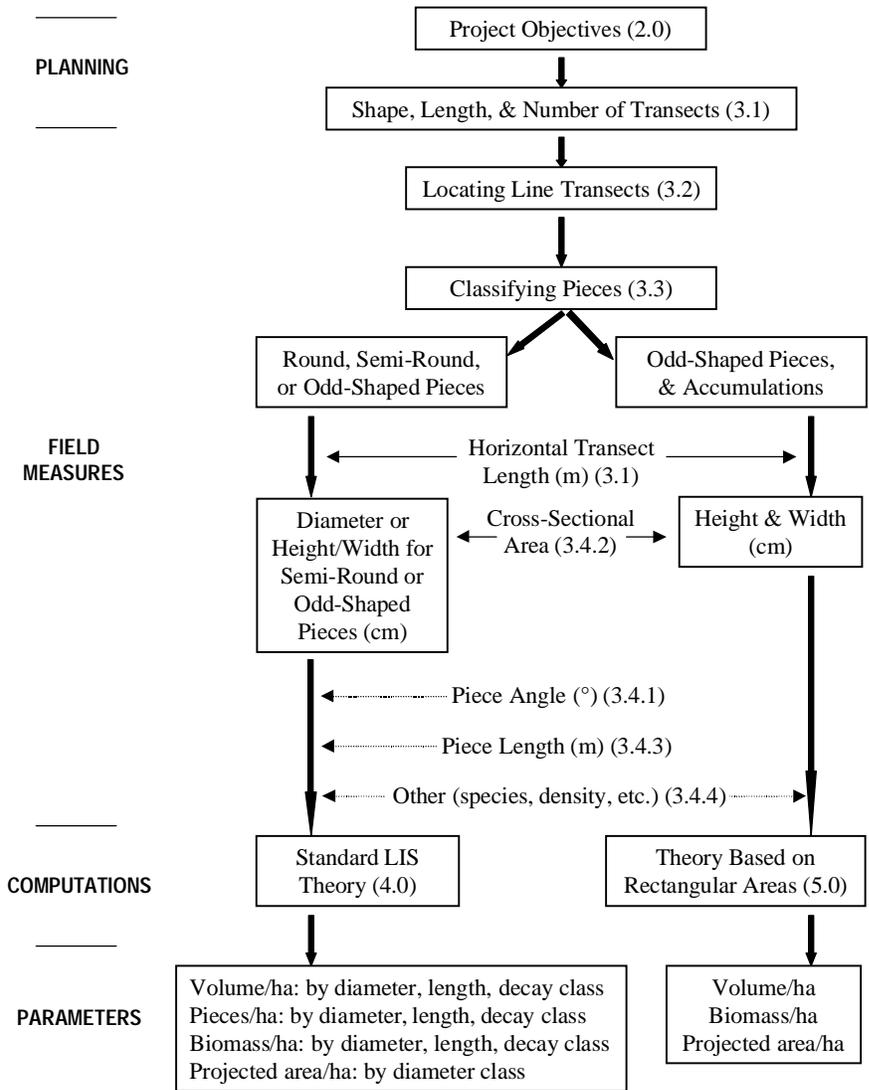
Figure 1. Flowchart of activities for conducting line intersect sampling (LIS) of coarse woody debris (CWD). Numbers in brackets refer to sections of text in this report.

sampling point (e.g., a 30-m straight line) are likely to capture more information than some other shape (e.g., a star comprised of six 5-m lines or a triangle comprised of three 10-m sides). However, the time required to complete the measurements on a line transect may be slightly shorter for a transect shape that brings the field crew back to the starting point (e.g., a triangle). This becomes more important as the length of the line transect increases (Figure 2).

Transect Length

The variability of a CWD variable (e.g., volume of CWD per unit area) depends on the length of the line transects. In general terms, the longer each individual line transect is, the smaller the variability will be among lines. It follows that the longer the line transect is, the fewer line transects that need to be established to achieve a given sampling error level. However, longer line transects require more time to establish and require more

CWD pieces to be measured than shorter transects. Hence, the time (and cost) per line is increased with longer lines. A larger number of shorter transects can be sampled in the same time as a smaller number of longer transects.

The trade-off between fewer longer transects and more shorter transects has been examined in a number of studies (see, for example, Hazard and Pickford 1984 and Pickford and Hazard 1978, in Section 7). The consensus is that the total length of the line transects established over an area has much more impact on the overall precision of an estimate than how many individual line transects contribute to that length. For example, a total of 1000 m of line transects established on an area could be comprised of twenty-five 40-m or forty 25-m line transects. The precision of estimates from both of these samples should be similar. However, this relationship breaks down at the extremes. For example, it is unlikely that the precision and efficiency associated with a sample of two 500-m transects would be similar to those found for a sample of one-thousand 1-m transects located on the same area. Also, a small increase in sample size can considerably reduce confidence interval widths when the sample size is small (e.g., less than 10 sampling units) because the variance estimates increase in precision rapidly with increases in sample size when sample sizes are small.

Transect length as discussed above refers to the horizontal length measured in metres. To obtain an unbiased estimate, the horizontal transect length must be known. Preferably, all transects should be corrected for slope in the field so that all transects are of equal horizontal length. This simplifies the compilation and subsequent analyses.

Number of Transects

If the sampler has a good estimate of the population variability (or the coefficient of variation) associated with the size and shape of line transect for an area in question, it is possible to estimate the number of line transects required to achieve, on average, some pre-established level of precision. The level of precision is usually expressed as a percentage of the estimated value (percentage error), or in absolute terms (sampling error). The sample size formula depends on the sampling design used to locate the line transects

- The overall precision of CWD estimates is much more affected by the total length of line transects on an area than by how many individual line transects contribute to that length, except at very small sample sizes (e.g. <10) or very short line lengths (e.g. <2 m). There is a balance between area coverage, sampling time, and good estimates of within-area variability.

- Horizontal transect length must be known to get an unbiased estimate. Correcting for slope in the field simplifies computations.

- A good estimate of the population variability associated with the size and shape of line transect can be used to estimate the number of line transects required to achieve some pre-established level of precision, on average. However, sample sizes determined in advance of sampling do not guarantee that a pre-established level of precision will be achieved.
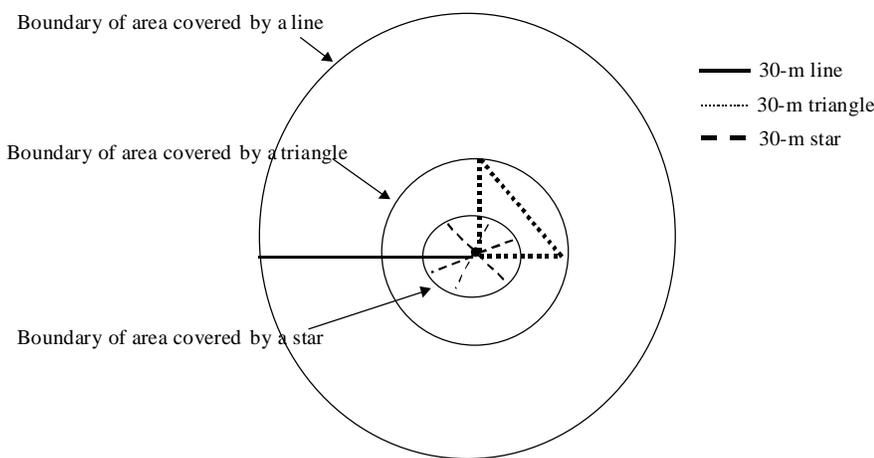

Figure 2. Area potentially covered by different shapes of line transects.

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on the area; the formula appropriate for simple random sampling is given in Section 5.1. This formula is also frequently used for systematic sampling.

Several cautions regarding sample size determination should be taken into account. Sample sizes that are determined in advance of sampling do not guarantee that a pre-established level of precision will be achieved by any given sample. Even when a good estimate of population variability is used in the sample size formula, only about half of the possible samples of size *n* that could be taken will result in estimates that achieve the precision level desired. Most of the time we do not know whether the estimate of population variability used is unbiased. In this situation, we cannot even rely on the probability statement made above. Various procedures exist for increasing the probability of achieving a pre-established level of precision; however, details on these procedures are beyond the scope of this report. See the paper by Marshall and others (1992) listed in Section 7 for details.

- The population variability among LIS transects is often quite high. Ensure that the sample size needed to achieve a pre-established level of precision is practical, given budgetary and personnel limitations, before committing to achieve that precision.

The population variability among LIS transects is often quite high due to the usual clumped distribution of CWD. This is especially true if shorter line transects are used or if larger-sized CWD pieces are targeted. It is best to ensure that the sample size thought to be necessary to achieve a pre-established level of precision is practical, given budgetary and personnel limitations, before committing to achieve that precision.

3.2 Locating Line Transects

Sometimes the location of line transects is covered by the protocol of other, more comprehensive sampling schemes (e.g., the VRI). However, when existing protocol does not specify the procedure to follow when locating line transects, the sampler must decide how to locate line transects over the area of interest.[2]

- Sample points are located, rather than line transects. The sample point represents a designated position on the line transect. In most cases the sample point is the end of the line transect, and it is where the measurements are started.

Technically, the sample points are located, not the line transects. The sample point represents a designated position on the line transect. In most cases the sample point is the end point of the line transect, and it is where piece measurements are initiated. Once a sample point is located, the line transect is installed following a specified routine.

- If existing protocol does not specify the procedure to follow when locating line transects, the sampler must decide how to locate line transects. Most commonly, systematic sampling with a random start is used, with the same spacing between sampling points within a row as between rows. Spacing between sampling points depends on the size of the area and the sample size desired.
- The location of the first sample point must be randomly selected.

Sample points may be randomly or systematically located. Most commonly, a systematic procedure is used to locate the sample points to help ensure complete coverage of the area of interest and to reduce on-site travel by the field crew. However, to ensure objectivity, the location of the first sample point must be randomly selected after the appropriate sample point spacing has been established.

