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FOREST FLOOR RECOVERY INDEX: A TOOL TO ASSESS FOREST RECOVERY AFTER RECLAMATION

C.H. Shaw, D.R. Hoffman, M.F. Voicu, S.J. Kull, and C. McNalty

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Cover image: Decaying wood, moss, and fungal components of the forest floor.

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ABSTRACT

In the oil sands region of Alberta, governments and industry have asked for tools to assess the recovery of forest ecosystems after resource extraction and land reclamation. In this report, we describe the rationale, data collection, and development of the Forest Floor Recovery Index (FFRI), a system that uses forest floor characteristics in natural stands as a reference condition to judge success of ecosystem recovery after reclamation. Data collected for nine ecosite types and five stand-age classes in the Central Mixedwood Subregion of Alberta were used to develop the FFRI. Nineteen forest floor classes are described that users can classify on reclaimed sites and then use to calculate an FFRI score that indicates how well the forest floor is recovering by comparison to the reference condition. Woody material is important to building forest floors, and recommended application rates of woody material are provided for sites with low FFRI scores. The FFRI is available as a field manual and an app. The FFRI has potential for application in other parts of Alberta and Canada to assess recovery of forested land after reclamation.

RÉSUMÉ

Dans la région des sables bitumineux de l'Alberta, les secteurs public et privé ont demandé des outils pour évaluer le degré de récupération des écosystèmes forestiers après des activités d'extraction des ressources et de réhabilitation du terrain. Dans le rapport, nous décrivons les critères, la collecte de données et l'élaboration de l'Indice de récupération du tapis forestier (IRTF), un système utilisant les caractéristiques du tapis forestier dans les peuplements naturels comme conditions de référence pour estimer la réussite de la récupération de l'écosystème après la réhabilitation. Les données recueillies pour neuf types d'écosites et cinq catégories d'âges de peuplement dans la sous-région centrale de peuplements mixtes de l'Alberta ont été utilisées pour élaborer l'IRTF. Ce dernier comprend 19 catégories de tapis forestiers que les utilisateurs peuvent utiliser aux sites réhabilités pour calculer une cote d'IRTF, indiquant la mesure dans laquelle le tapis forestier récupère comparativement aux conditions de référence. Les matières ligneuses sont importantes pour recréer les tapis forestiers, et des taux d'application recommandés de ces matières sont procurés pour des sites ayant une faible cote d'IRTF. L'outil IRTF est offert en manuel pratique et en application. Il pourrait être utilisé en d'autres parties de l'Alberta et du Canada pour évaluer le taux de récupération des terres forestières après la réhabilitation.

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INTRODUCTION

In the oil sands region of Alberta, governments and industry are asking for tools to assess the recovery of forest ecosystems after resource extraction and land reclamation. The Alberta Environmental Protection and Enhancement Act (EPEA) requires that reclamation of land "permanently returns it to a land capability equivalent to its pre-disturbance state" meaning that "the ability of the land to support various land uses after conservation and reclamation is similar to the ability that existed prior to an activity being conducted on the land" (Province of Alberta 2017). Consequently, government and industry have asked for methods to assess the recovery of forest land that has been disturbed in order to extract oil. Alberta Environment (AENV 2006), the Cumulative Environmental Management Association (CEMA; CEMA 2009), and the Alberta Biodiversity Monitoring Institute (ABMI; ABMI 2014) have described the need for benchmark monitoring programs and provide some guidance on criteria for assessing landscape, soil, and vegetation recovery after reclamation. For soil, the ABMI (2014) recommends monitoring pH, electrical conductivity, bulk density, organic carbon, penetration resistance, and depth of organic horizons (LFH). Most of these recommended criteria are for the mineral soil and not the forest floor (organic horizons). The Alberta Energy Regulator (AER; AER 2014) requires that the organic horizons (L, F, H, and O) be classified according to the Canadian System of Soil Classification (Soil Classification Working Group 1998) and the thickness of the forest floor be measured in the pre-disturbance assessment on sites seeking approval for in situ or surface mining of bitumen, but they have no requirement to measure the forest floor to obtain a reclamation certificate (AER 2016). The requirement to measure the forest floor before disturbance suggests acknowledgment that the forest floor is important, and the absence of such a requirement for certification may have resulted from a lack of any convenient method for monitoring the recovery of forest floors after reclamation or the means to assess the results of monitoring. In this report, we describe the rationale, data collection, and development of the Forest Floor Recovery Index (FFRI), a system that uses forest floor characteristics in natural stands as a reference condition to judge success of ecosystem recovery after reclamation.

In boreal forests (such as the forests in the oil sands region), organic soil horizons (L,F,H,O horizons in the Canadian System of Soil Classification [Soil Classification Working Group 1998]) or humus forms (Klinka et al. 1981) (hereafter referred to as the forest floor) are diverse in thickness, composition, and state of decomposition, which are properties that vary among ecosite types and over stand age (0–100 years). The FFRI recognizes the importance of the forest floor to boreal forest ecosystems and uses variations in its properties to help assess the success of forest ecosystem recovery after reclamation in the Central Mixedwood Subregion (Beckingham and Archibald 1996) in Alberta. The FFRI is easy for practitioners to understand and use in the field.

The forest floor is important to ecosystem-level function, and therefore ecosystem recovery, because it is where most interactions among vegetation, soil fauna, and microorganisms occur (Ponge 2003); and it is reflective of overall site quality (Klinka et al. 1990), biodiversity, soil fertility, and soil productivity (Ponge at al. 2002). Feedbacks (interactions) that take place in the forest floor influence the processes and properties of the ecosystem as a whole (Wardle et al. 2004). This is especially true in the boreal, where nutrient cycling and soil biodiversity is concentrated in the forest floor, and where the forest floor can be thick and store significant amounts of carbon (C), at times equivalent to C storage in the above ground vegetation (Goodale et al. 2002). The accumulation of large amounts of C in thick forest floors of the boreal is a result of cold temperatures and acidic conditions (Deluca and Boisvenue 2012), which result in slow decomposition of dead mosses and dead tree biomass. Contributions of dead tree biomass to the forest floor can be large following natural disturbances (e.g., wildfire or windthrow).

A number of studies have shown that the absence of a forest floor can disrupt many of the interactions and processes that normally occur in forest ecosystems. In the Canadian boreal, removal of the forest floor caused microbial biomass C and nitrogen (N) to decrease in the surface mineral soil (Tan et al. 2005) and reduced total microbial biomass and enzyme activities (Tan et al. 2008). Forest floor removal also caused increased understory cover and decreased growth of both white spruce and aspen (Tan et al. 2006), possibly due to increased competition from the understory. After 10 years, the heights of white spruce and aspen continued to be negatively affected on sites where the forest floor was removed (Kabzems 2012). The disruption of fungal mycorrhizal networks can be a potential contribution to the negative effects of forest floor removal because most trees in the boreal forest form associations with ectomycorrhizal fungi to improve access to water and nutrients (Smith and Read 2008) and resistance to drought and disease (Van der Heijden et al. 2008). Mycorrhizae influence nutrient and C cycles (Wilson et al. 2009), especially in colder climates. The shift from bacterial to fungal decomposition that occurs as forests age is important to the development of soil structure, C sequestration, and nutrient availability (Hendrix et al. 1986; Beare et al. 1997). A goal of restoration ecology is to facilitate this shift earlier in ecosystem development (Harris 2009). Mackenzie and Naeth (2010) showed that transferring salvaged forest floor to reclamation sites can help to develop understory plant communities that are more similar to undisturbed upland forests in a shorter period of time, demonstrating the importance of the forest floor in maintaining plant biodiversity.

In many cases, coarse woody debris (CWD) in various states of decay is a significant contributor to forest floors. Tree stemwood and branches that produce CWD are added after major natural disturbances and during canopy closure. For the most part, these inputs may be absent on reclamation sites, as stemwood on a site destined for oil and gas development has often been harvested, burned, or buried. However, in naturally disturbed boreal mixedwood forests, volumes of woody debris may be as high as 400 m^3 ha^{-1} over small areas, and 65 m^3 ha^{-1} averaged at the plot level (Ter-Mikaelian et al. 2008). Efforts have been made to promote the integration of woody debris management in reclamation planning (Pyper and Vinge 2013). The benefits of woody debris in the forest ecosystem include reduced soil erosion (Whisenant 2005), increased microbial functional diversity (Kwak et al. 2015), improved competition of native over non-native species (Brown and Naeth 2014) and of seedlings over understory plants (Tedersoo et al. 2008). It also provides favorable substrate (Bernier 1996) and microsite (Gray and Spies 1997) conditions, which aid seedling establishment and survival. Decayed woody debris can prevent losses of soil N after disturbance, when N is translocated into wood from the soil by woody-decay fungi or when N in a soil water solution is absorbed by woody debris (Philpott et al. 2014). Removal of CWD can have long-term effects on forest ecosystems. For example, tree growth was reduced over 10–20 years after harvesting (Jacobson et al. 2000; Thiffault et al. 2011) on sites where whole tree harvesting removed most woody debris, and in Northern British Columbia Hartmann et al. (2012) found that the soil microbial community remained strongly affected up to 15 years after harvesting — with fungi showing a stronger response than bacteria. Coarse woody debris inputs and decay are critical to forest ecosystem health, and the FFRI system provides recommendations for woody debris application rates to reclaimed sites with low FFRI scores.

The approach used in the development of the FFRI compares forest floor properties on test sites ("one of a population of sampling locations that are exposed in some degree to environmental stressors or anthropogenic disturbances" [Ciborowski et al. 2013]) with data analyzed from stands established by natural (wildfire) disturbances as reference sites ("one of a population of sampling locations that, taken collectively, represent the best ecological conditions attainable given the prevailing climate, topography, soil, geology, potential vegetation, and general land use of the region" [Ciborowski et al. 2013]); further, it uses changes in these properties during stand development as an indicator of ecosystem recovery as a whole. In place of using the forest adjacent to a reclaimed site as a reference, forest floor data were collected on upland reference sites ranging from 0 to 100 years since the last major disturbance at as many regional ecosite types as possible (ABMI 2014). This approach allows for comparisons of reclaimed sites to reference sites where a similar amount of time has passed since the stand initiating disturbance (a site reclaimed 10 years before can be compared to a set of reference sites sampled 6–15 years after a forest fire, and a site reclaimed 20 years before can be compared to a set of reference sites sampled 16–40 years after a forest fire).

The development of the FFRI initially used the humus form classification system of Klinka et al. (1981) for classification of forest floors in the field. The classification system was then modified to include types unique to the Central Mixedwood Subregion (Beckingham and Archibald 1996) that were not found in Klinka et al. (1981) and then simplified for regional users. Humus forms, Mull, Moder, and Mor, are forest floor taxonomic classes that differ in structure, nutrient cycling, and biological communities (including soil organisms like collembola, mites, insect larvae) (Klinka et al. 1981). Generally, Mulls are associated with high rates of nutrient cycling, mixing of organic and mineral soil by soil fauna, and decomposition dominated by bacteria. There is less activity of macrofauna in Mors; the organic horizons accumulate on the surface of the mineral soil rather than being mixed, and decomposition is mainly fungal. Moders have properties that transition between those of Mulls and Mors. Most often, the humus forms that develop under the cold, acidic conditions encountered in boreal forests are classified as Mors (Klinka et al. 1981), and these are the focus of the FFRI.

The FFRI system comprises a field manual and an app; this Information Report describes the data collection and development of the FFRI system. The field manual provides a simple explanation of the system and direction on how to sample and describe forest floors. It provides many images of different forest floor types to help users with classification. The manual guides users through simple calculations to arrive at an FFRI score, which can be used to evaluate recovery of the forest floor while taking into account differences in ecosite types and time since reclamation. Finally, it provides recommendations8 for woody debris application rates based on ecosite type and FFRI score. The FFRI app contains all the information in the FFRI manual, is easy to use in the field for data collection, and it calculates the FFRI score as data are being entered. The FFRI was developed for soils with organic horizons ≤ 40 cm thick overlying mineral soil. It should not be used for peatlands or soils in the Organic Order (> 40 cm thick) (Soil Classification Working Group 1998).

METHODS

Reference Condition Approach

The FFRI uses a reference condition approach (RCA). This approach has been used to conduct bioassessments of freshwater ecosystems through comparison of anthropogenically disturbed test sites to minimally disturbed reference sites (Hughes 1995; Reynoldson et al. 1997; Bailey et al. 2004), but it can be used to monitor ecosystem properties other than biodiversity indicators and has the potential to be adapted to the boreal forest (Ciborowski et al. 2013). The RCA defines healthy ecosystems empirically through the establishment of a reference condition by sampling of a series of reference sites. The FFRI uses forest floor properties within different ecosite types, and stand ages (0 to 100 years since disturbance), as an indication of overall ecosystem recovery. It compares forest floors sampled at disturbed (test) sites to a set of reference sites that have been sampled to establish forest floor recovery criteria. The FFRI is consistent with the approach of CEMA, which uses criteria and indicators that include measures, methods, and thresholds (CEMA 2009). Measures are qualitative or quantitative variables that can determine if a standard has been achieved or if there is a trend in an indicator; methods are used to assess the procedures for attaining measures; and thresholds are minimum values of measures that must be exceeded to achieve an indicator (CEMA 2009). The FFRI measures are thickness, Woody and Mixed material groups, and F Mor and H Mor horizon groups. Methods for assessing these measures are described in the first sections of the FFRI field manual (Hoffman et al. 2017, 2018a) and app (Hoffman et al. 2018b), and threshold values are presented for each combination of age class and ecosite in the index tables, all of which will be described in this report. Threshold values in the beta version of the FFRI (Hoffman et al. 2017) were updated in the second edition (Hoffman et al. 2018a), and practitioners interested in calculating a score to assess recovery should use the second edition. Those interested in information about forest floors and their classification can use either FFRI manual (Hoffman et al. 2017, 2018a).