Sample points are most often established in a square grid to give equal area coverage in all directions. Using a square grid, the distance (in metres) between sample points is determined as:

$$d = \sqrt{\frac{A}{n}}$$

where A is the size of the area being sampled in m^2 and *n* is the number of sample points.

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[2] An "area of interest" depends on the study objectives, as does the treatment of features within the area of interest. Depending on the study objectives, some features may be included, excluded, or sampled as separate strata. For example, an area of interest may be defined as including everything within the boundaries of a clearcut except such things as swamps, roads, wildlife tree patches, etc. See Figure 11.

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It is possible to deviate from a square grid (e.g., by having sample points closer together within a line than between lines). This is sometimes used to reduce the distance travelled on a site by a field crew, but this efficiency is gained at the cost of poorer coverage of the area being sampled.

The theory underlying LIS assumes that CWD pieces are randomly oriented with respect to the line transects. Because this cannot be assured, by the orientation of the CWD pieces on the ground, line transects must be randomly oriented in the field.

• Line transects must be randomly oriented in the field.

3.3 Classifying CWD Pieces

CWD classes must be established prior to field sampling to best address the range of piece shapes on the area to be sampled. Pieces are classified because different cross-sectional shapes require different field measures in order to obtain good estimates of piece volume. CWD pieces are most frequently classified as follows:

1. Round or semi-round in cross-section.
2. Some other cross-sectional shape (odd-shaped pieces).
3. CWD accumulations.[3]

In some applications (e.g., the VRI), accumulations are treated similarly to odd-shaped pieces and the classes are combined.

• It may be necessary to classify CWD pieces to improve estimates of volume/ha. Pieces in the different classes will require different field measures and formulas.

Clear rules are required to determine how pieces are classified. While the absence of clear rules will not bias the estimate of the CWD volume/ha, it may result in less precise estimates of volume for some pieces than if the pieces were properly classified, and consequently a less precise estimate of total volume/ha. Further, consistency among crews will be poor. Consistency is important if the results are to be compared across a range of sites or conditions.

• Clear rules are needed to classify pieces. This will ensure consistency. Inconsistency in classifying pieces will not lead to bias, but it may result in less accurate estimates of volume/ha and may complicate comparisons among areas.

Section 4 explains the theory behind LIS for round pieces, semi-round (oval- or half-moon-shaped[4]) pieces, and odd-shaped pieces, where the diameter or an "equivalent" diameter of a circle has been estimated from the cross-sectional area of the odd-shaped piece. The theory underlying the rectangular area approach to estimating the volume/ha of odd-shaped pieces or accumulations is covered in Section 5. Each class requires separate parameter estimates (e.g., volume/ha). The estimate of the total volume/ha of CWD is the sum of the estimates for each group, as discussed in Section 6.

• Estimates of total volume/ha are made separately for each class. Classes may be combined to give an overall estimate of total volume/ha.

3.4 CWD Piece Measurements

How and which CWD measurements are collected depend on the CWD class and the project objectives. Table 1 summarizes the piece attributes that must be measured in order to estimate the CWD parameters of interest. In all cases, the line transect must cross the center axis of the individual piece or group of pieces in order for the piece or group of pieces to be tallied.

To estimate total volume/ha of round or semi-round pieces, the following two attributes must be measured: 1) diameter, or "equivalent" round diameter, perpendicular to the center axis of the piece at the point the line

• To estimate total volume/ha of round or semi-round pieces, the following two attributes must be measured:

  1. Diameter, or "equivalent" round diameter, perpendicular to the center axis of the piece at the point the line transect crosses.

  2. The angle of the piece from horizontal.

  Several other parameter estimates (e.g., pieces/ha, average piece length) require the length of each piece to be measured.

• To estimate total volume/ha of odd-shaped pieces or accumulations, the height and width of the rectangle formed along the plane where the line transect crosses the piece are measured.

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[3] Depending on the study objectives, fixed-area plots are sometimes used to determine the volume of accumulations of CWD. If that is the case, it is appropriate to use volume-estimation procedures like those detailed by Little (1982).

[4] Technically, oval- and half-moon-shaped pieces are odd-shaped. However, in the field it is fairly easy to calculate the diameter of a circle of equivalent cross-sectional area. They are therefore often treated similarly to pieces that are round in cross-section.

Table 1. Summary of measurements required for estimating various CWD parameters.

Parameters, by CWD class	Piece attributes							
	Transect length (m)	Species	Piece angle from the horizontal (degrees)	Piece diameter (cm)	Rectangle length and width (cm)	Piece length (m)	Piece decay (Class)	Piece density (g/cm^3)
Round or semi-round pieces								
Total volume (m^3/ha)	x	x	x	x				
Volume, by diameter class (m^3/ha)	x	x	x	x				
Total projected area (m^2/ha) [a]	x	x	x	x				
Projected area, by diameter class (m^2/ha)	x	x	x	x				
Volume, by diameter & length classes (m^3/ha)	x	x	x	x		x		
Total pieces (no./ha)	x	x	x	x		x		
Pieces, by diameter class (no./ha)	x	x	x	x		x		
Pieces, by diameter & length classes (no./ha)	x	x	x	x		x		
Projected area, by diameter & length classes (m^2/ha) [a]	x	x	x	x		x		
Volume, by diameter & decay classes (m^3/ha)	x	x	x	x			x	
Pieces, by diameter & decay classes (no./ha)	x	x	x	x		x	x	
Total biomass (kg/ha)	x	x	x	x			x	x
Biomass, by diameter class (kg/ha)	x	x	x	x			x	x
Biomass, by diameter & length classes (kg/ha)	x	x	x	x		x	x	x
Odd-shaped pieces, & accumulations								
Total volume (m^3/ha)	x	x			x			
Total projected area (m^2/ha) [a]	x	x			x			
Total biomass (individual pieces only) (kg/ha)	x	x			x		x	x

[a] Total projected area refers to the surface or ground area "covered" by CWD. If the calculations are made based on piece diameters using the formula presented in Section 4.3, then corrections must be made for piece overlap. If intersection widths are measured along the line transects, then the formula presented in Section 5 applies and no corrections for overlap are necessary.

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transect crosses, and 2) the angle of the piece from horizontal. To estimate total volume/ha of odd-shaped pieces or accumulations requires that the height and width of the rectangle formed along the plane of intersection where the line transect crosses the piece be measured.

If an estimate of total CWD biomass is desired, then decay class and density must also be determined (Section 3.4.4); these measurements are normally taken on a subset of the pieces or they are acquired from other studies. Parameters that require individual piece length to be measured (e.g., number of pieces/ha or average piece length) should be estimated using only the technique described for round or semi-round pieces.

3.4.1 Piece Angle

In the case of round or semi-round CWD, it is necessary to measure the angle of each piece from the horizontal. Pieces that do not lie flat on a horizontal plane have a shorter effective length on this plane than their actual length. This reduces the probability of the piece being crossed by a line transect. If the acute angle of the piece from horizontal is known, this can be accounted for. (See Section 4.1 for details.) If the piece angle is less than 10 or 15 degrees it has little effect on effective piece length (approximately 2 to 4% reduction).

Angles may be measured in degrees or as percentages. The formulas provided in Section 4 assume the angle is measured in degrees; however, it is a simple matter to translate angle measurements from one unit to the other.

In the case of odd-shaped pieces or accumulations (i.e. where volumes are based on rectangular areas), piece angle is not required. In these cases, angled pieces simply have a larger rectangular area than they would have if they were lying horizontally. This compensates for the fact that they are less likely to be crossed by a line transect. (See Section 5 for more details.)

3.4.2 Diameter, and/or Height and Width

Typically, diameter (or height and width for non-round pieces and accumulations) is recorded in centimetres, as either inside or outside bark dimensions depending on study objectives.

Round or Semi-Round Pieces
If the CWD piece is round, it is necessary to record only the piece diameter. If the piece is semi-round (i.e. oval or half-moon shaped), approximate the equivalent diameter of a circle with the same cross-sectional area by measuring the diameter along the short (height, d_s) and long (width, d_l) axes (Figure 3), and determine the geometric mean of these two diameters as:
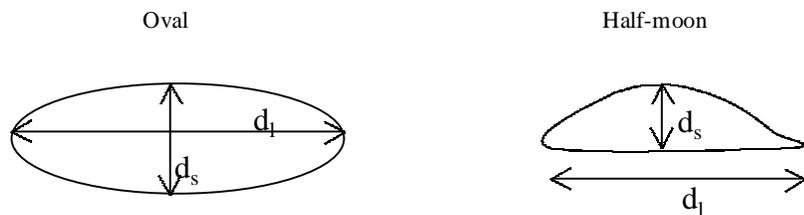

Figure 3. Diameter measurements on round or semi-round (oval- or half-moon-shaped) CWD pieces.

- Only parameters that do not require that piece length be measured can be estimated using the rectangular method.

- Piece angle is required only for pieces that will be compiled using standard LIS theory (i.e., where a round or equivalent round diameter has been recorded). Piece angle is not required where the rectangular area approach is used to estimate cross-sectional area on odd-shaped pieces and accumulations.

- How diameter or height/width are measured depends on how pieces are classified and how each class is treated:
  — Round pieces: Measure diameter perpendicular to the length of the piece where it is crossed by the line transect.
  — Semi-round pieces: Estimate an "equivalent" diameter of a circle based on the geometric mean of height and width measured perpendicular to the length of the piece where the piece is crossed by the line transect.
  — Odd-shaped pieces: Estimate the width and height of a rectangle that represents the cross-sectional area of the piece along the plane formed by the line transect.
  — Accumulations: 1) Individual pieces: As above; 2) Group of pieces: Estimate the width and height of a rectangle that represents the cross-sectional area of the accumulation along the plane formed by the line transect. The rectangular area should reflect only the solid content of the accumulation.

$$\hat{d}_{ij} = \sqrt{d_l \times d_s}$$

This can be done in the field using a calculator or as part of the compilation, if height and width are recorded on the field forms. The cross-sectional area, and hence the diameter, is estimated perpendicular to the center axis of the piece at the point at which it is crossed by the line transect.