Field Study Site Selection (Beta Version)

Reference sites in an RCA should be chosen based on criteria established a priori, and stratified based on geographic variation in the region (Omernik 1987). An acceptable site can be defined as existing in a minimally disturbed condition without a history of significant human disturbance or a least disturbed condition where the best available physical, chemical, and biological habitat conditions in the region occur, given the present state of the landscape (Stoddard et al. 2006). Our objective was to make the FFRI relevant to reclamation in the oil sands region of Alberta so sampling was conducted in the Central Mixedwood Subregion (Fig. 1). Sites were stratified according to ecosite or ecosite phase (Beckingham and Archibald 1996). Within each stratum, we organized sites to represent five age classes (0–5, 6–15, 16–40, 41–75, 76–100 years since the last stand-replacing disturbance). Age classes early in stand development were more finely divided than older age classes in order to provide reference data suitable for evaluation of the early stages of recovery after reclamation. Collecting data by age class is especially important in forest ecosystems that develop and change over decades. Having this data ensures that comparisons between disturbed and reference sites are made at similar stages of ecosystem development. Our goal was to find three sites for each combination of age class and ecosite or ecosite phase.

Reference sites sampled for the FFRI included reference plots (n = 11) established by CEMA (CEMA 2013), which were sampled in 2014, and temporary plots (n = 91) established by the Canadian Forest Service solely for the purpose of collecting data for the FFRI, which were sampled in 2015 and 2016 (Table 1; Appendix 1). All CEMA sites had been classified to ecosite phase by CEMA. Candidate sites for temporary plots were identified using an Alberta Vegetation Inventory (AVI) GIS layer from Alberta Pacific Forest Industries (AlPac) restricted to areas within 500 m of accessible roads. Information on leading tree species

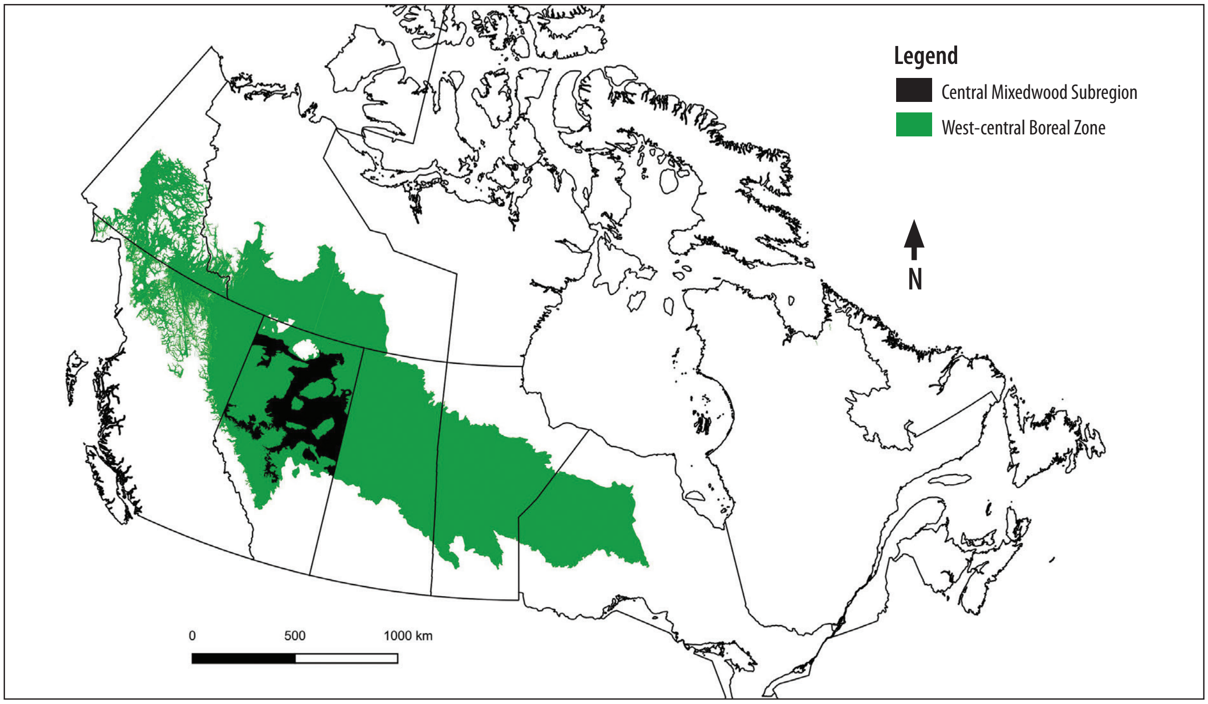


Figure 1. Map of Canada showing the Central Mixedwood Subregion (Beckingham and Archibald 1996), where data were collected to develop the Forest Floor Recovery Index (FFRI) and the West-central Boreal Zone (CNVC 2018). Forest floor development of the West-central Boreal Zone may be similar to the Central Mixedwood Subregion, and it could be a region where the FFRI could be used. Map courtesy of Ken Baldwin, Canadian Forest Service, Great Lakes Forestry Centre, Sault Ste. Marie, ON.

(*Picea glauca* (Moench) Voss [white spruce], *Populus tremuloides* Michx. [trembling aspen], *Pinus banksiana* Lamb. [jack pine], or a mix of these) and years since the last stand-replacing natural disturbance were used from the AVI to determine candidate sites. Candidate sites were evaluated for disturbance effects in the field to ensure that only sites subject to minimal or no anthropogenic disturbance were used. Sites sampled in 2015 were post-stratified by ecosite (a, b, c, e, f and h) and ecosite phases (d1, d2, and d3) (Beckingham and Archibald 1996), based on photographs of the sites and information recorded during sampling about the tree and understory plant species on the site. In 2016, ecosite and ecosite phase (Beckingham and Archibald 1996) classification was done on site. These sites were used to develop the beta version of the FFRI (Hoffman et al. 2017).

Data Collection (Beta Version)

Several photographs were taken of each plot for use in the FFRI manual and app, and for subsequent confirmation of ecosite classes, if necessary. Observations of understory plants at each site were recorded, along with macrofauna in the forest floor, such as earthworms, beetles, or beetle larvae. Coordinates (GPS) were taken using a Garmin GPSMAP 64st at the intersection of two perpendicular transects at the center of the site, or in cases where only one transect was used, on or between the central flag(s). Coordinate accuracy ranged between 3 m and 10 m.

At temporary plots, approximately 13 forest floor samples (Appendix 1) were taken every 4 m along a single transect or two perpendicular transects (Figs. 2, 3). At the CEMA plots, a 4-m x 4-m grid was used to sample the entire permanent plot (20 samples per plot). Detailed data were collected at these sites to support other scientific studies. The configuration of the transects was determined by the shape of the stand to ensure that sampling was contained within one ecosite type. Each forest floor sample was approximately 20 cm X 20 cm, excavated at least down to the mineral soil, and sometimes including several centimeters of the mineral soil (Fig. 4). Samples were classified in the field according to the *Taxonomic classification of humus forms in ecosystems of British Columbia* (Klinka et al.

Table 1. Number of sites sampled in each ecosite or ecosite phase and age class combination[a]

Ecosite/Ecosite phase[b]	Ecosite description	Age class (years)[c]				
		0 to 5	6 to 15	16 to 40	41 to 75	76 to 100
a	"a" ecosites (lichen) have jack pine as the leading species. Sites are xeric or subxeric with poor nutrient regimes and sandy textured, rapid- to well-drained soils.	6	3	1	3	1
b	"b" ecosites (blueberry) tend to have aspen as the leading species but may have white spruce or jack pine as a coleading or leading species. Sites are subxeric or submesic with poor or medium nutrient regimes and sandy or sandy loam textured, well-drained soils.	2	3	5	7	2
c	"c" ecosites (Labrador tea) have jack pine as the leading species and have a secondary canopy of black spruce. Sites are mesic or submesic with poor nutrient regimes and sandy to loamy textured, well-drained soils.	0	3	0	6	2
d1	"d1" ecosites (low-bush cranberry Aw) have aspen as the leading species. Sites are mesic with medium nutrient regimes and fine-textured, moderately well-drained soils.	2	1	7	9	3
d2	"d2" ecosites (low-bush cranberry Aw-Sw) have aspen as the leading species with white spruce as a secondary canopy. Sites are mesic with medium nutrient regimes and fine-textured to loamy, moderately well-drained soils.	2	1	3	7	4
d3	"d3" ecosites (low-bush cranberry Sw) have white spruce as the leading species. Sites are mesic or subhygric with medium nutrient regimes and fine-textured, moderately well to well-drained soils.	1	1	2	0	4
e	"e" ecosites (dogwood) have balsam poplar, aspen, and/or white spruce as the leading, coleading, or secondary canopy species. Sites are subhygric with rich nutrient regimes and fine-textured, imperfectly drained soils.	1	0	3	5	4
f	"f" ecosites (horsetail) have white spruce, balsam poplar, and/or aspen as the leading, coleading, or secondary canopy species. Sites are hygric with rich to very rich nutrient regimes and fine-textured, imperfectly drained soils.	0	1	3	0	1
h	"h" ecosites (Labrador tea/horsetail) have white spruce as the leading species and have a secondary canopy of black spruce. Sites are hygric with rich to very rich nutrient regimes and fine-textured, imperfectly drained soils.	2	0	0	0	4

[a] Note: sampled sites include 101 sites from beta version and 14 sites from field testing for a total of 115 sites.

[b] Ecosites and ecosite phases were classified according to Beckingham and Archibald (1996).

[c] Age-classes represent categories for the number of years since the last stand-replacing natural disturbance.

1981) and total thickness of the organic horizons was measured. Many photographs were taken of forest floor samples with the aim of recording the variation in their physical structure for use in the FFRI field manual and app.

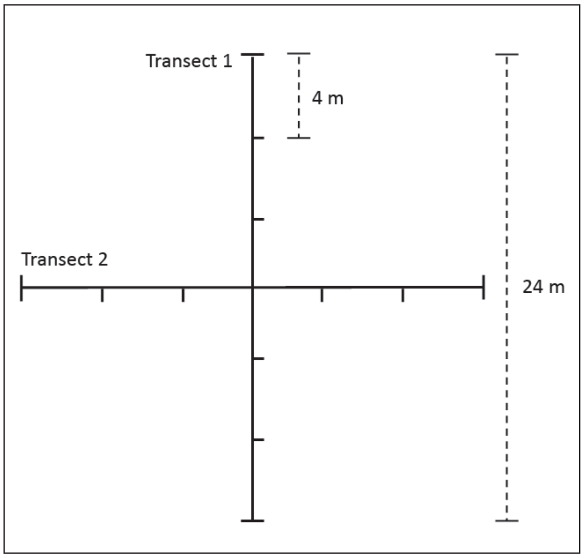


Figure 2. Sampling design used in the field study. Forest floor samples from the temporary plots were taken along two perpendicular transects at 4-m intervals for 13 samples (the intercept of the two transects was sampled only once). In some instances the dimensions of the site required that a single longer transect be used, and some of the Cumulative Environmental Management Association plots were sampled more intensively on a 2-m by 2-m, or 4-m by 4-m grid.

Figure 3. Flags marking sampling points along a transect.

Trees were cored at each plot to determine stand age based on the dominant softwood and/or hardwood species identified in the AlPac AVI polygon information. Two trees were cored for each dominant tree species at a plot. Trees selected for coring were chosen at random from the most common height class for the species within the plot. The diameter of each cored tree was measured in centimeters at approximately 1.3 m from the base of the tree (diameter breast height) using a Lufkin diameter steel tape. Cored tree height was measured using a Haglöf Vertex IV. These data were used to create the beta version of the FFRI (Hoffman et al. 2017).

Field Testing of the FFRI (Beta Version)

Field testing of the beta version of the FFRI was conducted in July and September of 2017 on 17 reclaimed well pads and in 14 reference forested sites adjacent to the well pads near Whitecourt and Slave Lake. Sites were a subset of plots that were used in the development of the Ecological Recovery Monitoring Protocols (ERMP 2017). Plot locations, well pad reclamation dates, and year of the most recent forest fire

Figure 4. Woody F Mor forest floor sample. Leaf litter is visible at the top of the sample, and the F horizon is made up mostly of a decomposing log. The mineral soil can be seen at the bottom of the sample.

for the adjacent forested site (which was taken as the year of stand initiation) were provided by Dr. Anne McIntosh from the Department of Renewable Resources, University of Alberta. The ecosite class was determined on site using the *Field guide to ecosites of northern Alberta* (Beckingham and Archibald 1996). At each site, the users were split into two groups according to whether they were an experienced user of the FFRI (two persons) or a new user (three persons). New users did not have experience in forest floor classification, including use of the FFRI. Both groups assessed the adjacent reference forested stand and the well pad. First, the experienced users established and sampled a plot in the reference forested stand, while the new users established and sampled near the center of the well pad. Then, the groups switched plots. Field staff used the same methods for sampling as those for the FFRI reference sampling in 2015 and 2016, with 13 samples taken across two perpendicular transects. Data for the thickness, horizon group, and material group of each sample were entered into a beta version of the FFRI app. After sampling the first site, the new users were given brief instructions on differentiating between F, H, and Ah horizons. On the second day at the next two sites (a well pad site and the adjacent naturally disturbed forest), the experienced users accompanied the new users as they sampled and classified the samples, answering any questions about differentiating horizons or materials and providing specific hints for making these distinctions. However, the new users made their own final decisions regarding the class of each sample, while the experienced users recorded their classification separately. At subsequent sites, new users were able to ask occasional questions about specific forest floor properties, but they were not told the classifications of the experienced users until they had entered their own data, and only then in cases where doing so illustrated certain distinctions between materials or horizons.

Modeling to Predict Woody Inputs

Woody material transferred to the forest floor through natural disturbance events (e.g., wildfire) is a significant input for building forest floors, but it is not routinely added to reclamation sites. To provide the organic material needed to build the forest floor, a modeling approach was used to develop recommendations for woody debris application rates on reclaimed sites. The Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) (Kurz et al. 2009) was used to estimate inputs for each ecosite type at the time of disturbance and over time (100 years) as a stand develops. The CBM-CFS3 is an upland forest stand- and landscape-level modeling framework that can be used to simulate the dynamics of all forest C stocks, including response to natural disturbances such as wildfire (Kurz et al. 2009). The main input that drives the model for a stand (or plot) is a merchantable yield curve. Yield curves were produced for each ecosite type with a SAS version of the Growth and Yield Projection System (GYPSY) (ASRD 2009). This was accomplished using planting densities by species groups (aspen, white spruce, and pine) for crown closure class AB (i.e., less than 51% of ground area covered by a vertical projection of tree crowns on the ground [AENV 2010]) and crown closure class CD (i.e., more than 51%). This follows specifications in AENV (2010) for dry and moist rich types (i.e., Tables 4–6, 4–8, 4–10, and 4–11 in AENV [2010]) (Appendix 2). Site index (minimum, average, and maximum), by species, was taken from Beckingham and Archibald (1996). For both coniferous and deciduous trees, the yield curves produced with GYPSY were developed at a 13/7 utilization standard (i.e., merchantable tree that has a minimum diameter of 13 cm outside bark at stump height [30 cm] and a minimum top diameter of 7 cm inside the bark [Alberta Government 2016]).

Along with tree species data, yield curves were used as inputs to the CBM-CFS3 to model transfers of C from live to dead woody biomass for each ecosite type at the time of a stand-replacing wildfire (at a stand age of 100 years), and resulting from stand closure for 100 years after the wildfire disturbance. Wood application rates were estimated for live merchantable stem wood (diameter ≥ 9 cm) to CWD, and other wood (living branches, bark, and non-merchantable sized trees with a diameter < 9 cm) to small/fine woody debris (SFWD). Modeled predictions were used to provide recommendations for tree volume inputs required to build natural forest floors. Modeled woody inputs estimated from the CBM-CFS3 are in C (measured in tonnes), which was converted to volume of wood (measured in cubic meters) using a multiplier of 4 (Appendix 3). Estimates were provided in wood volume rather than C or biomass because these are the units best understood by operators that would apply woody debris for reclamation purposes.

RESULTS

Field Data (Beta Version)

A total of 102 sites were sampled, 11 in 2014, and 91 in 2015 and 2016; these sites ranged in age from 0 to 105 years for ecosites "a" to "h" (Beckingham and Archibald 1996). The "g" ecosite type was excluded from the manual because only one "g" ecosite site was found, leaving 101 sites, which were used in development of the beta version of the FFRI. Eventually all data (101 sites from the beta version plus 14 sites from field testing) were used to develop the second edition of the FFRI (Table 1; Appendix 1). Our overall goal was to sample three sites for each combination of ecosite type and age class, but we did not fully achieve this due to limitations in time and availability of accessible sites for some combinations of ecosite (or ecosite phase) and age class (Table 1). In particular, it was difficult to find sites for the full range in ecosite types for the more finely divided younger age classes and for the wetter ecosite types (e–h). However, the distribution of plots across ecosite types was similar to Beckingham and Archibald (1996) (Table 2), suggesting that our sample was proportionally representative of the ecosite types in the subregion. The possibility of representing all age classes in all ecosite types depends on the frequency and distribution of stand-replacing natural (wildfire) disturbances in relation to the distribution of ecosite types on the landscape. Consequently, it was easy to find "d" ecosite phases in the 16–40 year age class because this type dominates the landscape south of Ft. McMurray on highway 63 as a result of the Mariana Lake fire in 1995, but it was difficult to find all ecosite types in the 6–15 year age class because there were few large fires in the subregion 6–15 years ago.

In the field, all forest floors were classified according to the humus form classification system of Klinka et al. (1981). After examining all the data, they were organized into 19 forest floor classes (Table 3; Hoffman et al. 2017, 2018a), each with a simple name using colloquial terms to make regional forest floor classification easy for users of the manual and app. Most of the forest floor classes have an equivalent classification in Klinka et al. (1981), with the

Table 2. Comparison of sampling for the *Field guide to ecosites of northern Alberta* (Beckingham and Archibald 1996) with sampling for the Forest Floor Recovery Index (FFRI)[a]

	Field guide to ecosites of northern Alberta		Forest Floor Recovery Index	
Ecosite[b]	N	Percent of all samples	N	Percent of all samples
a	75	5.1	14	12
b	110	7.5	19	17
c	49	3.3	11	10
d1	639	43.6	22	19
d2	233	15.9	17	15
d3	74	5.1	8	7
e	167	11.4	13	11
f	95	6.5	5	4
h	22	1.5	6	5

[a] The percentage for ecosite d1 was much lower for FFRI than for the field guide, and higher for ecosites a, b, c, and h. This is because sampling effort for the FFRI was allocated to provide replication in each ecosite type, whereas sampling for the field guide was allocated proportional to the area occupied by each ecosite type.

[b] Ecosites and ecosite phases were classified according to Beckingham and Archibald (1996).

Table 3. Descriptions of the Forest Floor Recovery Index (FFRI) forest floor classes and their equivalent class in *Taxonomic classification of humus forms in ecosystems of British Columbia* (Klinka et al. 1981)

FFRI class[a]	Number of samples[b]	Horizon sequence	Description	Equivalent class in Klinka et al. 1981
Ordinary L Mor	91 (89)	L, F	The L horizon accounts for at least 70% of the L, F, and H combined thickness. Ordinary L Mors have a thin F horizon accounting for less than 30% of the total thickness of the combined organic horizons, and tree litter makes up a significant portion of the organic material.	Orthivelomor, Amphivelomor
New L Mor	33 (-)c	L	The L horizon accounts for nearly 100% of the L, F, and H combined thickness. New L Mors are made up of undecomposed tree litter (needles or leaves).	Neovelomor
Ordinary F Mor	28 (23)	L, F, (H)	The F horizon accounts for at least 70% of F and H combined thickness. In Ordinary F Mors, partially or well-decomposed tree litter makes up at least 50% of the organic material.	Orthihemimor
Woody F Mor	128 (123)	L, F, (H)	The F horizon accounts for at least 70% of F and H combined thickness. Woody F Mors have F horizons made up of at least 50% decaying wood. Most of this wood originates from coarse (≥ 7 cm diameter) woody debris.	Lignohemimor
Mixed F Mor	24 (11)	L, F, (H)	The F horizon accounts for at least 70% of F and H combined thickness. Mixed F Mors contain a mixture of recognizable plant residues (small wood fragments < 7 cm diameter, roots, bark, needles, cones) with yellow, brown, or red colors.	No equivalent class
Mossy F Mor	46 (45)	L, F, (H)	The F horizon accounts for at least 70% of F and H combined thickness. Mossy F Mors have an F horizon made up almost entirely of dead moss. The surface of the forest floor may be mostly live moss.	No equivalent class
Fungal F Mor	3 (-)	L, F, (H)	The F horizon accounts for at least 70% of F and H combined thickness. Fungal F Mors have an F horizon made up of at least 50% yellow or white fungal hyphae.	Mycohemimor
Ordinary FH Mor	19 (16)	L, F, H	There is no dominance of either the F or H horizon, each horizon accounting for between 30% and 70% of their combined thickness. In Ordinary FH Mors, partially or well-decomposed tree litter makes up at least 50% of the organic material.	Orthihemihumimor
Woody FH Mor	164 (144)	L, F, H	There is no dominance of either the F or H horizon, each horizon accounting for between 30% and 70% of their combined thickness. Woody FH Mors have F and H horizons made up of at least 50% decaying wood. Most of this wood originates from coarse (≥ 7 cm diameter) woody debris.	Lignohemihumimor
Mixed FH Mor	82 (56)	L, F, H	There is no dominance of either the F or H horizon, each horizon accounting for between 30% and 70% of their combined thickness. Mixed FH Mors contain a mixture of recognizable plant residues (small wood fragments < 7 cm diameter, roots, bark, needles, cones) with yellow, brown, or red colors.	Residuohemihumi-mor
Mossy FH Mor	26 (23)	L, F, H	There is no dominance of either the F or H horizon, each horizon accounting for between 30% and 70% of their combined thickness. Mossy FH Mors have F and H horizons made up almost entirely of moss. The surface of the forest floor may be mostly live moss.	No equivalent class

Table 3. Concluded

FFRI class[a]	Number of samples[b]	Horizon sequence	Description	Equivalent class in Klinka et al. 1981
Fungal FH Mor	3 (-)[c]	L, F, H	There is no dominance of either the F or H horizon, each horizon accounting for between 30% and 70% of their combined thickness. Fungal FH Mors have F and/or H horizons made up of at least 50% yellow or white fungal hyphae.	Mycohemihumimor
Ordinary H Mor	194 (166)	L, (F), H	The H horizon accounts for at least 70% of F and H combined thickness. In Ordinary H Mors, partially or well-decomposed tree litter makes up at least 50% of the organic material.	Orthihumimor
Woody H Mor	368 (344)	L, (F), H	The H horizon accounts for at least 70% of F and H combined thickness. Woody H Mors have an H horizon made up of at least 50% decaying wood. Most of this wood originates from coarse (≥ 7 cm diameter) woody debris.	Lignohumimor
Mixed H Mor	190 (152)	L, (F), H	The H horizon accounts for at least 70% of F and H combined thickness. Mixed H Mors contain a mixture of recognizable plant residues (small wood fragments < 7 cm diameter, roots, bark, needles, cones) with yellow, brown, or red colors.	Residuohumimor
Mossy H Mor	25 (24)	L, (F), H	The H horizon accounts for at least 70% of F and H combined thickness. Mossy H Mors have an H horizon made up almost entirely of decomposed moss. The surface of the forest floor may be mostly live moss.	No equivalent class
Fungal H Mor	4 (-)	L, (F), H	The H horizon accounts for at least 70% of the total thickness of F and H horizons. Fungal H Mors have an H horizon made up of at least 50% yellow or white fungal hyphae.	Mycohumimor
Hydromor	27 (17)	L, F, H, (Of, Om, Oh)	Hydromors were developed under prolonged but not permanent saturation of at least a portion of the profile, with F and H horizons accounting for at least 50% of the total thickness of organic horizons.	Hydromor
O Hydromor	15 (12)	(L, F, H), Of, Om, Oh	O Hydromors were developed under permanent saturation of at least a portion of the profile, resulting in poor aeration, with the O horizons accounting for at least 50% of the total thickness of organic horizons.	Histomor

[a] Each class consists of a combination of a horizon group (Table 7) and a material group (Table 6), which are reflected in the descriptions and horizon (Table 8) sequences. Figure 15 shows an example of how each class is presented in the FFRI manual, including four images of the class along with the information presented in this table (excluding equivalent class in Klinka et al. 1981).

[b] The number inside the parentheses is the total number of samples used for the beta version of the FFRI.

[c] Dashes indicate no change in value.

exception of Mixed F Mor and the three Mossy Mors (Mossy F, FH and H). The Mixed F Mor comprises a mixture of a variety (small wood fragments, roots, bark, needles, and cones) of moderately decomposed plant residues. Klinka et al. (1981) only recognizes these types in the more decomposed FH (Residiohemihumimor) and H (Residiohumimor) humus forms. Mixed F Mors, as defined in the FFRI manual and app, were observed at all ecosites except for "d1," "d2," and "f." Mosses are ubiquitous in the boreal forest, and this was reflected in the types of forest floors that were observed. We created three Mossy forest floor classes to recognize their importance at a high level of organization in the FFRI forest floor classification system. Although Klinka et al. (1981) uses "O" master horizons, they are defined by being associated with wetlands and not by being composed of mainly mosses, and they are used at a low level of organization with adjectives such as "histic" and "sapric" to describe the stage of decomposition of O horizons. An update to Klinka et al. (1981), by Green et al. (1997), includes a “sphagno” designation for samples with moss dominated F horizons, but in our field study we encountered more variation in moss forest floor types. Mossy material groups were most common at “h” ecosites (21%), followed by “a” and “c” ecosites (both about 17%). Of the Mossy material group classes, Mossy F Mors were most common (*n* = 45), followed by Mossy H Mors (*n* = 24), and Mossy FH Mors (*n* = 22).

As a result of natural disturbance regimes, more than 60% of all forest floor samples were dominated by woody material (classified in either a Woody or Mixed horizon group), demonstrating how ubiquitous decaying wood is in the forest floors of the Central Mixedwood Subregion. Woody H Mors were the most commonly encountered forest floor type (*n* = 344; Table 3), followed by Woody FH Mors (*n* = 144), Mixed H Mors (*n* = 152), Ordinary H Mors (*n* = 166), and Woody F Mors (*n* = 123). There were 611 samples designated as a Woody material group, compared to 219 as a Mixed material group, and 294 as an Ordinary material group. H Mors were the most common horizon group (*n* = 690), followed by FH Mors (*n* = 242), F Mors (*n* = 205), L Mors (*n* = 122), and then Hydromors plus O Hydromors (*n* = 29) (Table 3). The most commonly observed material across all of the sites was well-decomposed woody material.

Field Testing of the FFRI (Beta Version)

Field testing of the beta version of the FFRI (Hoffman et al. 2017) allowed us to evaluate how the system (forest floor classification and resulting FFRI scores of 1–3 [see section on “Development of the FFRI”]) worked on an independent set of sites for experienced users, and how well inexperienced users were able to use the system. Results from the field testing of the beta version by experienced users showed that more than half of the forested reference sites received a score of 1, and all but one of the others had a score of 2 (Table 4). Our expectation was that a larger proportion, if not all, of the forested sites would receive a score of 1, suggesting that the threshold values in the beta version were too stringent in some cases, and these would have to be modified for the second edition of the FFRI (Hoffman et al. 2018a). Scores for the forested reference sites were the same between experienced and inexperienced users about 40% of the time. For the remaining forested reference sites, scores differed by one, except for on the first day where the score from experienced users was 1, and for inexperienced users 3 (Table 4). Final scores for the well pad sites were identical for experienced and inexperienced users. All reclaimed well pads except one (site 10; Table 4) received a score of 3, and according to the FFRI, would require application of woody material to help the development of a forest floor.