Odd-Shaped Pieces

There are various approaches to determining the volume of these pieces. One of the more common approaches (used with the VRI) is to estimate the dimensions of a rectangle with an equivalent cross-sectional area to the cross-section of the odd-shaped piece, along the plane formed by the intersection of the line transect with the piece (Figures 4 and 5).

When estimating the cross-sectional area as a rectangle, piece diameter is not measured; instead, the width of the rectangle associated with the odd-shaped piece is measured along the length of the line transect, while the effective height of the odd-shaped piece is estimated. The cross-sectional area required for this approach is the cross-sectional area of the piece as crossed by the line, not perpendicular to the center axis of the piece. See Section 5 for more details.

Accumulations

Accumulations of CWD (e.g., windfalls, cedar-shake waste) crossed by a line transect can be treated as a number of single pieces, or as a single entity. In the former case, field measures depend on the cross-sectional
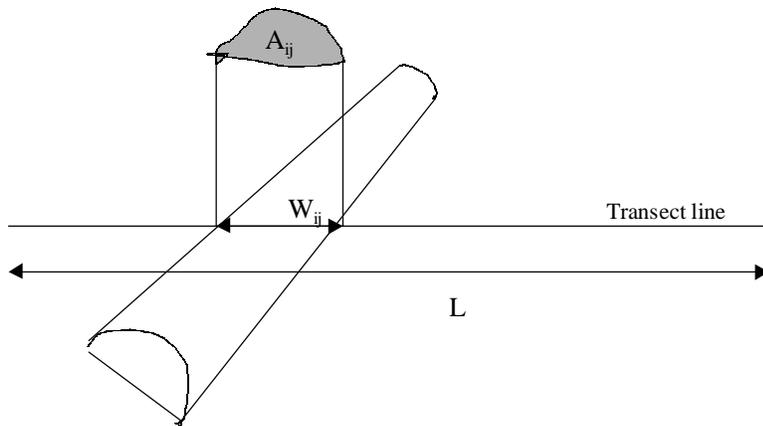

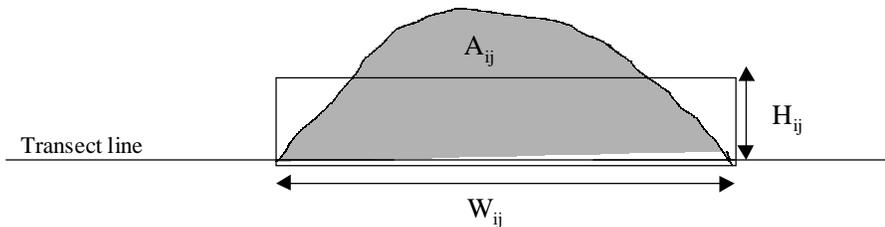Figure 4. Odd-shaped CWD piece crossed by a line transect.

Figure 5. Cross-sectional area of an odd-shaped CWD piece depicted as a rectangle.

shape of each piece and the class (see Table 1). In the latter case, the cross-sectional area of the group is estimated as a rectangle, as outlined above. The rectangular area should reflect only the solid content of the accumulation (i.e., not including air space) to avoid overestimating the CWD volume.

Estimating the cross-sectional area of CWD accumulations as a rectangle will be quicker than measuring single pieces, but may result in less precise estimates of volume.

3.4.3 Piece Length

Piece length is required in the calculation of some parameters (Table 1). Measuring piece length is time consuming compared to measuring diameter. It is perhaps most time consuming for small diameter pieces and curved pieces (e.g., branches, forked deciduous stems). Piece length is typically recorded in metres.

Piece length can be problematic to define. Clear rules governing the measurement of piece length are required. In the case of LIS, piece length must be measured along the center axis of the piece, regardless of the piece shape (Figure 6). Further piece length is often considered to include only that portion of the CWD piece that is greater than or equal to the minimum diameter (e.g., 10 cm).

Consistency is important to ensure that a branched or crooked piece is treated identically whether it is intersected once or more than once. Failure to treat pieces in a consistent manner will introduce bias into the sampling process.

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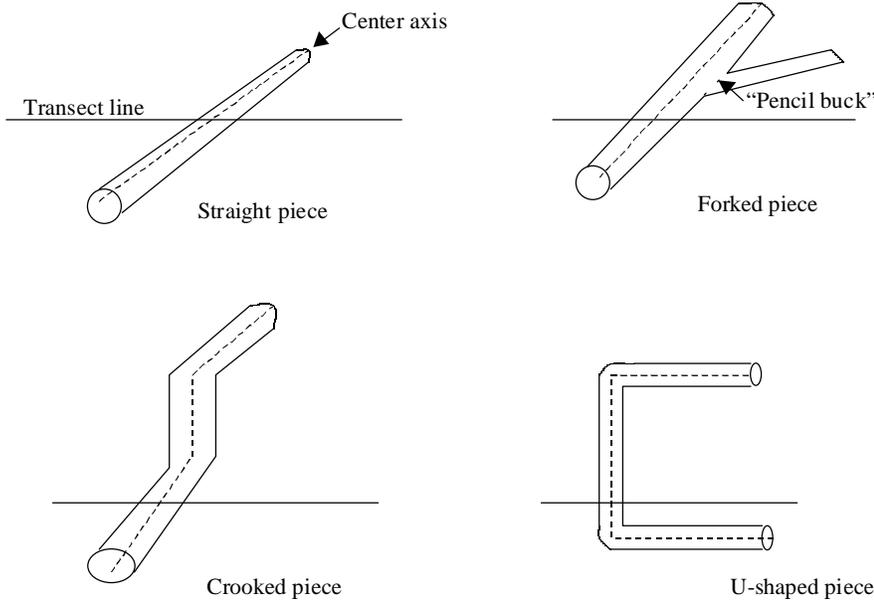

Figure 6. Examples of four different CWD piece shapes. Regardless of piece shape, piece length must be measured along the center axis of the piece (dashed line). The second leader of a forked piece is not measured unless crossed by the line transect.

In the case of forked pieces, length is measured along the main section only (i.e., the portion with the larger diameter). The second leader is considered a separate piece, and is "pencil bucked" at the main stem. It is therefore not measured unless the transect line crosses it. In the case of U-shaped pieces, the length of the entire U is recorded.

3.4.4 Other Measurements

Species

While it is not required in the volume/ha or piece density formulas, species is a routine measurement. It is frequently used in summaries of volume/ha by diameter and/or length class to provide insight into fuel loading hazards, successional trends, and habitat requirements. The tree species codes—which are particular to the VRI—are provided in such documents as the BCMOF's *Vegetation Inventory Ground Sampling Procedures* (1999).

Decay and Density

- The study objectives determine whether attributes such as species, decay, and merchantability are measured.

CWD pieces are commonly placed into three to five decay classes. Decay class is not required in the volume/ha or piece density formula; therefore, whether or not the decay class is measured is determined by the study objectives.

Decay classes are defined by both physical (e.g., presence of leaves, twigs, branches, percentage of bark cover, shape) and biological indicators (e.g., moss cover, root invasion). The five-class system outlined in the BCMOF's *Vegetation Inventory Ground Sampling Procedures* (1999) is widely used throughout North America. It is possible to base assessment of the decay class on either the condition of the piece at the point of intersection or on an "average" condition for the entire piece; however, the same assessment procedure should be used throughout the study.

Piece density (kg/m^3) is required to convert volume/ha (m^3/ha) to kg/ha. Depending on the study objectives, piece density can be determined from the literature or from field samples. Field measurements of piece density are based on intact CWD cores or slabs collected for volume and oven-dry-weight measurements. Field samples are generally stratified by species, diameter/length classes, and decay class. Stratification may be extended to wood type (e.g, bark, sapwood, heartwood) to meet certain study objectives. In areas of high species diversity, it may be necessary to group species within a genus or within some larger functional class. Detailed field measures are often restricted to decay rate and nutrient mineralization studies.

Merchantability

Indices of merchantability (e.g., log grade, % sound wood), while not required in the volume/ha or piece density formulas, may represent a useful summary parameter for some study objectives. For example, this information may be useful in a post-harvest assessment of CWD under different harvesting treatments, but may be of limited use in a habitat assessment for salamanders. When measured, attributes such as log grade and % sound wood should be closely tied to inventory and residue and waste standards. Generally, these sorts of assessments are based on an examination of the entire piece.

3.5 Other Issues: Multiple Intersections, and Unequal Transect Lengths

This section addresses two common field-related questions about using LIS: one regarding multiple transect intersections, and the other regarding unequal transect lengths.

Research Disciplines: Ecology ~ Geology ~ Geomorphology ~ Hydrology ~ Pedology ~ Silviculture ~ Wildlife

What steps are required when a CWD piece is crossed by a line transect more than once at a sampling point?

This situation might occur for any one of these four reasons:

1. More than one line transect segment is located at a sample point (Figure 7).
2. The piece is branched or forked (Figure 8).
3. The piece is crooked (Figure 9).
4. The piece is U-shaped (Figure 10).

Regardless of the reason for multiple crossings, each intersection is treated as a separate observation (i.e., independent of the other intersections) and measurements taken as if each intersection is the only one on the CWD piece.

For example, if a straight piece is intersected twice (Figure 7), record the diameter of the first intersection and the full length of the piece, and record the diameter at the second intersection and the full length again; i.e. the full length is recorded twice, once for each intersection, because the piece is actually treated as two separate pieces. In another example, if a crooked piece is intersected three times (Figure 9), record the diameter of each intersection point, plus record the full length for each intersection; i.e. in these cases the piece is actually treated as three separate pieces.[5] The same protocol applies to a U-shaped CWD piece that is intersected twice (Figure 10).

If a forked or branched piece is intersected twice (Figure 8), the forked leaders are also treated as separate pieces, with both diameter and length being recorded. However, this means that the length of the main leader of the piece will be different than the second leader, as one is usually longer than the other.