Differences in forest floor classification between experienced and inexperienced users were large on day one (Table 4). However, the differences between user groups became smaller with minimal training (approximately 3 hours) and as experience of new users developed over the 8-day test period. This indicated that future users would benefit from some training from experienced users. The differences in forest floor classification did not have a large effect on the final score, indicating that the flexibility built into the system for calculating the score worked well. Scores that did not match but were close would be reconciled by modifying some threshold values that the testing indicated were too stringent. New users found it particularly difficult to distinguish H horizons from Ah and F horizons and to determine the origins of materials within H horizons. They asked for more explanation of rarely occurring forest floor types that are not Mors. The new users were inclined to rely more heavily on the images (Reference Examples section in the field manual) than descriptions in the text (Reference Examples or Forest Floor Classification sections in the field manual), and that could lead to misclassifications. Experienced users noted the importance of illustrating to new users the effect of invasive earthworm disturbance on forest floors. They also emphasized the need to provide examples of forest floors on well pads to illustrate to new users the fundamental differences between a forest floor on a reclaimed site compared with a natural site. All results and observations from the field testing were used to improve the second edition of the FFRI (Hoffman et al. 2018a).

Modeling to Predict Woody Inputs

Two estimates for the volume (measured in cubic meters per hectare) of coarse and small/

Table 4. Comparison of sampling results in the adjacent forested reference sites and reclaimed well pad sites from experienced (e) and new (n) users of the beta version of the Forest Floor Recovery Index

Site type	Site[a] number	Site[b] name	Day	Thickness (cm)		Horizons H		Horizons F		Horizons FH		Mixed/ Woody		Score	
				e	n	e	n	e	n	e	n	e	n	e	n
Forested	1	bor1	1	7	4	8	0	4	0	4	0	8	0	1	3
	2	foot13	1	11	13	9	8	2	5	2	5	11	5	1	3
	3	foot15	2	5	5	2	2	2	3	2	3	7	6	2	2
	4	bor4	2	18	21	7	12	6	1	6	1	13	13	1	2
	5	bor6	3	11	13	7	0	4	12	4	12	9	7	2	2
	9	foot7	4	17	18	11	12	2	1	2	1	5	7	2	2
	10	bor15	5	17	11	8	3	5	7	5	7	12	8	1	2
	11	bor9	5	16	16	8	7	4	4	4	4	12	12	1	1
	12	foot3	5	11	13	5	7	6	5	6	5	7	6	1	2
	13	foot9	6	27	23	8	12	5	1	5	1	8	7	1	2
	14	bor14	6	13	13	2	2	3	7	3	7	13	8	2	1
	15	bor10	7	20	17	8	8	5	5	5	5	10	9	1	1
	16	foot11	7	14	15	8	6	4	7	4	7	11	11	1	1
	17	foot12	8	40	40	0	1	0	0	0	0	3	2	3	3
Well pad	1	bor1	1	7	5	7	0	4	12	4	12	9	7	3	3
	2	foot13	1	2	5	3	10	1	3	1	3	1	0	3	3
	3	foot15	2	1	1	0	0	0	0	0	0	0	0	3	3
	4	bor4	2	3	5	8	10	0	0	0	0	1	0	3	3
	5	bor6	3	2	8	1	5	1	5	1	5	3	3	3	3
	6	bor7	3	6	6	0	0	1	0	1	0	0	0	3	3
	7	foot10	3	3	5	6	13	0	0	0	0	0	0	3	3
	8	bor8	3	5	8	10	13	0	0	0	0	0	0	3	3
	9	foot7	4	3	5	6	13	0	0	0	0	0	0	3	3
	10	bor15	5	24	16	9	9	2	2	2	2	4	4	2	2
	11	bor9	5	6	7	6	6	0	0	0	0	2	2	3	3
	12	foot3	5	8	10	12	7	0	4	0	4	1	1	3	3
	13	foot9	6	8	6	0	4	7	6	7	6	1	3	3	3
	14	bor14	6	6	7	9	7	3	6	3	6	0	0	3	3
	15	bor10	7	5	5	13	10	0	3	0	3	0	1	3	3
	16	foot11	7	4	3	2	0	6	2	6	2	1	0	3	3
	17	foot12	8	2	4	2	0	3	3	3	3	0	0	3	3

[a] Forested sites 6–8 were not sampled as an appropriate reference site (minimally disturbed sites of wildfire origin suitable for ecosite classification) could not be located.

[b] Name of site provided by Dr. Anne McIntosh, University of Alberta.

fine wood transferred from living biomass to the forest floor were estimated for each ecosite using the CBM-CFS3. The first value is an estimate of the volume for the year of disturbance, and the second value is an estimate of the cumulative volume for the additions over the subsequent 100 years (Table 5). Final values for volumes of coarse wood ranged from 23 m^3 ha^{-1} (ecosite "d^3") to 116 m^3 ha^{-1} (ecosite "d1") at the time of the disturbance and from 2 m^3 ha^{-1} (ecosites "h" and "d3") to 18 m^3 ha^{-1} (ecosite "d1") for the annual additions related to the subsequent 100 years. Final values for volumes of small/fine wood were 23 m^3 ha^{-1} (ecosite "d3") to

Table 5. Predicted volumes of woody material transferred from living biomass to dead wood at the time of a wildfire (year 0), and over the following 100 years (years 1–100), modeled using the CBM-CFS3

Ecosite[a]	Volume coarse wood (m^3 ha^{-1})[b]		Volume small/fine wood (m^3 ha^{-1})	
	Year 0	Years 1–100	Year 0	Years 1–100
a	76	12	46	161
b	98	15	56	183
c	75	11	46	161
d1	116	18	71	207
d2	114	16	66	191
d3	23	2	23	23
e	58	8	46	119
r	59	8	47	125
h	24	2	24	24

[a] Ecosites and ecosite phases are classified according to Beckingham and Archibald (1996).

[b] A multiplier of 4 (Appendix 3) was used to calculate the volume of wood (measured in cubic meters per hectare) from the amount of C (tonnes per hectare) modeled using the CBM-CFS3 for merchantable stemwood transferred to coarse woody debris and other wood transferred to small/fine woody debris in the forest floor at the time of disturbance (year 0), and over the following 100 years (years 1–100).

71 m^3 ha^{-1} (ecosite "d1") at the time of disturbance and 23 m^3 ha^{-1} (ecosite "d3") to 207 m^3 ha^{-1} (ecosite "d1") for the annual additions related to the subsequent 100 years (Table 5).

Development of the Forest Floor Recovery Index

The FFRI was developed to be ecologically credible, and easy to understand and calculate for rapid assessment in the field. It used data from 1470 forest floor samples collected at 115 sites (101 sites used in the beta version plus 14 forest reference sites in the field testing). Considerable flexibility was built into the index for judging success because there will be variability in users' abilities to classify some forest floors; we were mindful that this was the first attempt at using the forest floor as an index of recovery, and we did not want the final assessment to be overly conservative.

The FFRI uses the forest floor material groups that occurred most often in the data collected at all sites to develop the reference condition criteria (Fig. 5, Table 6). These were the wood-dominated Woody and Mixed forest floor material types (Fig. 5). The FFRI is based on three criteria: forest floor thickness (measured in centimeters) (Fig. 6), material group (Fig. 7), and horizon group (Table 7, Figs. 8 and 9), which confirm the importance of woody material in the development of forest floors in the Central Mixedwood Subregion. The F and H horizon groups are the primary horizon group data used in determining the reference condition for the horizon group criteria as they represent degrees of advanced decomposition, demonstrating that soil organisms are affecting processes in the forest floor (Figs. 8 and 9). Samples classified in the FH horizon group can be added to the F or H group to adjust these proportions in the calculation of the index to provide flexibility in the assessment.

The reference condition for some combinations of age class and ecosite type had to be estimated (Figures 7, 8, and 9) where field data were insufficient. In the beta version, where values were missing in an age class for forest floor thickness, values for forest floor thickness were estimated using simple linear regression of mean forest floor thickness against age class after removal of extreme outliers. The upper limits of the age classes (e.g., using 15 to represent age class 6–15) were used in the regression analysis and the lower limits (e.g., using 6 to represent age class 6–15) were used to estimate missing thickness values so that in the index, thickness requirements for a score of one or two were not overly difficult to achieve. Missing values for the percentage of Woody and Mixed material groups and for missing horizon groups in an age class were conservatively estimated as the average of the percentages for the bounding age classes unless the 0–5 year age class was the missing

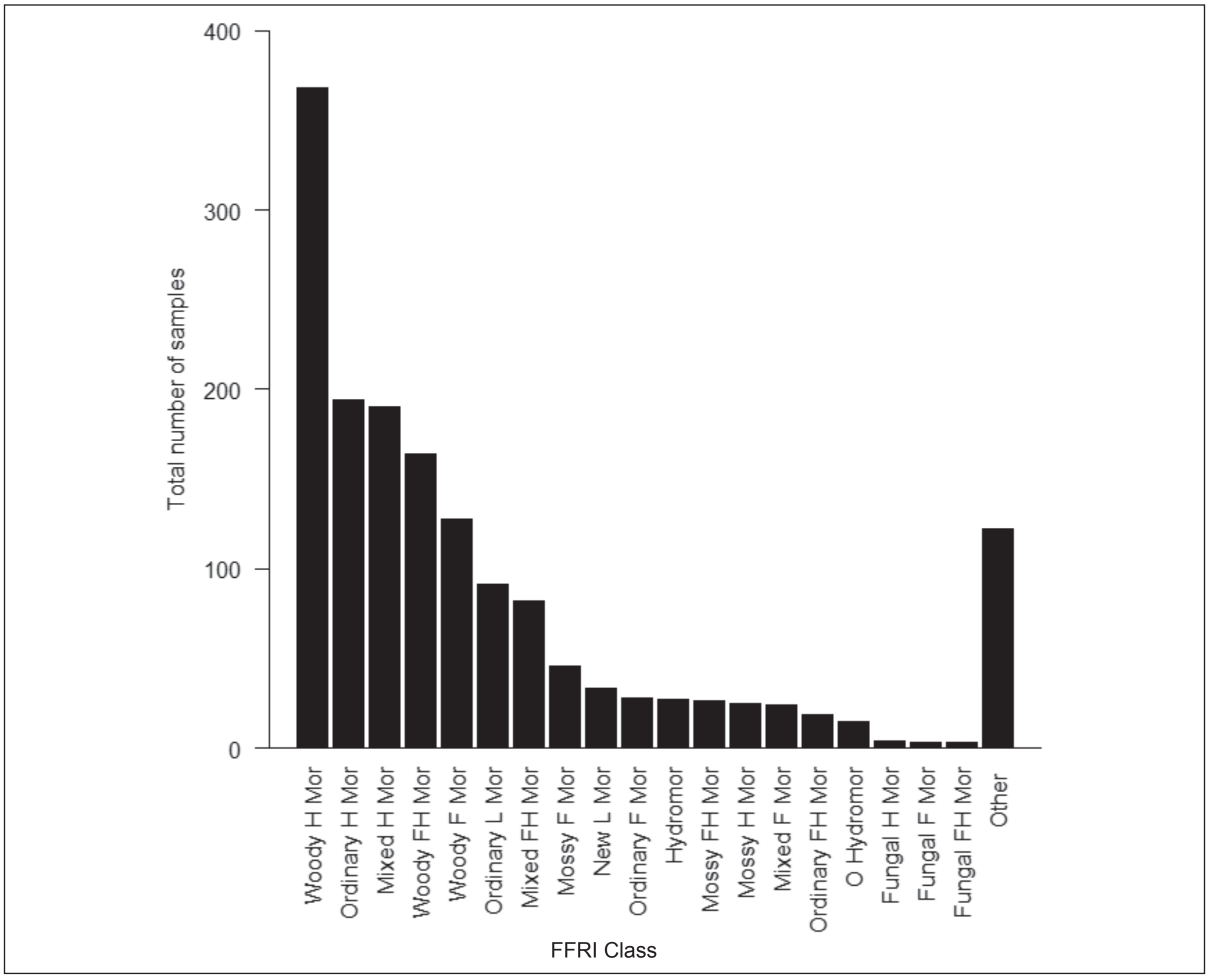


Figure 5. Distribution of forest floor samples taken from all reference sites (including forested sites from testing of the beta version) by forest floor class. See Table 3 for descriptions of forest floor classes.

Table 6. Descriptions of material groups

Group	Description
Ordinary	Partially or well-decomposed tree litter makes up at least 50% of the organic material, and neither wood nor moss dominates.
New	The forest floor is made up of undecomposed tree litter (needles or leaves).
Woody	The dominant horizon is made up of at least 50% decaying wood. Most of this wood originates from coarse (≥ 7cm diameter) woody debris.
Mixed	The dominant horizon contains a mixture of recognizable plant residues (small wood fragments < 7 cm in diameter, roots, bark, needles, cones) with yellow, brown, or red colors.
Mossy	The dominant horizon is made up almost entirely of dead moss. The surface of the forest floor may be mostly live moss (live moss is not measured when determining the thickness of the forest floor, although some litter material may be mixed in with the live moss).
Fungal	The dominant horizon is made up of at least 50% yellow or white fungal hyphae. If this condition is met, the Fungal designation overrides the material in which it is growing (e.g., Mossy, Woody).