Other than length, the piece measurements are straightforward. As mentioned earlier (Sections 3.3 and 3.4.3), consistency is important when measuring length to ensure that a branched or crooked piece is treated identically no matter how many times it is intersected. Failure to treat pieces in a consistent manner will introduce bias to the sampling process.

What should be done regarding unequal lengths of line transects at various sampling points?

Unequal lengths of line transects at various sampling points can be caused by two sources, both of which are beyond the control of the field crew: (1) intersection of some portion of the line with the boundary of the area of interest, and (2) intersection of a portion of the line with some other feature (e.g., a road) that is not part of the sample area or that is unsafe to sample. These situations can be addressed by using approximation techniques.

The boundary of the area of interest depends on the study objectives, as will the treatment of other features (e.g., wildlife tree patches, non-productive areas) within the boundary. Depending on the study objectives, some features may be included, excluded, or possibly sampled as separate strata (Figure 11).

Where the boundary of the area of interest is encountered when establishing a line transect, use a "bounce-back" technique, like that suggested by

- When a CWD piece is crossed by the transect line more than once, treat each intersection independently and record measurements as if each intersection is the only one.

- Treat branched or crooked CWD pieces identically whether they are intersected once or more than once.

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[5] Proof for measuring length on non-straight pieces is provided in de Vries (1986).
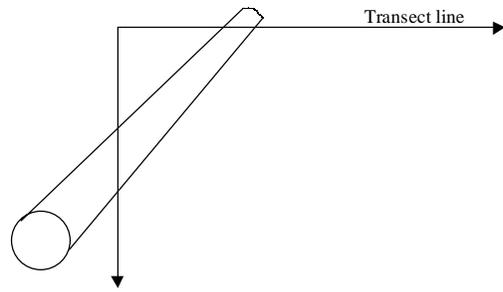
Figure 7. A straight piece of CWD crossed twice because of line transect shape. Treat as two separate pieces, with diameter measured at each point of intersection. Measure length once, but record each time the piece is crossed.
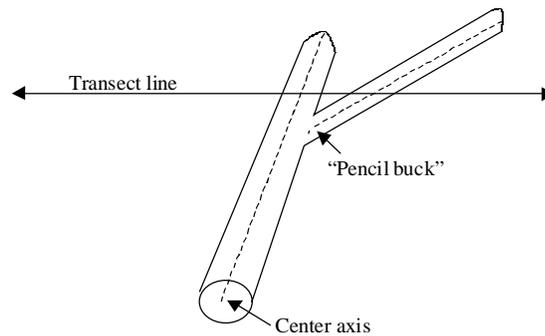

Figure 8. A piece of CWD crossed twice because it is branched. Treat as two separate pieces , with diameter measured at each point of intersection. Record the length of each piece separately.
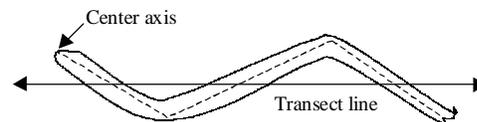

Figure 9. A piece of CWD crossed three times because it is crooked. Measure diameter at each point of intersection. Measure length once, but record each time the piece is crossed.
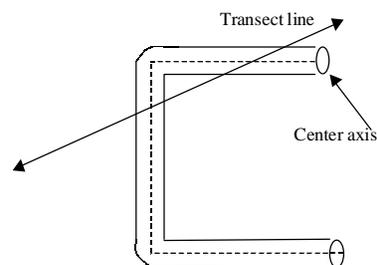

Figure 10. A U-shaped piece of CWD crossed twice by the transect line. Measure diameter at each point of intersection. Measure length once, but record each time the piece is crossed.

the VRI protocol. This involves doubling back along a line transect from the point at which it intersects a boundary, until the appropriate length of line transect is reached. Each CWD piece that is crossed a second time is counted as an additional observation. If the boundary is intersected before the halfway point of the line transect, the bounce-back extends back past the point of origin of the line transect.

If a portion of the line transect falls into an excluded area (e.g., road, wide stream) or encounters an area that is unsafe to sample, the length of the line transect that is actually sampled is recorded. For example, if a line transect crosses a road or non-productive area that is to be "netted out", then CWD pieces are measured up to and beyond the road or non-productive area, but not through those areas (Figure 11). To estimate the excluded area, the total area is multiplied by the proportion of the total length of all the transects that fall into areas which are to be "netted out".

If unequal line transect lengths exist within a sample, an unbiased estimate of the variance of any CWD estimate is no longer guaranteed. It is usually best to weight the estimate, giving values from longer line transects proportionally more weight than those from shorter transects. (See Equations 21 and 22 in Section 6.)

- Use a "bounce-back" technique when the line transect encounters boundaries for the area of interest.
- Other situations causing less than a full line transect to be established can be addressed by using the actual line length sampled in the formulas.
- If line transects are of unequal length, an unbiased estimate of the variance of any CWD estimate is no longer guaranteed. Weight estimates by the length of the line transect actually sampled.
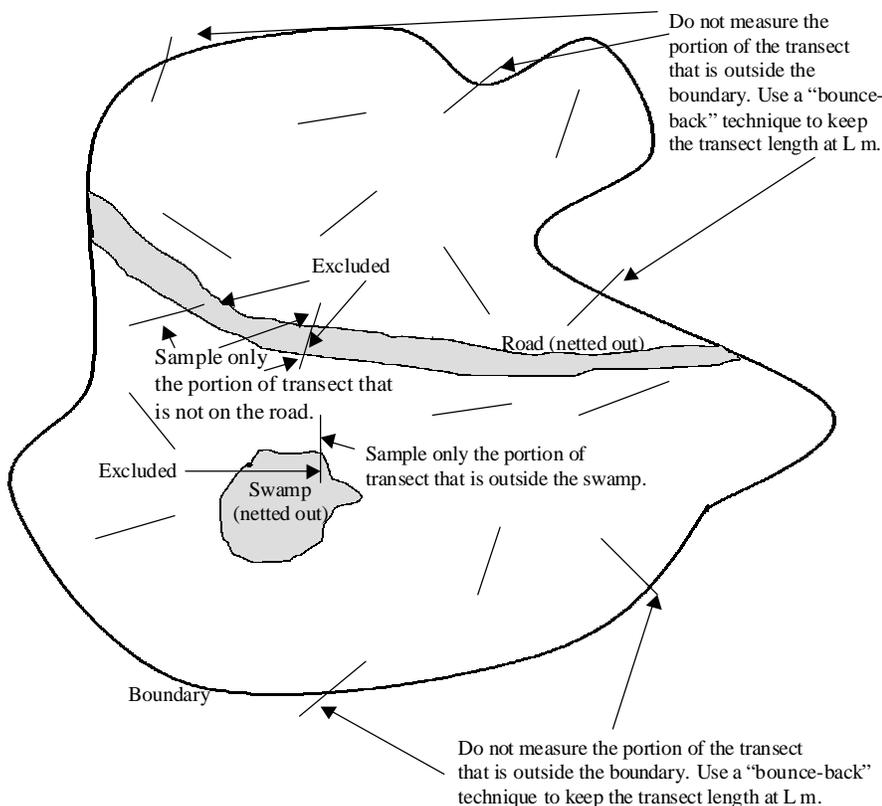

Figure 11. Hypothetical random layout of line transects on an area of interest.

Research Disciplines: Ecology ~ Geology ~ Geomorphology ~ Hydrology ~ Pedology ~ Silviculture ~ Wildlife

4 LIS THEORY FOR ROUND, SEMI-ROUND, AND ODD-SHAPED PIECES WHERE AN EQUIVALENT DIAMETER IS ESTIMATED

4.1 Derivation of the LIS Formula for a Single Line Transect

The variable of interest associated with a single line transect (y_i) (e.g., volume/ha) equals the sum of the ratios between the variable value for a piece (y_{ij}) (e.g., volume/piece) and the probability of that piece being crossed by the line (p_{ij}), for all pieces crossed by the transect. This is expressed mathematically as:

[1]
$$y_i = \sum_{j=1}^{m_j} \frac{y_{ij}}{p_{ij}}$$

Use this equation for any variable of interest, providing it can be measured on each piece and the probability of the transect intersecting the piece can be determined.

To determine the probability that line transect i, with length L, will intersect a CWD piece with a length of l_{ij}, first define an arbitrary area of size A on which the CWD pieces are found. Assume line transect i is located randomly on A, away from its edges. Imagine a rectangle of size L W, where W is the width of the rectangle, to be centered on the transect (Figure 12). Assume that W is greater than the length of any of the pieces being considered. The probability that transect i will intersect a piece of length l_{ij} with a midpoint M_{ij} depends on: (1) M_{ij} being in the rectangle; and (2) transect i intersecting the piece, given that M_{ij} is in the rectangle. That is:

$p_{ij} = \text{Prob}(M_{ij}$ is in the rectangle)

$\times \text{Prob}$(intersection given that M_{ij} is in the rectangle).

The probability that M_{ij} is in the rectangle is simply:

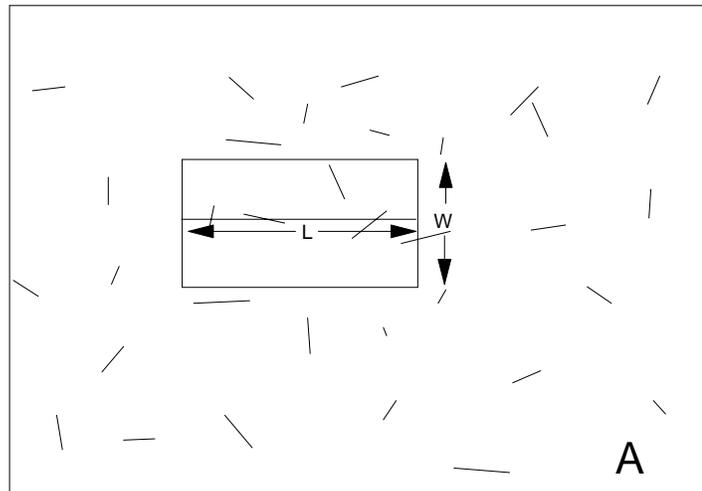[2] $\text{Prob}(M_{ij}$ is in LW) $= \dfrac{L \times W}{A}$

Figure 12. CWD pieces randomly scattered over area *A*.