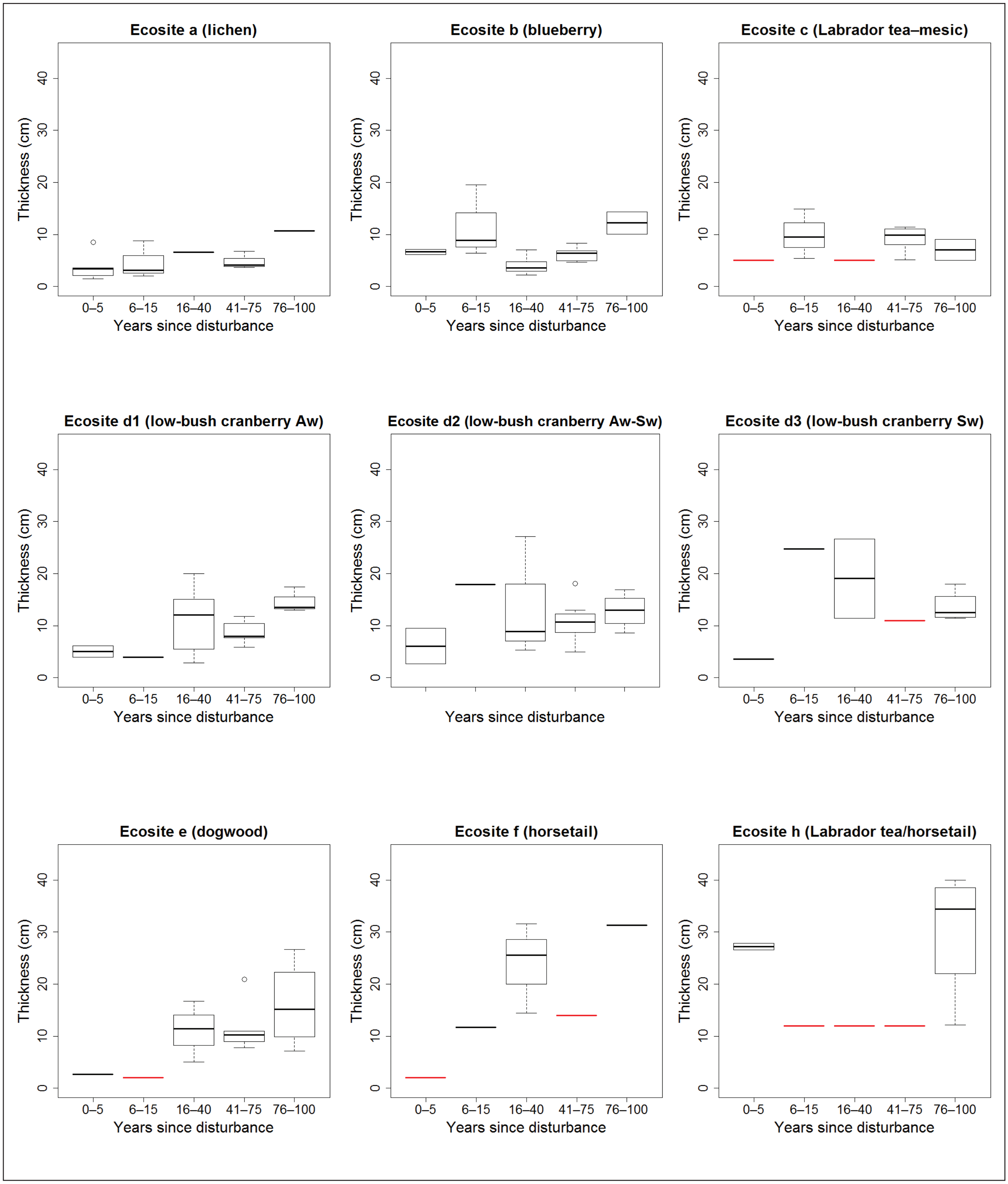


Figure 6. Median thickness of forest floor samples for ecosites "a" to "h" (Beckingham and Archibald 1996) including all age classes: median thickness, lower and upper quartiles, minimum and maximum values, and outliers (removed for determination of index score values) are shown for each ecosite or ecosite phase and age class. Median values (shown in red) were estimated. All sites sampled from 2014 to 2017 were included. Aw = trembling aspen; Sw = white spruce.

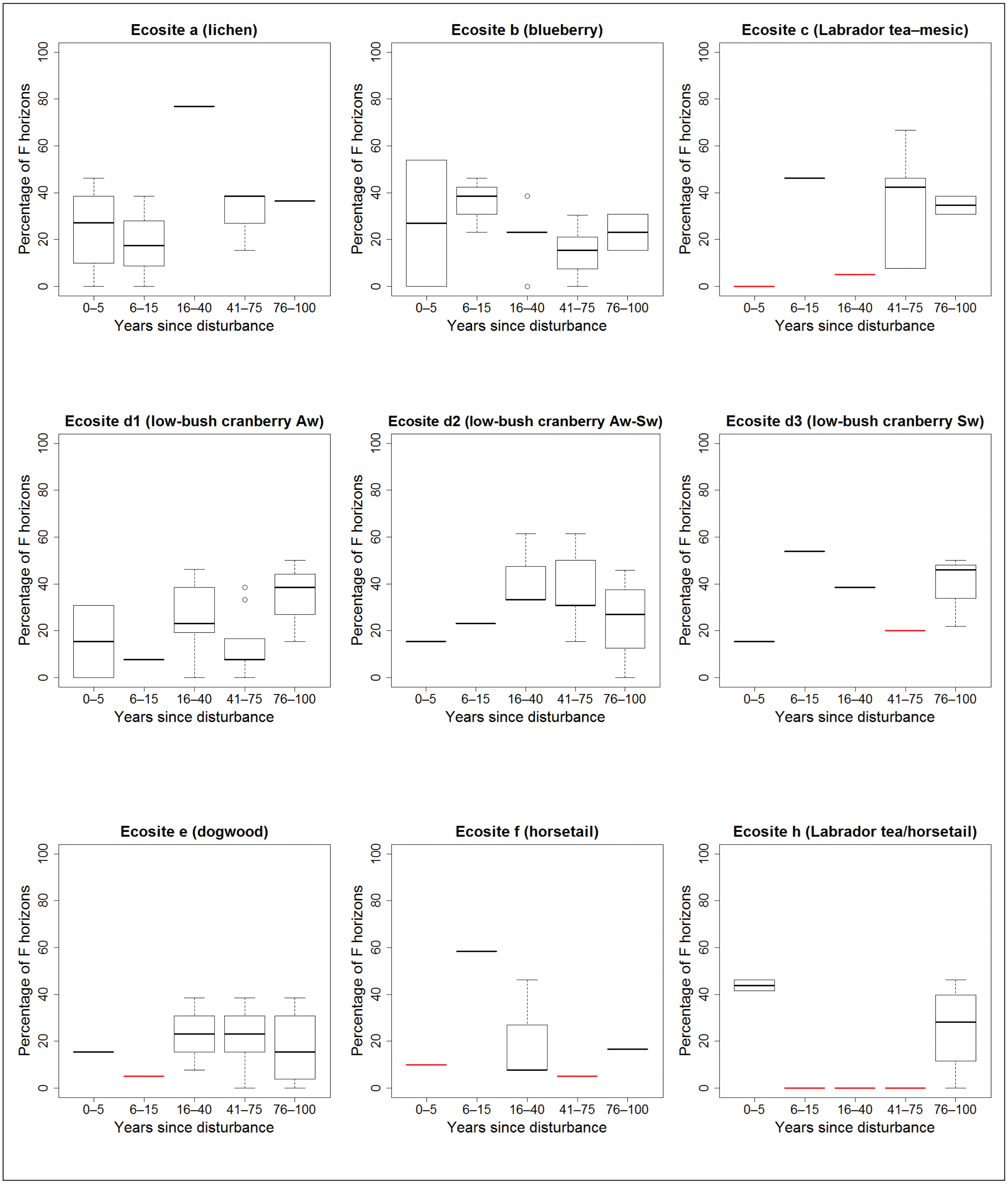


Figure 7. Median percentages of Woody and Mixed material groups for ecosites "a" to "h" (Beckingham and Archibald 1996) including all age classes: median percent Woody and Mixed, lower and upper quartiles, minimum and maximum values, and outliers (removed for determination of index score values) are shown for each ecosite or ecosite phase and age class. Median values (shown in red) were estimated values. All sites sampled from 2014 to 2017 were included. Aw = trembling aspen; Sw = white spruce.

Table 7. Descriptions of horizon groups

Group	Description[a]	Type
L Mor	The L horizon accounts for at least70% of the L, F, and H combined thickness.	Well drained
F Mor	The F horizon accounts for at least 70% of the F and H combined thickness.	Well drained
FH Mor	The F and H horizons each account for between 30% and 70% of F and H combined thickness, or the F and H horizons may be mixed together; neither F nor H dominates.	Well drained
H Mor	The H horizon accounts for at least 70% of F and H combined thickness. It is often difficult to distinguish between different material groups in H Mors because H horizons are so well decomposed.	Well drained
Hydromor	The F and H horizons account for at least 50% of the L, F, H and O combined thickness; poorly aerated because of saturated conditions in part of the profile for a portion of the year, sometimes resulting in O horizon(s) in the lower part of the profile. Often, much of the O horizon(s) is formed from dead moss.	Poorly drained
O Hydromor	The O horizon(s) accounts for at least 50% of L, F, H, and O combined thickness; very poorly aerated, with at least part of the profile being permanently saturated. L, F, and H horizons may form above O horizons. Often, much of the O horizon(s) is formed from dead moss.	Poorly drained

[a] See Table 8 for description of L, F, H, and O horizons.

value, in which case the 0–5 year age class values from the nearest drier/poorer ecosite was used (e.g., using values from the 0–5 year age class of ecosite "b" for the missing 0–5 year age class of ecosite "c"). Tabular data in an index table are the reference values multiplied by 0.8 for an index score of one, and multiplied by 0.4 for an index score of two. This builds flexibility into the FFRI. A test site does not have to match exactly the data from the reference values, but only exceed a percentage (80% for a score of one, or 40% for a score of two) of the observed values to succeed. Thickness values are rounded down to the nearest centimetre, and other values are rounded down to the nearest 5%. When calculating percentages for the horizon groups at a test site for comparison to the reference condition, samples identified in the FH group can be added to either the F or H group to increase their percentage value to meet the criteria of a particular index score. This approach builds further flexibility into the index.

The results of field testing prompted a number of changes to the second edition of the FFRI. Of the 14 forested reference test sites, 36% did not meet the criteria for an FFRI score of 1. As a score of 1 is meant to represent stands originating from natural disturbances, a new set of index scores was developed by modifying the method used in the beta version. Outlier values for thickness, percent F, percent H, and percent Mixed and percent Woody were discarded before any calculations. For each age class and ecosite combination, the value for achieving a score of 1 was either 80% of the average of all sites in that group or the site with the lowest value within that group, whichever was less. For example, the two percentages for F horizon groups on sites sampled in the 76–100 age class for ecosite "c" were 30.77% (lowest value) and 38.46% (average value). The lower of the sampled values was 30.77%, while 0.8 of the average was 27.69%. We used the smaller value (rounded down to the nearest 5%) resulting in a required percent F of 25% to achieve a score of 1. Values for age class and ecosite combinations for which no sites were found were set to whichever of the two values from the adjacent age classes was lower. Missing values for the 0–5 age class were set to match either the 0–5 age class of the nearest poorer/drier ecosite, or the adjacent 6–15 age class, whichever was lower. Where only one site was found for a given age class and ecosite combination, and the value of an indicator was higher than either of the adjacent age classes, that value was averaged with the two adjacent values. For example, only one site was sampled in the 6–15 age class for the "d2" ecosite, and the forest floor thickness value to achieve an

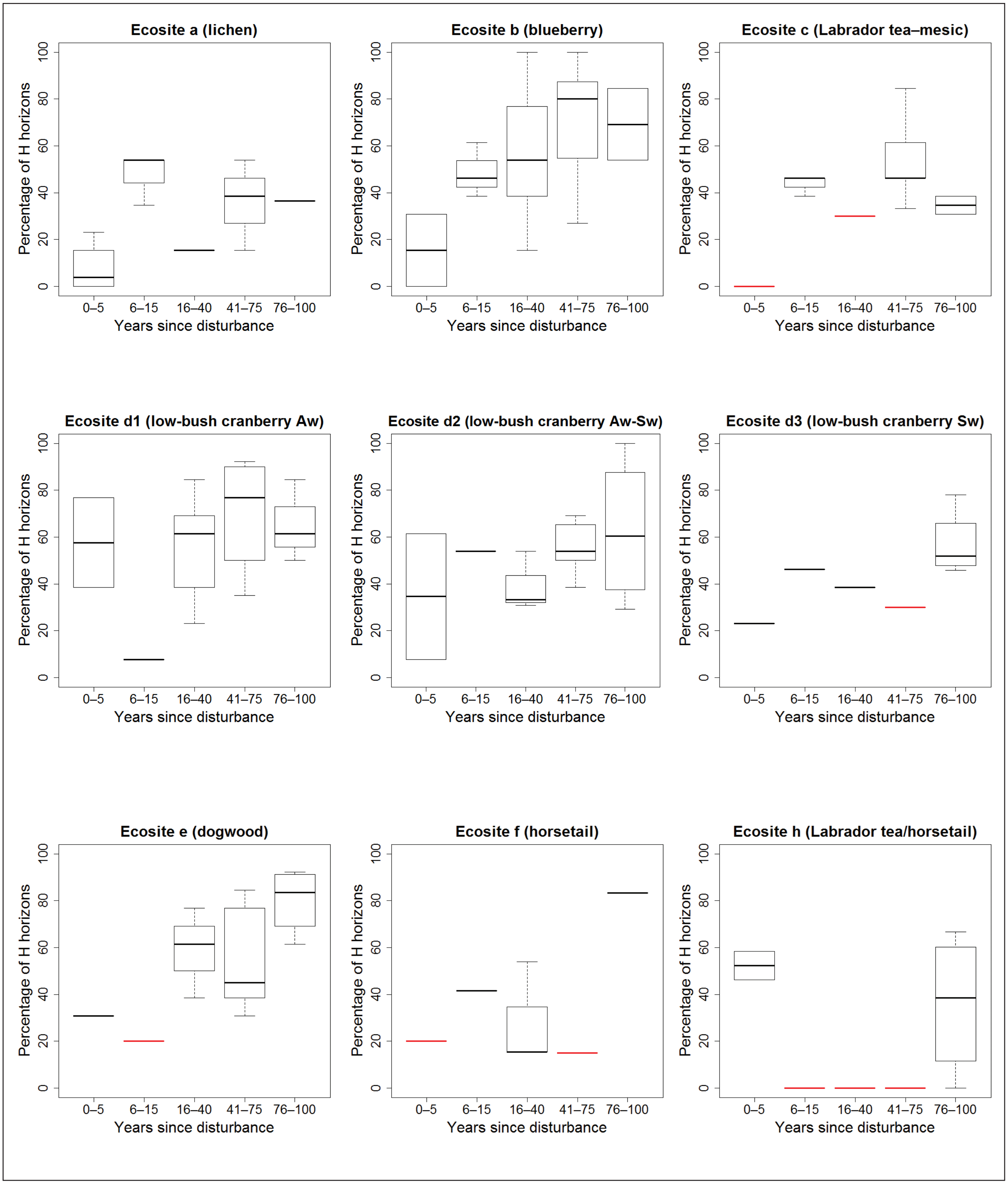


Figure 8. Median percentages of F horizon groups for ecosites "a" to "h" (Beckingham and Archibald 1996) including all age classes: median percent F, lower and upper quartiles, minimum and maximum values, and outliers (removed for determination of index score values) are shown for each ecosite or ecosite phase and age class. Median values (shown in red) were estimated. All sites sampled from 2014 to 2017 were included. Aw = trembling aspen; Sw = white spruce.