The probability that transect i intersects the piece, given that M_{ij} is in the rectangle, depends on the angle between the transect and the piece, and the length of a perpendicular line from M_{ij} to the transect. In Figure 13, θ_{ij} is the acute angle between the piece and the transect, m_{ij} is the perpendicular distance between M_{ij} and the transect, and X_{ij} is the distance from M_{ij} to the transect measured along the piece. θ_{ij} ranges from 0 to 90 degrees (0 to $\pi/2$ radians). If M_{ij} is in the rectangle, then m_{ij} ranges from 0 to a maximum that will be less than $W/2$. The denominator for the second part of the probability statement is defined as the product of the maximum values of these ranges. Symbolically:

$$\text{Prob(intersection given that } M_{ij} \text{ is in the rectangle)} = \frac{?}{W/2 \times \pi/2}$$

All that remains to be determined is when the transect will cross the piece. If θ_{ij} is 0 radians, then m_{ij} must also be 0 in order for the transect to intersect the piece, since $\theta_{ij} = 0$ implies that the transect is parallel to the piece (i.e., it must be on top of the piece to intersect it). At the other extreme, when θ_{ij} is $\pi/2$ radians, m_{ij} can range from 0 to $l_{ij}/2$ and the transect will touch the piece. Between these two extremes, m_{ij} will range from 0 to a value less than $l_{ij}/2$ (Figure 14).

- LIS theory assumes that CWD pieces are randomly oriented with respect to the line transect, and that they lay flat on a horizontal plane.
  — In practice, CWD pieces are often not randomly oriented across the area. Instead, the assumption of random orientation is addressed by randomly orienting the transects.
  — If CWD pieces are not lying flat on a horizontal plane, then the effective length of each piece on this plane must be determined from the acute angle of each piece from the horizontal.
- The probability of a given CWD piece being crossed by a line transect is proportional to the length of the transect and the length of the piece, and is inversely proportional to the unit area on which the piece is found.
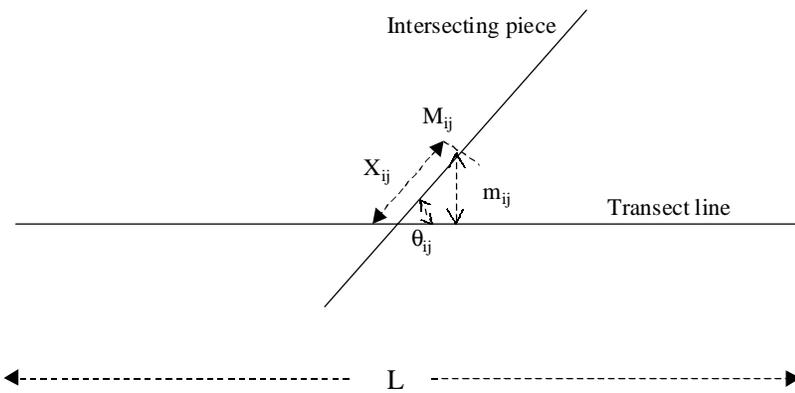

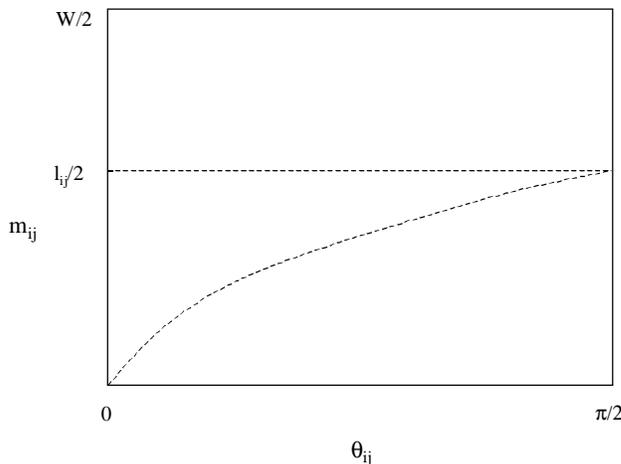Figure 13. Measuring angle and length for an intersecting piece.

Figure 14. Combinations of m_{ij} and θ_{ij} for intersecting pieces.

An equation for the upper limit of m_{ij} can be derived from the relationship between m_{ij} and X_{ij} shown in Figure 13. In order for the transect to intersect a piece, X_{ij} must be less than or equal to $l_{ij}/2$. Since $m_{ij} = X_{ij} \times \sin\theta_{ij}$ and $X_{ij} = m_{ij}/\sin\theta_{ij}$, it follows that:

$$\frac{m_{ij}}{\sin\theta_{ij}} \leq \frac{l_{ij}}{2}$$

Therefore:

$$m_{ij} \leq \frac{l_{ij}}{2} \times \sin\theta_{ij}$$

Thus the second part of the probability statement is:

Prob(intersection given that M_{ij} is in the rectangle)

$$= \frac{\text{area defined by } m_{ij} \leq \dfrac{l_{ij}}{2} \times \sin\theta_{ij}}{\dfrac{W}{2} \times \dfrac{\pi}{2}}$$

The area under the curve $m_{ij} \leq l_{ij}/2 \times \sin\theta_{ij}$ for the range of angles between 0 and $\pi/2$ radians is:

$$area = \int_{\theta=0}^{\pi/2} \frac{l_{ij}}{2} \times \sin\theta \ d\theta$$

$$= \frac{l_{ij}}{2} \times \left[-\cos\theta \Big|_0^{\pi/2} \right]$$

$$= \frac{l_{ij}}{2} \times \left[-\cos\left(\frac{\pi}{2}\right) + \cos(0) \right]$$

$$= \frac{l_{ij}}{2}$$

Thus:

[3]   Prob(intersection given that M_{ij} is in the rectangle) $= \dfrac{\dfrac{l_{ij}}{2}}{\dfrac{W}{2} \times \dfrac{\pi}{2}}$

The two parts of the probability of transect i intersecting a piece (Equations 2 and 3) can now be combined to yield:

$$p_{ij} = \frac{L \times W}{A} \times \frac{\dfrac{l_{ij}}{2}}{\dfrac{W}{2} \times \dfrac{\pi}{2}}$$

This simplifies to:

[4] $p_{ij} = \dfrac{2 \times L \times l_{ij}}{A \times \pi}$

If a piece does not lie flat on a horizontal plane, its effective horizontal length must be calculated by multiplying l_{ij} by the cosine of the acute angle of the piece from the horizontal (λ_{ij}):

$$[5] \quad p_{ij} = \frac{2 \times L \times (l_{ij} \times \cos \lambda_{ij})}{A \times \pi}$$

Since the cosine of any acute angle is less than 1, this correction decreases the probability of intersection (i.e., it reduces the effective length of the piece).

4.2 Estimating Volume Per Hectare from a Single Line Transect

The volume per unit area represented by the pieces crossed by any transect can be determined by substituting piece volume (v_{ij}, in m^3) for y_{ij} in Equation 1. This yields:

$$[6] \quad y_i = \sum_{j=1}^{m_i} \frac{v_{ij}}{p_{ij}}$$

where y_i is the total volume (m^3) on area A represented by the round or semi-round CWD pieces intersected by transect i, v_{ij} is the volume of piece j on line i in m^3, and p_{ij} is the probability of transect i crossing piece j (determined using Equations 4 or 5).

Huber's Formula provides an estimate of v_{ij} based on the cross-sectional area at the middle of the piece (A_{Mij}, in cm^2), which is determined from the diameter at that point (d_{Mij}, in cm), providing the log is circular. The piece length in m is l_{ij}; and 10 000 is used to convert cross-sectional area from cm^2 to m^2:

$$v_{ij}(m^3) = A_{M_{ij}} \times l_{ij} = \frac{\pi}{10000} \times \left(\frac{d_{M_{ij}}}{2}\right)^2 \times l_{ij} = \frac{\pi \times d_{M_{ij}}^2}{40000} \times l_{ij}$$

For semi-round pieces, use the "equivalent" diameter of a circle in the above formula.

Assuming that the line transect intersects a piece at its midpoint on average, Huber's Formula can also be used to estimate volume of the piece using the diameter (d_{ij}) measured at the point of intersection of the line and the piece:

$$[7] \quad v_{ij}(m^3) = \frac{\pi \times d_{ij}^2 \times l_{ij}}{40\,000}$$

Equations 7 and 5 can be substituted into Equation 6 to obtain the total volume on area A (y_i) represented by each line, where L and l_{ij} are in m, d_{ij} is in cm, and λ_{ij} is in degrees:

$$y_i(m^3) = \frac{\left(\sum_{j=1}^{m_i} \frac{\pi \times d_{ij}^2 \times l_{ij}}{4 \times 10\,000}\right)}{\left(\frac{2 \times L \times l_{ij} \times \cos(\lambda_{ij})}{A \times \pi}\right)}$$

This simplifies to:

$$y_i(m^3) = \frac{\pi^2 \times A}{80000 \times L} \times \sum_{j=1}^{m_i} \frac{d_{ij}^2}{\cos(\lambda_{ij})}$$

If A is 1 ha (10 000 m^2), then the above equation simplifies further to:

- The simplified formula for estimating volume/ha assumes that CWD pieces are round (or that an equivalent round diameter is recorded at the point where the piece is crossed), and that Huber's formula is appropriate for estimating the volume of the pieces.

[8] $$y_i(m^3/ha) = \frac{\pi^2}{8 \times L} \times \sum_{j=1}^{m_i} \frac{d_{ij}^2}{\cos \lambda_{ij}}$$

When λ_{ij} is small, $\cos(\lambda_{ij})$ is close to 1 and the angle of the piece from horizontal has little impact on the estimated volume/ha.

If all of the pieces can be assumed to lie almost horizontal, then the formula simplifies further to:

[9] $$y_i(m^3/ha) = \frac{\pi^2}{8 \times L} \times \sum_{j=1}^{m_i} d_{ij}^2$$

4.3 Determining Per-Hectare Values Other Than Volume From a Single Line Transect

Equation 1 can be used for any attribute that can be measured on a CWD piece in order to combine the measurements into an estimate of value per unit area. In the few examples that follow, the assumption is that the unit area of interest (i.e., A) is 1 ha (10 000 m^2). Thus,

$$p_{ij} = \frac{2 \times L \times l_{ij} \times \cos \lambda_{ij}}{10\,000 \times \pi}$$

Total Number of Pieces Per Hectare
For pieces/ha, y_{ij} equals 1 for each piece crossed, and Equation 1 becomes:

[10] $$y_i(pieces/ha) = \frac{10\,000 \times \pi}{2 \times L} \times \sum_{j=1}^{m_i} \frac{1}{(l_{ij} \times \cos \lambda_{ij})}$$

If piece count per size class is desired, Equation 10 is applied separately to each class, using only the pieces in that class.

Average Piece Length
To determine the average length of a piece in a given class, divide the total length of pieces in that class (per ha) by the total number of pieces in that class (per ha). The number of pieces/ha in a class is estimated using Equation 10. The total length of pieces in a class, on a per-hectare basis, is determined by replacing y_{ij} in Equation 1 by l_{ij} and summing over the total number of pieces in that class. Symbolically:

$$\sum_{j=1}^{m_i} \frac{l_{ij}}{p_{ij}}(m/ha) = \sum_{j=1}^{m_i} \frac{l_{ij}}{\left(\dfrac{2 \times L \times l_{ij} \times \cos \lambda_{ij}}{10\,000 \times \pi}\right)} = \frac{10\,000 \times \pi}{2 \times L} \times \sum_{j=1}^{m_i} \frac{1}{\cos \lambda_{ij}}$$

Combining this with Equation 10 yields:

$$y_i(m) = \left(\frac{10\,000 \times \pi}{2 \times L}\right) \times \sum_{j=1}^{m_i} \frac{1}{\cos\lambda_{ij}} \Bigg/ \left(\frac{10\,000 \times \pi}{2 \times L} \times \sum_{j=1}^{m_i} \frac{1}{(l_{ij} \times \cos\lambda_{ij})}\right)$$

[11]
$$= \frac{\displaystyle\sum_{j=1}^{m_i} \frac{1}{\cos\lambda_{ij}}}{\displaystyle\sum_{j=1}^{m_i} \frac{1}{(l_{ij} \times \cos\lambda_{ij})}}$$

where y_i is the average piece length in some class based on information collected on transect i.

If it can be assumed that all pieces are lying horizontally (i.e., $\cos\lambda_{ij} = 1$), then Equation 11 simplifies to:

[12]
$$y_i(m) = \frac{m_i}{\displaystyle\sum_{j=1}^{m_i} \frac{1}{l_{ij}}}$$

- Estimates of average piece length and number of pieces/ha require that the length of each piece crossed by a line tansect be measured.

Total Projected Area

The projected area of each intersected piece can be determined as:

$$y_{ij}(m^2) = \frac{d_{ij}}{100} \times l_{ij}$$

Thus, the estimated projected area of CWD/ha, based on a single transect is:

$$y_i(m^2/ha) = \sum_{j=1}^{m_i} \frac{\dfrac{d_{ij}}{100} \times l_{ij}}{\dfrac{2 \times L \times l_{ij} \times \cos\lambda_{ij}}{10000 \times \pi}}$$

Which simplifies to:

[13]
$$y_i(m^2/ha) = \frac{50 \times \pi}{L} \sum_{j=1}^{m_i} \frac{d_{ij}}{\cos\lambda_{ij}}$$

If it can be assumed that all pieces are lying horizontally (i.e., $\cos\lambda_{ij} = 1$), then Equation 13 simplifies to:

[14]
$$y_i(m^2/ha) = \frac{50 \times \pi}{L} \sum_{j=1}^{m_i} d_{ij}$$

Equation 14 provides an estimate of total projected area; however, it assumes no piece overlap. Typically overlap of CWD pieces will be low in mature stands, but will be extremely common in young stands that have incurred recent disturbances. Overlap in mature stands may occur through group mortality (i.e., insect damage, windthrow). An estimate of the proportion of overlap that occurs must be used to reduce the total projected area estimate, if it is to represent the projected CWD area on a unit area. This approach permits estimates of projected area by diameter class.

Equation 18 in Section 5 provides an alternative approach to estimating projected area. In that approach the length of line transect intersected by CWD, rather than the diameter of each piece crossed, is recorded and used

- Total unit area estimates, or unit area estimates by diameter class, for the following parameters do not require piece length measurements: volume/ha, biomass/ha, and projected area/ha.

to calculate projected area; it requires no correction for piece overlap. If projected area by diameter class is desired, then the equivalent round diameter of individual pieces perpendicular to the line transect must be estimated and recorded.

5 RECTANGULAR AREA APPROACH TO ESTIMATING VOLUME PER HECTARE FOR ODD-SHAPED PIECES AND ACCUMULATIONS FROM A SINGLE LINE TRANSECT

This approach requires the sampler to estimate the dimensions of a rectangle of equivalent area to the cross-sectional area of the piece, or accumulation, as projected onto a vertical plane that cuts through the piece along the line transect (Figures 4 and 5). The cross-sectional shape of the piece on the vertical plane may be quite irregular and it may be difficult to match the area with a rectangle. However, every effort should be made to estimate the area of the rectangle as carefully as possible.

- The rectangular area approach to estimating the volume/ha requires the sampler to imagine the cross-sectional area of a piece or accumulation as a rectangle of equivalent area and to estimate the dimensions of that rectangle.

- Recording the dimensions of a rectangle with equivalent area to the cross-sectional area of an odd-shaped piece may be difficult to do precisely. This does not necessarily lead to bias, but does decrease the overall precision of the estimate of volume/ha.

- Height and width may be recorded as either centimetres or metres.

  – If recorded in centimetres, the formula is simplified because the factor for converting the cross-sectional area in cm^2 to m^2 (1/10 000) cancels the factor required to expand the result from a single metre of line transect to a per-hectare basis (10 000).

  – If recorded as metres, the formula includes an expansion factor of 10 000 m^2/ha to convert from a value per metre of line transect to m^3/ha.

The volume/ha represented by a single odd-shaped piece or accumulation crossed by a line transect is expressed as:

$$[15] \qquad v_{ij}(m^3/ha) = \frac{W_{ij} \times H_{ij}}{L} \times \frac{1}{10\,000} \times 10\,000$$

where v_{ij} is the volume represented by odd-shaped piece or accumulation j crossed by line transect i, W_{ij} is the width (cm) of the rectangle associated with odd-shaped piece or accumulation j, as measured along the length of line transect i, H_{ij} is the effective height (cm) of the odd-shaped piece or accumulation j, and L is the length (m) of the line transect. The factor for converting the cross-sectional area in cm^2 to m^2 (1/10 000) cancels the factor required to expand the result from a single line transect to a per-hectare basis (10 000). Equation 15 then simplifies to:

$$[16] \qquad v_{ij}(m^3/ha) = \frac{W_{ij} \times H_{ij}}{L}$$

In the case of accumulations it may be more convenient to record W_{ij} and H_{ij} in metres rather than centimetres. The area of the rectangle is then simply $W_{ij} \times H_{ij}$ in m^2. Dividing this area by L converts this to a value per metre. Multiplying by a scaling factor of 10 000 m^2/ha converts the value per metre to m^3/ha:

$$[17] \qquad v_{ij}(m^3/ha) = \frac{W_{ij} \times H_{ij}}{L} \times 10\,000$$

H_{ij} should be determined as an "average" along W_{ij}, such that the area of the rectangle that is formed is approximately that of the surface area that would be exposed if the piece or accumulation were split vertically along the plane formed where the piece is crossed by a horizontal line transect. As depicted in Figures 15 and 16, pieces or accumulations that are at an angle (vertical and/or horizontal) to the line transect have a larger surface area than if they were lying horizontally. This applies whether they are round or odd-shaped. Often, there will be angles present on both the vertical and horizontal planes. In these cases, a combination of the effects shown in Figures 15 and 16 will occur. The larger surface area associated with angled pieces on a vertical plane compensates for the fact that these pieces are less likely to be crossed by a line transect than a horizontal piece, and explains why a correction for piece angle is not required with the rectangular approach.

Every odd-shaped piece or accumulation crossed by a line transect contrib-

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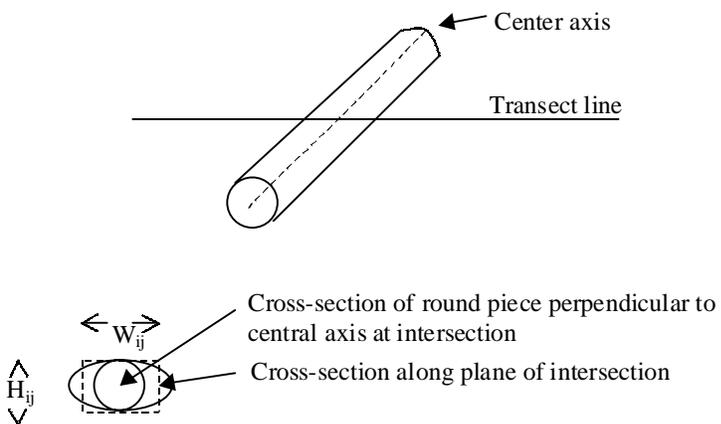
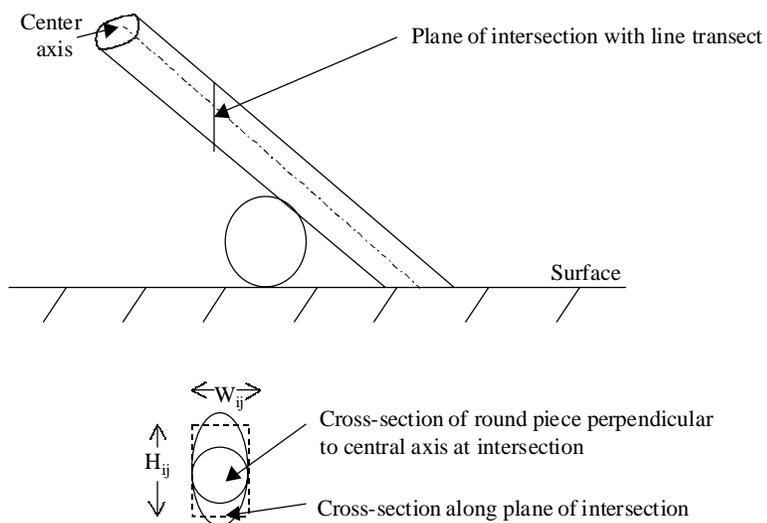Figure 15. Overhead view of a CWD piece at a horizontal angle to the line transect.