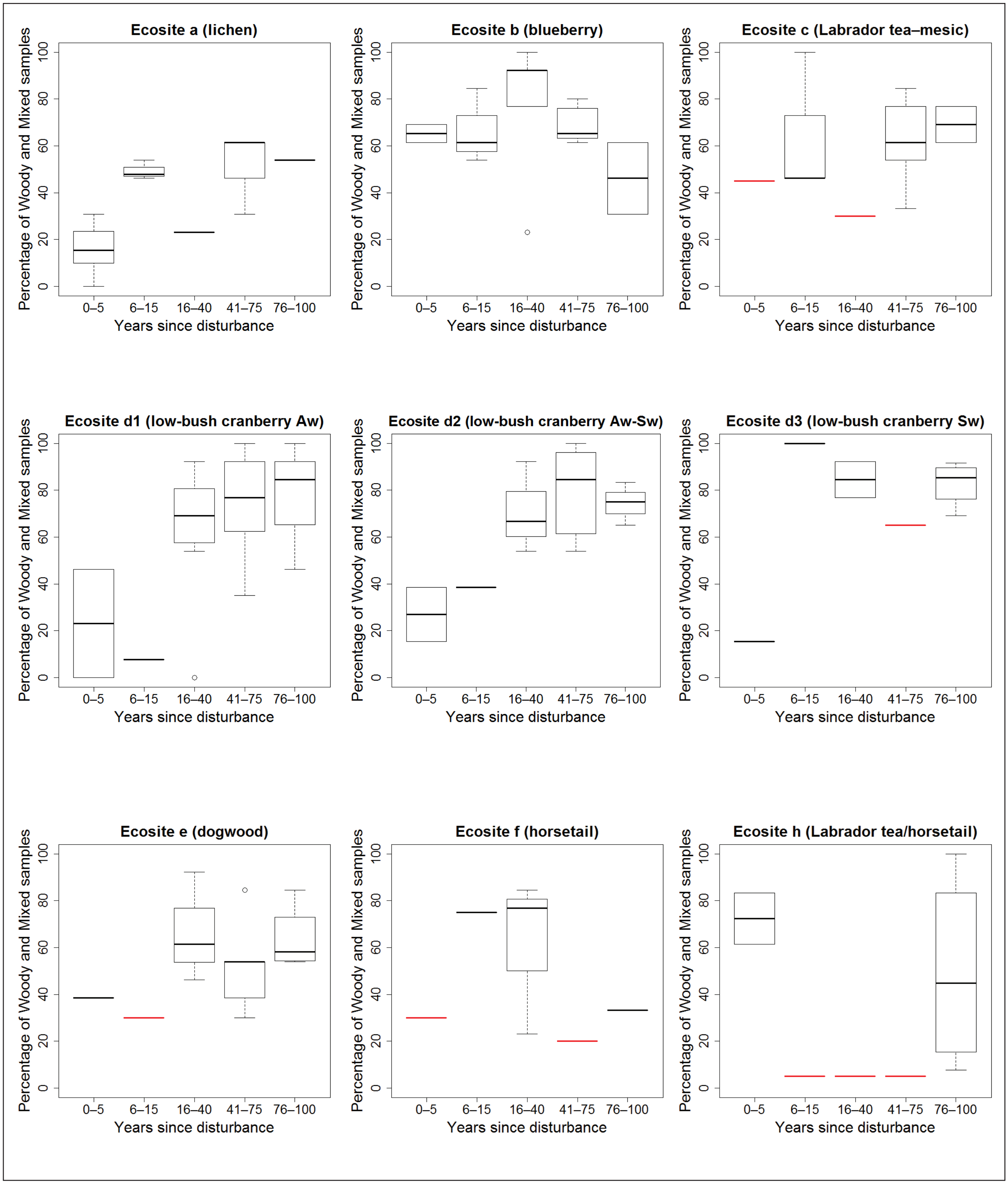


Figure 9. Median percentages of H horizon groups for ecosites "a" to "h" (Beckingham and Archibald 1996) including all age classes: median percent H, lower and upper quartiles, minimum and maximum values, and outliers are shown for each ecosite or ecosite phase and age class. Median values (shown in red) were estimated. All sites sampled from 2014 to 2017 were included. Aw = trembling aspen; Sw = white spruce.

index score of 1 was the average for that one site (14.34 cm). Compared with the 0–5 age class value of 2.69 cm and the 16–40 age class value of 5.31 cm, the 6–15 age class appears to be an outlier, so the three values were averaged and rounded down to the nearest centimeter, resulting in a value for the thickness criteria of 7 cm for the 6–15 age class. The new values resulting from the new methodology, including data from forested sites sampled for the testing of the beta version, were used to produce the index tables in the second edition of the FFRI.

To determine an index score, a user compares data collected on a test site using the FFRI field manual (Hoffman et al. 2018a) with the final set of index table values for the appropriate ecosite/ecosite phase and age class combination. The values in the tables are those that must be exceeded to achieve an FFRI score of 1 (meeting forest floor recovery objectives, with no recommendations for management actions), 2 (somewhat meeting forest floor recovery objectives, with a suggestion to add some woody inputs to improve forest floor recovery), or 3 (not meeting forest floor recovery objectives, with a suggestion to add a larger amount of woody inputs to improve forest floor recovery).

The FFRI Field Manual (Second Edition)

A synthesis of field data, modeling results, and the recovery index tables, were used to create the second edition of the FFRI manual (Hoffman et al. 2018a) and app (Hoffman et al. 2018b). The objectives of the FFRI manual were to give users information and images from reference samples explaining how to describe and classify the forest floor; allow users to monitor the forest floor as an indicator of ecosystem recovery after reclamation; and provide guidelines for the amount of tree volume inputs needed to establish forest floors indicative of functional, resilient forest ecosystems on reclaimed sites. It was developed for soils with organic horizons ≤ 40 cm thick overlying mineral soil and should not be used for peatlands or soils in the Organic Order (> 40 cm thick) (Soil Classification Working Group 1998). The FFRI manual consists of six sections: Background, Forest Floor Classification, Sampling and Recording Data, Reference Examples, Forest Floor Recovery Index, and Woody Biomass Input Guidelines. These sections are briefly described in the following text.

The first section, Background, introduces important concepts about forest floor development in the boreal: Mor, Moder, and Mull forest floors are discussed, and there are descriptions of L, F, H, Of, Om, and Oh organic horizons and A mineral horizons (Table 8). The second section, Forest Floor Classification, introduces the concepts of horizon groups (Table 7; Figs. 10 and 11) and material groups (Table 6; Fig. 12), which combine to form the 19 FFRI forest floor classes (Table 3) described in the manual. This section also provides information about the effects of earthworms on forest floors and briefly describes how forest floors can differ between reclaimed well pads and natural sites. The classification system developed for the FFRI makes it easy to describe and classify the forest floor, while still providing valuable information about relevant forest floor properties. During the data collection phase, we used the *Taxonomic classification of humus forms in ecosystems of British Columbia* (Klinka et al. 1981) to classify samples. In developing the FFRI manual, only those classes that were encountered in the Central Mixedwood Subregion during sampling were included, and only Mor humus forms were used in developing the FFRI forest floor classification system. Informal language was used in the FFRI to make the classification system easier to understand and remember. We used observable physical characteristics to differentiate forest floor classes and divided these characteristics into two groups: horizon groups and material groups. The horizon groups include six categories: L Mor, F Mor, FH Mor, H Mor, Hydromor, and O Hydromor; they represent the state of decomposition and moisture conditions, of the dominant horizon(s) of the sample (Table 7). The material groups also include six categories: New, Ordinary, Woody, Mixed, Fungal, and Mossy; they represent the dominant organic materials in the sample, or in some cases the dominant organic materials in the dominant horizon of the sample (Table 6). Each forest floor class is described by a combination of a horizon group and a material group (with the exception of Hydromor and O Hydromor, which are defined only by the horizon group), resulting in 19 classes in total (Table 3; Fig. 5).

The third section, Sampling and Recording Data, provides a list of sampling supplies, describes transect layout, sampling design and procedures

Table 8. Descriptions of organic horizons and the mineral A horizon

Symbol	Description	Type
L	Litter: the least decomposed. L horizons are made up of identifiable materials, such as intact leaves or needles, sitting on the surface of the forest floor.	Organic[a], well drained
F	Fermented: intermediate decomposition. F horizons are made up of plant residues in which partial structures are still identifiable; the F horizon usually occurs below the L horizon and above the H horizon.	Organic, well drained
H	Humic: the most decomposed. H horizons are made up of fine plant residues that are, for the most part unrecognizable and dark in color.	Organic, well drained
A	Mineral horizon: < 30% organic matter by mass. A horizons are not organic horizons but are sometimes present just below the organic horizons. They are dark in color and often gritty because of mixing of the mineral soil with organic matter.	Mineral
Of[b]	Fibric: a surface O horizon that consists of poorly decomposed, identifiable plant residues. The Of horizon produces relatively clear water when squeezed.	Organic, poorly drained
Om	Mesic: an O horizon that consists of partly decomposed, mushy plant residues at a stage of decomposition between Of and Oh horizons. The Om horizon produces muddy brown water when squeezed.	Organic, poorly drained
Oh	Humic: an O horizon that consists of well-decomposed plant residues, which for the most part have been transformed into humic materials (as in H horizons). The Oh horizon produces a dark paste when squeezed, and few recognizable plant structures can be seen.	Organic, poorly drained

[a] Organic horizons in the Forest Floor Recovery Index are at least 30% organic matter by mass.

[b] O horizons (Of, Om, and Oh) occur in areas affected by a high water table for a significant portion of each year. They are often dominated by mosses but may also include significant amounts of woody material.

Organic horizons: well-drained sites

Organic horizons are made up of at least 30% organic matter by mass.

L (litter); the least decomposed. L horizons are made up of identifiable materials, such as intact leaves or needles, sitting on the surface of the forest floor.

F (fermented); intermediate decomposition. F horizons are made up of plant residues in which partial structures are still identifiable; the F horizon usually occurs below the L horizon and above the H horizon.

H (humic); the most decomposed. H horizons are made up of fine plant residues that are, for the most part unrecognizable and dark in color.

A (mineral horizon); < 30% organic matter by mass. A horizons are not organic horizons but are sometimes present just below the organic horizons. They are dark in color and often gritty because of mixing of the mineral soil with organic matter.

Figure 10. Photographs depicting organic soil horizons on well-drained sites from the Forest Floor Recovery Index field manual (Hoffman et al. 2018a).

Horizon groups: well-drained sites

In this manual, the forest floor is classified by identifying and combining horizon groups and material groups. Horizon groups are defined by the dominant horizon(s).

L Mor The L horizon accounts for at least 70% of the L, F, and H combined thickness.

If a sample does not meet the requirements to be designated an L Mor, the thickness of the L horizon is not taken into account when determining whether the sample is an F Mor, FH Mor, or H Mor, as defined below.

F Mor The F horizon accounts for at least 70% of F and H combined thickness.

FH Mor The F and H horizons each account for between 30% and 70% of F and H combined thickness, or the F and H horizons may be mixed together; there is no dominance between F and H horizons.

H Mor The H horizon accounts for at least 70% of F and H combined thickness.

It is often difficult to distinguish between different material groups in H Mors because H horizons are so well decomposed. Extra hints are provided for distinguishing Ordinary and Woody H Mors in the Reference Examples section (pages 37 and 38).

Figure 11. Descriptions of horizon groups of well-drained sites from the Forest Floor Recovery Index (FFRI) field manual (Hoffman et al. 2018a). Each horizon group is defined by the dominant horizon(s) L, F, H, or O, which are at different stages of decomposition, or in the case of O horizons, undergoing anaerobic decomposition. Each forest floor class in the FFRI is a combination of a horizon group and a material group. Other horizon groups not shown in in this figure are Hydromor and O Hydromor (see "Horizon groups: poorly drained sites" in the FFRI manual and Tables 3 and 7 in this report for descriptions of Hydromors and O Hydromors).