Figure 16. Side view of a CWD piece at a vertical angle to the line transect.

utes to the total cross-sectional area associated with that transect in an additive fashion. This can be thought of as rectangles representing the cross-sectional area being stacked on top of one another. The volume/ha represented by a single transect is expressed as:

$$[18] \quad v_i(m^3/ha) = \frac{\sum\limits_{j=1}^{m_i} W_{ij} \times H_{ij}}{L}$$

or

$$[19] \quad v_i(m^3/ha) = \frac{\sum\limits_{j=1}^{m_i} W_{ij} \times H_{ij}}{L} \times 10\,000$$

where m_i is the number of odd-shaped pieces and accumulations crossed by line transect i. Equation 18 applies where H_{ij} and W_{ij} are recorded in centimetres, while Equation 19 applies where H_{ij} and W_{ij} are recorded in metres.

If projected area/ha of the CWD is of interest (A_i measured in m^2/ha and W_{ij} is measured in cm), then:

$$A_i(m^2/ha) = \frac{\sum\limits_{j=1}^{m_i} \left(\dfrac{W_{ij}}{100}\right)}{L} \times 10\,000$$

This simplifies to:

$$[18] \quad A_i(m^2/ha) = \left(\sum\limits_{j=1}^{m_i} W_{ij}\right) \times \frac{100}{L}$$

This approach to measuring total projected area requires no adjustment for piece overlap.

6 COMPILATION

6.1 Parameter Estimates from Combining Several Line Transects

The mean value of y_i (e.g., average CWD volume/ha, number pieces/ha) and its standard error is calculated using formulas appropriate for the sampling design used to locate the line transects. Simple random sampling formulas are often used with both simple random sampling or systematic location of sampling units. The mean is determined as:

$$[19] \quad \overline{y} = \frac{\sum\limits_{i=1}^{n} y_i}{n}$$

where n is the number of transects and y_i is the value for the attribute of interest based on line i. Its standard error is determined as:

$$[20] \quad S_{\overline{y}} = \sqrt{\frac{\sum\limits_{i=1}^{n} y_i^2 - \dfrac{\left(\sum\limits_{i=1}^{n} y_i\right)^2}{n}}{n \times (n-1)}}$$

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If y_i is on a per-hectare basis, estimates of the total and its standard error are determined by multiplying Equations 17 and 18, respectively, by the number of hectares in the area.

If $\bar{y}$ is normally distributed, its $(1-\alpha) \times 100\%$ confidence interval is expressed as:

$$P(\bar{y} - t_{n-1,\alpha/2} \times S_{\bar{y}} \leq \mu_y \leq \bar{y} + t_{n-1,\alpha/2} \times S_{\bar{y}}) = 1-\alpha$$

where $t_{n-1,\alpha/2}$ is the appropriate value from the t-distribution with n-1 degrees of freedom and a $\alpha/2$ probability of a larger value. $\bar{y}$ will be normally distributed if either y_i is normally distributed or n is sufficiently large that the central limit theorem comes into play. If y_i is far from normally distributed, which may well be the case if concentrations of CWD are found in a few specific locations on the area of interest, then n needs to be quite large before $\bar{y}$ will be normally distributed.

If line transects at different sampling points have different lengths, then estimates should be weighted by the line transect length. The mean and its standard error become:

[21] $\quad \bar{y}_w = \dfrac{\sum\limits_{i=1}^{n} w_i y_i}{n}$

- Equations 19-22 apply if the line transects have been located using simple random sampling or systematic sampling.
- If line transects of unequal length are used, then Equations 21-22 are appropriate.

[22] $\quad S_{\bar{y}} = \sqrt{\dfrac{\sum\limits_{i=1}^{n} w_i \times (y_i - \bar{y}_w)^2}{n \times (n-1)}}$

where w_i equals $\dfrac{L_i}{(\sum\limits_{i=1}^{n} L_i)/n}$, and L_i is the length of transect i.

The differences between unweighted and weighted estimates should be small.

6.2 Sample Size

As was discussed in Section 2.2, it is possible to estimate the sample size required, on average, to achieve a pre-established level of precision. Assuming simple random sampling with replacement and the precision requirement stated in absolute terms (e.g., m^3/ha) as the half-width of a 1-α confidence interval:

[23] $\quad n = \dfrac{t_{n-1,\alpha/2}^2 \times S_y^2}{AE^2}$

where S_y^2 is the estimated population variability and AE is the desired half-width of the 1-α confidence interval. If the precision requirement is stated as a percentage of the estimated mean, then the sample size formula becomes:

- If the desired precision of the estimate of a parameter is stated in either absolute or percentage terms, and the variability of the associated variable can be estimated, then the sample size required, on average, to achieve the precision can be calculated.

[24] $\quad n = \dfrac{t_{n-1,\alpha/2}^2 \times CV^2}{PE^2}$

where PE is the desired percentage error and CV is the estimated coefficient of variation (i.e., an estimate of the population standard deviation expressed as a percentage of the estimated mean).

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- If the CWD is separated into two or more classes prior to measurement, the mean and its standard error for each group can be determined individually.

- The overall estimate of a parameter of interest is the sum of the individual group estimates.

- In order to determine the standard error for an overall estimate of a parameter, the values for each of the groups must be first summed on each of the transects prior to applying the appropriate formula.

6.3 Combining Sub-Populations

If the CWD pieces are separated into two or more classes based on the nature of the pieces, this is akin to estimating the value for two or more separate populations. The mean and its standard error for each class can be determined using Equations 19 and 20 (or 21 and 22) given above. The overall estimate of the parameter of interest (e.g., volume/ha) is simply the sum of the estimates for each group.

In order to determine the standard error for this combined estimate, group estimates need to be summed first for each transect to yield n combined estimates (Y_i). Symbolically,

$$Y_i = \sum_{h=1}^{H} y_{hi}$$

where y_{hi} is the value of the attribute of interest (e.g., volume/ha) for group h on transect i. There are H groups in total. Y_i can be substituted for y_i in Equations 19 and 20 (or 21 and 22) to yield a combined estimate of the mean and its associated standard error.

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Appendix I. Interpretation of Symbols

λ_{ij}	Acute angle from the horizontal of CWD piece j crossed by line transect i (degrees).
θ_{ij}	Acute angle between CWD piece j crossed by line transect i and line transect (degrees).
A	Size of the area on which the CWD pieces are found.
A_i	Projected area of CWD (m^2/ha).
A_{ij}	Cross-sectional area of CWD piece j and line transect i, at point of intersection (cm^2).
A_{Mij}	Cross-sectional area at the midpoint of CWD piece j crossed by line transect i (cm^2).
AE	Desired half-width of the 1-α confidence interval.
CV	Coefficient of variation (standard deviation of a variable expressed as a percentage of the statistic of interest).
d	Distance between sample points (m).
d_l	Diameter measured along the long axis of CWD piece that is oval or half-moon shaped in cross-section (cm).
d_s	Diameter measured along the short axis of CWD piece that is oval or half-moon shaped in cross-section (cm).
d_{ij}	Diameter of CWD piece j crossed by line transect i, measured perpendicular to centerline of the piece at the point at which piece is crossed by line transect (cm).
$\hat{d}_{ij}$	Estimated diameter of CWD piece j crossed by line transect i, measured perpendicular to centerline of piece at the point at which piece is crossed by line transect (cm).
d_{Mij}	Diameter at midpoint of CWD piece j crossed by line transect (cm).
H	Number of groups of CWD pieces.
H_{ij}	Height of the rectangle associated with odd-shaped piece or accumulation j crossed by line transect i (cm or m).
l_{ij}	Length of CWD piece j crossed by line transect i (m).
L	Length of line transect (m).
L_i	Length of line transect i (m).

m_i Number of CWD pieces crossed by line transect i.

m_{ij} Perpendicular distance between midpoint of CWD piece j crossed by line transect i and line transect (m).

M_{ij} Midpoint of CWD piece j crossed by line transect i.

n Number of line transects established on an area.

p_{ij} Probability of line transect i crossing CWD piece j.

PE   Desired percentage error (sampling error expressed as a percentage of the statistic of interest).

$S_{\bar{y}}$ Sample estimate of the standard error of a mean value per unit area (e.g. standard error of the average volume/ha).

$t_{n-1,\alpha/2}$ Value from the t-distribution with n-1 degrees of freedom and a $\alpha/2$ probability of a larger value.

v_i Volume of CWD pieces/ha based on line transect i (m^3/ha).

v_{ij} Volume of CWD piece j crossed by line transect i (m^3).

w_i Weight given to a value from line transect i, equal to the length of that line transect divided by average length of all line transects.

W Arbitrary width of rectangle used in LIS proof.

W_{ij} Width of the rectangle associated with odd-shaped piece or accumulation j crossed by line transect i, measured along the intersection with the line transect (cm or m).

X_{ij} Distance between midpoint of CWD piece j crossed by line transect i and the line transect, measured along the piece (m).