Material groups

Material groups are defined by the dominant organic material making up the forest floor or part of the forest floor.

Ordinary Partially or well-decomposed tree litter makes up at least 50% of the organic material, so neither wood nor moss dominates.

New The forest floor is made up of undecomposed tree litter (needles or leaves).

Woody The dominant horizon is made up of at least 50% decaying wood. Most of this wood originates from coarse (≥ 7 cm diameter) woody debris.

Figure 12. Photographs depicting material groups from the Forest Floor Recovery Index (FFRI) field manual (Hoffman et al. 2018a). Each material group is defined by the dominant material making up the forest floor. Other material groups include Mixed, Mossy, and Fungal (see "Material groups" in the FFRI manual and Table 6 in this report for descriptions of the material groups).

(Fig. 13), and includes a template for a data recording sheet (Fig. 14). The sampling design recommended in the FFRI is similar to that used for sampling at the reference sites and consists of two perpendicular transects sampled at 5-m intervals for approximately 13 samples. For larger sites, it is recommended that longer transects and sampling intervals be used and users may make other adjustments based on the shape of the site, such as using a single longer transect. The sampling procedure involves extracting the forest floor organic horizons down to or including some mineral soil (Fig. 4). The users are then instructed to measure the thickness (measured in centimeters) of the forest floor, determine the horizon and material groups, and record all of the information on a data sheet. The fourth section, Reference Examples, describes the 19 forest floor classes and provides multiple example images illustrating a range of appearances of each forest floor class so that users can make comparisons in the field to determine or verify a classification. Four example photographs, in which horizons are labeled and delineated by white lines, and a description of the class including dominant material(s), dominant horizon(s), and a typical horizon sequence (e.g., Fig. 15), are provided for each forest floor class.

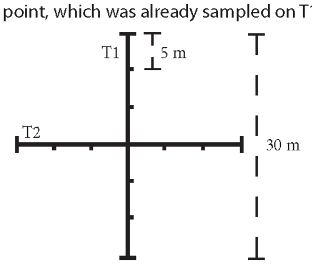
The fifth section, Forest Floor Recovery Index, explains how to summarize test site data for comparison to the index tables that contain reference values for thickness, percent Woody plus Mixed samples, and percent F and H horizons (e.g., Fig. 16). It includes index tables for each ecosite type that contain reference values for each of five age classes since disturbance (or since reclamation). The final section, Woody Biomass Input Guidelines, provides estimates of woody input volumes required to build natural forest floors (Table 5). Our recommendations for woody volume inputs are not based on field data but rather on predictions using the CBM-CFS3.

The FFRI App

The FFRI app (Android) (Hoffman et al. 2018b) makes available all the information contained in the FFRI manual in a user-friendly tool that calculates the recovery index as the data for samples are being entered. The app consists of a home page (Fig. 17) where users can access an "About" page (*see* 3 dots in upper right-hand corner), a "Record Samples and View Results" page, an "Instructions" page, an "Import Plan" page, and an "Export Data" page. The largest button on the home page gives users access to the "Record Samples and View Results" component of the app. There is also a place on the home page to enter "Name(s) of surveyor(s) taking samples." The "Instructions" pages begin with general instructions, including the purpose of the app, and how to use it. The remaining pages in "Instructions" consist of information

Sampling design

1. Before sampling, record your target ecosite ("a" to "h") and years since reclamation.
2. Establish two perpendicular transects 30 m long, as illustrated in the diagram.
3. Sample at 5-m intervals starting at the beginning of the first transect (T1).
4. Sample at 5-m intervals starting at the beginning of the second transect (T2), with the exception of the middle sampling point, which was already sampled on T1.



For large sites, you may want to sample at greater intervals along longer transects. For example, on a 1-ha site, sampling every 15 m may be appropriate. Depending on the layout of the site, a single straight transect can substitute for two perpendicular ones.

Figure 13. Depiction of the sampling design from the Forest Floor Recovery Index (FFRI) field manual (Hoffman et al. 2018a). The recommended sampling design involves taking 13 samples approximately 5-m apart along one or two transects.

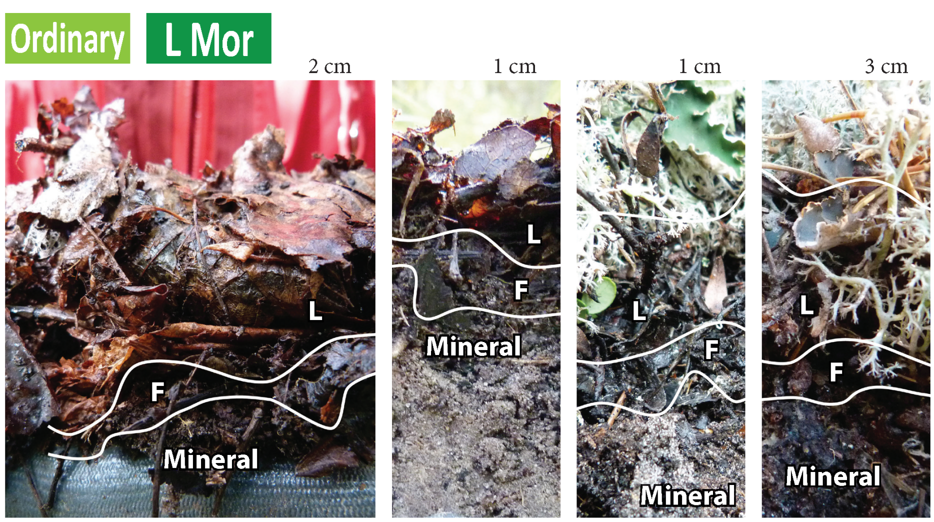
Site name:

Ecosite: Years since reclaimed: Surveyor(s): Date: dd mm yy

Material group, Horizon group	Thickness (cm)	Comments

Average thickness: Percent woody and mixed: Percent F: Percent FH: Percent H:

Figure 14. Sample sheet template for data recording from the Forest Floor Recovery Index (FFRI) field manual (Hoffman et al. 2018a). The sampling sheet requires users of the FFRI manual to record site information, forest floor class, and thickness for each sample. At the bottom of the template, there is space for users to summarize their data for comparison with index tables.



Horizon sequence: L F

The L horizon accounts for at least 70% of the L, F, and H combined thickness. Ordinary L Mors have a thin F horizon accounting for less than 30% of the total thickness of the combined organic horizons, and tree litter makes up a significant portion of the organic material.

Figure 15. Photographs depicting Ordinary L Mor reference example from the Forest Floor Recovery Index (FFRI) field manual (Hoffman et al. 2018a). There are a total of 19 forest floor classes in the FFRI manual, each represented by four images with horizons delineated and labeled, thicknesses of the samples shown, a description of the class, and a horizon sequence. At the top of each reference example page is the name of the class, which is made up of a combination of a material group and a horizon group (except for Hydromor and O Hydromor, which are defined by the horizon group only).

“a - lichen” index table

“a” ecosites (lichen) have jack pine as the leading species. Sites are xeric or subxeric with poor nutrient regimes and sandy textured, rapid- to well-drained soils (Beckingham and Archibald 1996).

Score	0–5 years	6–15 years	16–40 years	41–75 years	76–100 years
1	0% Woody and Mixed 0% F, 0% H 1 cm	35% Woody and Mixed 0% F, 30% H 2 cm	15% Woody and Mixed 25% F, 10% H 3 cm	30% Woody and Mixed 15% F, 15% H 3 cm	40% Woody and Mixed 25% F, 25% H 6 cm
2	Site does not meet the criteria to obtain a score of 1.	15% Woody and Mixed 15% F and H 1 cm	5% Woody and Mixed 15% F and H 1 cm	15% Woody and Mixed 15% F and H 1 cm	20% Woody and Mixed 25% F and H 3 cm
3	A score of 3 does not apply to this age-class for “a” ecosites.	Site does not meet the criteria to obtain a score of 1 or 2.	Site does not meet the criteria to obtain a score of 1 or 2.	Site does not meet the criteria to obtain a score of 1 or 2.	Site does not meet the criteria to obtain a score of 1 or 2.

Figure 16. Depiction of Ecosite “a” index table from the second edition of the Forest Floor Recovery Index (FFRI) field manual (Hoffman et al. 2018a). Index tables present criteria for obtaining index scores of 1, 2, or 3 for each combination of ecosite or ecosite phase and age class. The criteria that must be met include minimum values for the percentage of samples dominated by woody material, the percentages of F and H horizons, and forest floor thickness. Each ecosite or ecosite phase is described according to Beckingham and Archibald (1996) along with an example image of the ecosite or ecosite phase. The results of comparing summarized test site data to the appropriate index table determines the recommended management actions (the amount of woody material that should be added to the test site) in the “Woody Biomass Input Guidelines” section of the FFRI field manual.

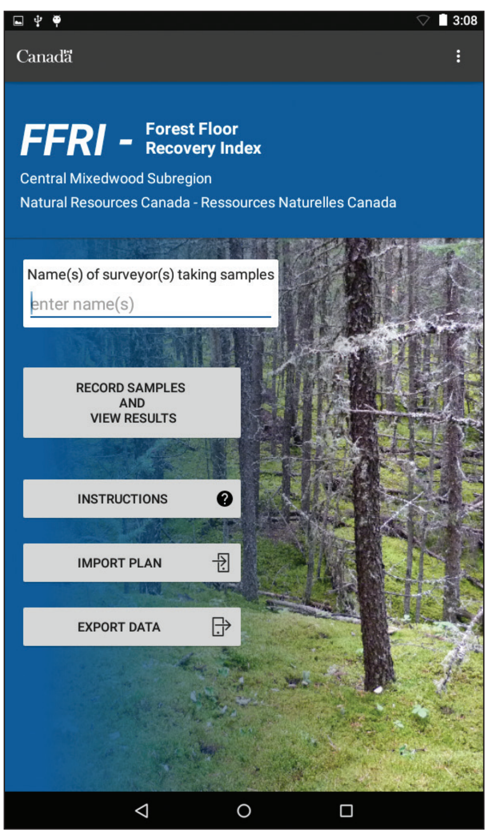


Figure 17. Photograph depicting the homepage for the Forest Floor Recovery Index app (Hoffman et al. 2018b).

on Mors, soil horizons, horizon groups, material groups, sampling procedures, effects of earthworms, and forest floor on reclaimed well pads, similar to what appears in the FFRI manual. The "Import Plan" page allows users to import a Microsoft Excel (Microsoft 2007) file they have filled in before conducting field work. This page contains site information (such as ecosite/ecosite phase), stand age, and the number of samples planned. The "Export Data" page allows a final Excel report containing site and sample data, to be exported from the app.

The "Record Samples and View Results" component consists of several sections. The main page is where users can enter their site name, the data, site age (years since reclamation), ecosite/ecosite phase, and the number of samples planned, as well as accessing "View Ecosite Examples," "View Recommended Woody Material Input," "Add Site Photo," and, most importantly, "Enter Sample." When the user accesses the "View Ecosite Examples" page, they are presented with descriptions of each of the ecosites/ecosite phases, accompanied by example photographs and they are able to select the appropriate ecosite/ecosite phase for their site. This is useful when the target ecosite type is not known before field sampling. The "Enter Sample" page includes options for sample thickness, horizon group, material group, and taking sample photographs. Both horizon groups and material groups are described, and example photographs are provided that users can review when making a determination of the forest floor sample type. After sample data has been submitted, an index score and associated woody input recommendation are calculated automatically and are continually updated as more samples are added. The recommendations for woody debris application rates are shown on the "View Recommended Woody Material Input" page. If a mistake is made while entering data, or a user wishes to review previously entered samples, a "Review/Edit Samples" button is available on the "Enter Sample" page.

CONCLUSIONS

The FFRI provides a method to assess ecosystem recovery following reclamation; it also provides recommendations for woody inputs needed to build natural forest floors. The focus on samples containing woody material is the result of a number of considerations based on science, evidence from the field, and practicality. In the case of anthropogenically disturbed and subsequently reclaimed oil sands sites, it is recommended that CWD and SFWD be added by reclamation professionals. The FFRI provides a method to assess the presence of woody material in the forest floor (along with other physical characteristics) and determine how much needs to be added both at the time of reclamation and following assessment with the FFRI. Despite wood being the most common input for forest floor development, the field study identified that moss, litter, and fine roots were also common inputs. Litter and roots will be provided by trees and other plants following reclamation, but further research would be required to develop methods to facilitate the establishment of mosses. Obtaining knowledge of how all these components of the forest floor are developing on reclamation sites is important to understanding ecosystem recovery. Going forward, comparisons of FFRI results to other metrics of ecosystem health such as tree growth and biodiversity of native organisms could provide more information about the importance of the forest floor in boreal forests, and how different metrics of ecosystem recovery interact following reclamation. The FFRI was developed for the Central Mixedwood Subregion of Alberta, but it has the potential for application in similar ecosystem types in other parts of Alberta and Canada (Fig. 1); however, this remains to be tested.