$\bar{y}$ Sample estimate of the mean value per unit area (e.g. average volume/ha).

y_i Value per unit area based on line transect i (e.g. volume/ha).

y_{hi} Value per unit area for CWD pieces belonging to group h based on line transect i (e.g. volume/ha of odd-shaped pieces).

y_{ij} Value per CWD piece (e.g. volume of a CWD piece).

Y_i Value per unit area, comprised of the sum of values per unit area of the various groups of CWD associated with line transect i (e.g. total volume/ha of regular, odd-shaped, and accumulations of CWD pieces).

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APPENDIX II. WORKED EXAMPLE

This example illustrates how CWD data collected in the field can be compiled. For the sake of simplicity, it is assumed that only three line transects are established on an area using simple random sampling (i.e., n = 3). All three of the line transects are L-shaped with two 15-m segments (i.e., L = 30).

The CWD data measured on these three lines are displayed in Table II-1.

Table II-1. CWD data.

Transect number	Piece number	Piece diameter [a] d_{ij} (cm)	Diameters for semi-round pieces d_l (cm)	d_s (m)	Piece length l_{ij} (m)	Angle from horizontal (λ_{ij})
1	1	15			3.5	0
	2	35			5.6	5
	3	21			4.2	10
	4	32 [b]	64	16	6.8	0
	5	45			7.5	15
2	1	26 [b]	52	13	3.3	0
	2	22			4.7	5
	3	17			2.9	0
	4	40			5.8	10
3	1	16			2.5	5
	2	42			5.3	10
	3	73			6.2	20
	4	32			4.0	5
	5	20			3.1	0
	6	21			2.9	15

[a] Diameter is assumed to be measured perpendicular to the centerline of the piece at the point at which the line transect crosses the piece.
[b] Diameter determined as the geometric mean of the long and short diameters (Figure 3).

Average Volume Per Hectare

Equation 8 is used to determine volume/ha associated with each line transect:

$$y_i(m^3/ha) = \frac{\pi^2}{8 \times L} \times \sum_{j=1}^{m_i} \frac{d_{ij}^2}{\cos \lambda_{ij}}$$

Using this equation:

$$y_1 = \frac{\pi^2}{8 \times 30} \times \left(\frac{15^2}{\cos(0)} + \frac{35^2}{\cos(5)} + \frac{21^2}{\cos(10)} + \frac{32^2}{\cos(0)} + \frac{45^2}{\cos(15)} \right)$$

$$= 0.041123 \times (225.00 + 1229.68 + 447.80 + 1024.00 + 2096.43)$$

$$= 206.56$$

$$y_2 = \frac{\pi^2}{8 \times 30} \times \left(\frac{26^2}{\cos(0)} + \frac{22^2}{\cos(5)} + \frac{17^2}{\cos(0)} + \frac{40^2}{\cos(10)} \right)$$

$$= 0.041123 \times (676.00 + 485.85 + 289.00 + 1624.68)$$

$$= 126.48$$

$$y_3 = \frac{\pi^2}{8 \times 30} \times \left(\frac{16^2}{\cos(5)} + \frac{42^2}{\cos(10)} + \frac{73^2}{\cos(20)} + \frac{32^2}{\cos(5)} + \frac{20^2}{\cos(0)} + \frac{21^2}{\cos(15)} \right)$$

$$= 0.041123 \times (256.98 + 1791.21 + 5671.00 + 1027.91 + 400.00 + 456.56)$$

$$= 394.93$$

The average volume of CWD/ha may is estimated using Equation 21:

$$\bar{y}(m^3/ha) = \frac{\sum_{i=1}^{n} y_i}{n}$$

Therefore, the estimate of average volume of CWD/ha is:

$$\frac{206.56 + 126.48 + 394.93}{3} = 242.66 \, m^3/ha.$$

The standard error of the estimate of the average volume of CWD/ha is determined using Equation 22:

$$S_{\bar{y}} = \sqrt{\frac{\sum_{i=1}^{n} y_i^2 - \frac{\left(\sum_{i=1}^{n} y_i \right)^2}{n}}{n \times (n-1)}}$$

Therefore, its standard error is:

$$\sqrt{\frac{(206.56^2 + 126.48^2 + 394.93^2) - \frac{(206.56 + 126.48 + 394.93)^2}{3}}{3 \times (3-1)}} = 79.57 \, m^3/ha$$

Confidence intervals are determined using the following equation:

$$P(\bar{y} - t_{n-1,\alpha/2} \times S_{\bar{y}} \leq \mu_y \leq \bar{y} + t_{n-1,\alpha/2} \times S_{\bar{y}}) = 1 - \alpha$$

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The 95% confidence interval for the estimate of average CWD volume/ha is:

$$P(242.66 - 4.303 \times 79.57 \le \mu_y \le 242.66 + 4.303 \times 79.57) = 1 - 0.05$$

$$P(-99.73 \le \mu_y \le 585.05) = 0.95$$

This confidence interval is quite wide because of the relatively high variability in CWD volume among the line transects and the small number of line transects established.

Average Number of CWD Pieces Per Hectare

The number of CWD pieces/ha based on each line transect is estimated using Equation 10:

$$y_i = \frac{10\,000 \times \pi}{2 \times L} \times \sum_{j=1}^{m_i} \frac{1}{(l_{ij} \times \cos \lambda_{ij})}$$

Using this equation:

$$y_1 = \frac{10\,000 \times \pi}{2 \times 30} \times \left(\frac{1}{3.5 \times \cos(0)} + \frac{1}{5.6 \times \cos(5)} + \frac{1}{4.2 \times \cos(10)} + \frac{1}{6.8 \times \cos(0)} + \frac{1}{7.5 \times \cos(15)} \right)$$

$$= 523.59 \times (0.28571 + 0.17925 + 0.24177 + 0.14706 + 0.13804)$$

$$= 519.31$$

$$y_2 = \frac{10\,000 \times \pi}{2 \times 30} \times \left(\frac{1}{3.3 \times \cos(0)} + \frac{1}{4.7 \times \cos(5)} + \frac{1}{2.9 \times \cos(0)} + \frac{1}{5.8 \times \cos(10)} \right)$$

$$= 523.59 \times (0.30303 + 0.21358 + 0.34483 + 0.17507)$$

$$= 542.71$$

$$y_3 = \frac{10\,000 \times \pi}{2 \times 30} \times \left(\frac{1}{2.5 \times \cos(5)} + \frac{1}{5.3 \times \cos(10)} + \frac{1}{6.2 \times \cos(20)} + \frac{1}{4.0 \times \cos(5)} + \frac{1}{3.1 \times \cos(0)} + \frac{1}{2.9 \times \cos(15)} \right)$$

$$= 523.59 \times (0.40153 + 0.19159 + 0.17164 + 0.25095 + 0.32258 + 0.35699)$$

$$= 887.63$$

As was the case for average volume of CWD/ha, the number of CWD pieces/ha is estimated using Equation 21:

$$\frac{519.31 + 542.71 + 887.63}{3} = 649.88 \text{ pieces/ha.}$$

Its standard error is:

$$\sqrt{\frac{(519.31^2 + 542.71^2 + 887.63^2) - \frac{(519.31 + 542.71 + 887.63)^2}{3}}{3 \times (3-1)}} = 119.07 \text{ pieces/ha}$$

The 95% confidence interval for the estimate of average number of CWD pieces/ha is:

$$P(649.88 - 4.303 \times 119.07 \le \mu_y \le 649.88 + 4.303 \times 119.07) = 1 - 0.05$$

$$P(137.52 \le \mu_y \le 1162.24) = 0.95$$

This confidence interval is quite wide because of the relatively high variability in CWD piece numbers among the line transects and the small number of line transects established.

Average Total Projected Area of CWD Per Hectare

Assuming that there is no overlap among the CWD pieces, Equation 13 can be used to estimate the total projected area/ha based on each line transect:

$$y_i = \frac{100 \times \pi}{2 \times L} \sum_{j=1}^{m_i} \frac{d_{ij}}{\cos \lambda_{ij}} \, \text{m}^2/\text{ha}$$

Using this equation:

$$y_1 = \frac{100 \times \pi}{2 \times 30} \times \left(\frac{15}{\cos(0)} + \frac{35}{\cos(5)} + \frac{21}{\cos(10)} + \frac{32}{\cos(0)} + \frac{45}{\cos(15)} \right)$$

$$= 5.2360 \times (15 + 35.134 + 21.324 + 32 + 46.587)$$

$$= 785.63$$

$$y_2 = \frac{100 \times \pi}{2 \times 30} \times \left(\frac{26}{\cos(0)} + \frac{22}{\cos(5)} + \frac{17}{\cos(0)} + \frac{40}{\cos(10)} \right)$$

$$= 5.2360 \times (26 + 22.084 + 17 + 40.617)$$

$$= 553.45$$

$$y_3 = \frac{100 \times \pi}{2 \times 30} \times \left(\frac{16}{\cos(5)} + \frac{42}{\cos(10)} + \frac{73}{\cos(20)} + \frac{32}{\cos(5)} + \frac{20}{\cos(0)} + \frac{21}{\cos(15)} \right)$$

$$= 5.2360 \times (16.061 + 42.648 + 77.685 + 32.122 + 20 + 21.741)$$

$$= 1100.91$$

Again, Equation 21 is used to estimate the average:

$$\frac{785.63 + 553.45 + 1100.91}{3} = 813.33 \, \text{m}^2/\text{ha}.$$

Its standard error is:

$$\sqrt{\frac{(785.63^2 + 553.45^2 + 1100.91^2) + \dfrac{(785.63 + 553.45 + 1100.91)^2}{3}}{3 \times (3-1)}} = 158.64 \, \text{m}^2/\text{ha}$$

The 95% confidence interval for the estimate of average total projected area/ha is:

$$P(813.33 - 4.303 \times 158.64 < \mu_y > 813.33 + 4.303 \times 158.64) = 1 - 0.05$$

$$P(130.70 < \mu_y > 1495.96) = 0.95$$

This confidence interval is quite wide because of the relatively high variability in the total projected area of CWD pieces among the line transects and the small number of line transects established.