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APPENDIXES

Appendix 1. Description of plots and their locations[a]

SiteID[b]	Ecosite	Age class[c] (years)	Age (years)	Year sampled	Number of forest floor samples	Latitude (DD)	Longitude (DD)
cema_18	d1	41–75	59	2014	20	56.4536100	−111.1869400
cema_26	a	0–5	0	2014	20	57.5108300	−111.4300000
cema_27	a	0–5	0	2014	20	57.5050000	−111.4369400
cema_50	d2	76–100	76	2014	20	56.6450000	−111.0947200
cema_61	d1	41–75	55	2014	20	56.4391667	−111.1902780
cema_78	e	41–75	63	2014	20	55.8366667	−110.8675000
cema_79	e	76–100	84	2014	20	55.8361111	−110.8636110
cema_81	b	16–40	35	2014	20	56.1466667	−110.8844440
cema_82	b	41–75	52	2014	20	56.4275000	−111.0538890
cema_92	b	41–75	42	2014	20	56.1467722	−110.8861110
cema_93	b	41–75	51	2014	20	56.1452778	−110.8780560
bor1f	d2	41–75	42	2017	13	54.2210730	−115.4447120
bor4f	d2	41–75	67	2017	13	54.3776720	−116.9461030
bor6f	d3	76–100	77	2017	13	54.5703980	−116.7554500
bor9f	d1	16–40	20	2017	13	55.2314660	−114.4576540
bor10f	d1	16–40	19	2017	13	55.1894970	−114.5220900
bor14f	d2	41–75	73	2017	13	55.5889490	−115.0416370
bor15f	e	16–40	19	2017	13	55.2328990	−114.4249030
foot3f	e	41–75	67	2017	13	55.3055150	−115.0362690
foot7f	d1	76–100	100	2017	13	55.4564740	−114.8182280
foot9f	e	76–100	100	2017	13	55.4773670	−114.8518540
foot11f	d1	76–100	100	2017	13	54.4317980	−115.9582080
foot12f	h	76–100	100	2017	13	54.4974430	−115.9744480
foot13f	d2	41–75	70	2017	13	54.2637510	−115.6577090
foot15f	d2	16–40	30	2017	13	54.2056370	−115.9932150
a0-b	a	0–5	0	2016	13	56.0652111	−111.6005556
a0-d	a	0–5	0	2016	13	56.3878139	−111.0312028
a0-i	a	0–5	0	2016	13	56.3882806	−111.0300278
a0-o	a	0–5	0	2016	13	56.6449083	−111.1208889
a6-h	a	6–15	15	2015	23	55.8403611	−110.8524167
a6-s	a	6–15	ND	2016	13	ND[d]	ND
a6-u	a	6–15	14	2016	13	56.2415694	−111.6521444
a16-j	a	16–40	36	2016	13	56.2756278	−111.5808333
a41-y	a	41–75	62	2016	13	56.2799222	−111.5936111
a41-z	a	41–75	58	2016	13	56.2479333	−111.6375889
a41-s	a	41–75	65	2016	13	55.8155944	−110.7302944
a76-y	a	76–100	81	2016	13	55.7436583	−110.9132917
b0-b	b	0–5	0	2016	13	56.5167583	−111.2715667
b0-c	b	0–5	0	2016	13	56.6530417	−111.1827056
b6-d	b	6–15	14	2015	12	56.1623833	−111.7509917
b6-j	b	6–15	11	2016	13	55.8901278	−112.1279194
b6-q	b	6–15	13	2016	13	55.8735472	−112.1494444
b16-f	b	16–40	21	2015	13	56.2578611	−110.8909444

Appendix 1. Continued

SiteID[b]	Ecosite	Age class[c] (years)	Age (years)	Year sampled	Number of forest floor samples	Latitude (DD)	Longitude (DD)
b16-i	b	16–40	16	2015	12	56.1881750	–111.6034778
b16-l	b	16–40	34	2015	12	56.1533667	–111.7399306
b16-v	b	16–40	20	2015	13	56.2049444	–111.7211111
b41-i	b	41–75	45	2015	23	55.8371667	–110.8418333
b41-j	b	41–75	70	2015	13	55.9906639	–110.9426389
b41-m	b	41–75	60	2015	12	55.8395278	–110.8571111
b41-mi	b	41–75	74	2016	13	57.1425222	–111.5896694
b76-b	b	76–100	94	2015	13	56.3311111	–110.9786110
b76-t	b	76–100	79	2016	13	57.1768917	–111.6034778
c6-b	c	6–15	15	2016	13	56.1540389	–111.7466667
c6-k	c	6–15	13	2015	13	56.1538056	–111.7416250
c6-s	c	6–15	15	2016	13	56.1400639	–111.7694444
c41-u	c	41–75	50	2015	13	56.1230333	–111.7955190
c41-bp	c	41–75	62	2015	12	56.1722500	–111.7335556
c41-d	c	41–75	61	2015	13	56.3877778	–111.0300000
c41-m	c	41–75	63	2015	13	55.9923056	–110.9007222
c41-y	c	41–75	50	2015	13	56.2799306	–111.3407250
c41-bo	c	41–75	69	2016	13	55.8151389	–110.7323806
c76-ye	c	76–100	79	2016	13	55.7440167	–110.9124361
c76-yi	c	76–100	80	2016	13	55.7406889	–110.9300361
1d0-d	d1	0–5	0	2016	13	56.3184556	–110.9223972
1d0-f	d1	0–5	0	2016	13	56.2684556	–110.8859111
1d6-w	d1	6–15	15	2016	13	55.8902694	–112.1276694
1d16-b	d1	16–40	18	2016	13	56.3174778	–110.9605556
1d16-f	d1	16–40	18	2015	13	56.2029722	–111.7154444
1d16-k	d1	16–40	26	2015	12	55.8905361	–110.8186944
1d16-n	d1	16–40	21	2016	13	56.2899472	–110.9543972
1d16-c	d1	16–40	34	2016	13	56.4230083	–111.2336389
1d41-c	d1	41–75	61	2015	12	56.5196028	–111.3005222
1d41-o	d1	41–75	67	2015	13	56.2920222	–110.9498278
1d41-q	d1	41–75	67	2015	24	55.7327222	–110.9990833
1d41-sq	d1	41–75	41	2015	12	55.8260611	–110.8515000
1d41-sw	d1	41–75	66	2015	12	56.0433611	–110.8717222
1d41-ba	d1	41–75	67	2016	13	56.0662278	–110.8633694
1d41-bt	d1	41–75	53	2016	13	55.8962833	–110.8189444
1d76-f	d1	76–100	85	2015	12	56.2549167	–110.8937222
2d0-f	d2	0–5	5	2015	13	56.2556000	–110.8933861
2d0-s	d2	0–5	0	2016	13	56.3171278	–110.9594444
2d6-s	d2	6–15	14	2016	13	56.3957583	–111.4367389
2d16-t	d2	16–40	17	2016	13	56.3764889	–111.4894778
2d16-u	d2	16–40	22	2015	12	56.3721972	–111.5051167
2d41-b	d2	41–75	42	2016	13	56.5976389	–111.3274472
2d41-o	d2	41–75	55	2016	13	56.1570000	–110.8578278

Appendix 1. Concluded

SiteID[b]	Ecosite	Age class[c] (years)	Age (years)	Year sampled	Number of forest floor samples	Latitude (DD)	Longitude (DD)
2d41-s	d2	41–75	68	2015	12	56.1324444	−110.8921111
2d76-a	d2	76–100	89	2015	12	55.7894972	−110.8679417
2d76-n	d2	76–100	97	2015	12	56.3935833	−111.4414444
2d76-r	d2	76–100	82	2015	12	56.3746222	−111.2187250
3d0-e	d3	0–5	0	2016	13	56.6720722	−111.3540667
3d6-c	d3	6–15	10	2016	13	56.4000083	−111.4393500
3d16-f	d3	16–40	33	2016	13	55.8162222	−110.8252167
3d16-w	d3	16–40	35	2015	13	56.3536639	−111.5391583
3d76-p	d3	76–100	91	2015	32	55.7241750	−111.0450389
3d76-s	d3	76–100	76	2015	12	56.3805861	−111.2136389
3d76-w	d3	76–100	95	2016	12	56.2664333	−110.8905528
e0-s	e	0–5	0	2016	13	56.3335306	−110.9137583
e16-b	e	16–40	27	2016	13	56.4253306	−111.3550000
e16-c	e	16–40	40	2016	13	56.7453278	−111.4090361
e41-re	e	41-75	66	2016	13	56.0383444	−110.8740333
e41-ro	e	41-75	45	2016	13	56.8374750	−111.4372194
e41-w	e	41-75	60	2016	13	56.0649889	−110.8635083
e76-t	e	76–100	139	2016	13	56.3961278	−111.4352389
e76-h	e	76–100	85	2016	13	56.1649111	−110.8571306
f6-v	f	6–15	14	2015	12	56.3637222	−111.5355278
f16-d	f	16–40	19	2016	13	55.8136333	−110.8277167
f16-m	f	16–40	20	2015	13	55.8149000	−110.8249917
f16-w	f	16–40	23	2016	12	56.2548694	−110.9104111
f76-h	f	76–100	91	2015	12	56.4299722	−111.2456944
h0-sn	h	0–5	0	2016	13	56.6484889	−111.1022694
h0-z	h	0–5	0	2016	13	56.3178333	−110.9431111
h76-sn	h	76–100	105	2015	12	56.6484167	−111.0986944
h76-st	h	76–100	82	2016	13	56.65672222	−111.2543667
h76-z	h	76–100	79	2015	13	56.3178333	−110.9431111

[a] Note: sampled sites include 101 sites from beta version sampling and 14 sites from field testing for a total of 115 sites.

[b] Site IDs starting with "cema" identify the Cumulative Environmental Monitoring Association plots followed by their plot identification number. Temporary sampling sites are coded according to ecosite, the first year of their age-class and a unique letter code for the specific site.

[c] Age classes represent the amount of time that has passed since the last stand-replacing disturbance (at the time of sampling).

[d] ND = no data.

Appendix 2. Data used to produce yield curves with the Growth and Yield Projection System

Stand	Species[a]	N[b]	Top height (m)	Stand age (years)	Species (%)[c]	Source[d]
01_a1_PJ_Dry_CD_80_AvgDens_AvgTH_ofFairSites	PJ	777	10.7	80	100(100)	Table 4-6
02_b1_PJAW_Dry_CD_80_AvgDens_AvgTH_of_FairSites	PJ	602	10.7	80	67(60.5)	Table 4-6
02_b1_PJAW_Dry_CD_80_AvgDens_AvgTH_of_FairSites	AW	293.5	13.5	80	33(32.5)	Table 4-6
03_b2_AW_Dry_CD_60_AvgDens_AvgTH_of_FairSites	AW	787	13.5	60	100(77)	Table 4-6
04_b3_AWSW_Dry_CD_AvgDens_AvgTH_of_FairSites	AW	700	13.5	60	63.5(55)	Table 4-6
04_b3_AWSW_Dry_CD_AvgDens_AvgTH_of_FairSites	SW	403	9.3	60	36.5(41)	Table 4-6
05_b4_PJSW_Dry_CD_AvgDens_AvgTH_of_FairSites	PJ	576	10.7	80	50(32)	Table 4-6
05_b4_PJSW_Dry_CD_AvgDens_AvgTH_of_FairSites	SW	577.5	9.3	80	50(57)	Table 4-6
06_c1_PJSB_Moist_CD_AvgDens_AvgTH_of_FairSites	PJ	682.5	10.7	80	67.5(67.5)	Table 4-8
06_c1_PJSB_Moist_CD_AvgDens_AvgTH_of_FairSites	SB	325.5	7.7	80	32.5(32.5)	Table 4-8
07_d1_AW_Moist_CD_AvgDens_AvgTH_of_FairSites	AW	736	13.5	60	100(86)	Table 4-10
08_d2_AWSW_Moist_CD_AvgDens_AvgTH_of_FairSites	AW	729.5	13.5	60	63.5(46)	Table 4-10
08_d2_AWSW_Moist_CD_AvgDens_AvgTH_of_FairSites	SW	421.5	9.3	60	36.5(36)	Table 4-10
09_d3_SW_Moist_CD_AvgDens_AvgTH_of_FairSites	SW	1108.5	9.3	90	100(79.5)	Table 4-10
10_e1_AW_Moist_CD_AvgDens_AvgTH_of_FairSites	AW	736	13.5	60	100(54.5)	Table 4-10
11_e2_SWAW_Moist_CD_AvgDens_AvgTH_of_FairSites	SW	682.5	9.3	90	77(46.5)	Table 4-10
11_e2_SWAW_Moist_CD_AvgDens_AvgTH_of_FairSites	AW	204	13.5	90	23(27)	Table 4-10
12_e3_SW_Moist_CD_AvgDens_AvgTH_of_FairSites	SW	1108.5	9.3	90	100(72)	Table 4-10
13_f1_AW_Wet_CD_AvgDens_AvgTH_of_FairSites	AW	890.5	13.5	60	100(44.5)	Table 4-12
14_f2_SWAW_Wet_CD_AvgDens_AvgTH_of_FairSites	SW	761.5	9.3	90	75(52)	Table 4-12
14_f2_SWAW_Wet_CD_AvgDens_AvgTH_of_FairSites	AW	253.5	13.5	90	25(14.5)	Table 4-12
15_f3_SW_Wet_CD_AvgDens_AvgTH_of_FairSites	SW	1175	9.3	90	100(91.5)	Table 4-12
16_h1_SWSB_Wet_CD_AvgDens_AvgTH_of_FairSites	SW	677	9.3	90	49(70)	Table 4-12
16_h1_SWSB_Wet_CD_AvgDens_AvgTH_of_FairSites	SB	692	7.7	90	51(27)	Table 4-12

[a] Species codes: SW = *Picea glauca* (Moench) Voss (white spruce), AW = *Populus tremuloides* Michx. (aspen), PJ = *Pinus banksiana* Lamb. (jack pine), and SB = *Picea mariana* (Mill.) BSP (black spruce).

[b] N = the planting density of the given tree species for that particular ecosite, according to AENV (2010).

[c] Species percent without parentheses is the percentage of the tree species in a given ecosite according to averages taken from tables in AENV (2010), while the species percent within parentheses is according to values from Beckingham and Archibald (1996).

[d] Source tables from AENV (2010).

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(AENV) Alberta Environment. 2010. Guidelines for reclamation to forest vegetation in the Athabasca oil sands region. 2nd ed. Prepared by Terr. Subgr., Reclam. Work. Group, Cumulative Environ. Manag. Assoc., Fort McMurray, AB. (December 2009.) Available from: https://open.alberta.ca/publications/9780778588252#detailed.

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Appendix 3. Derivation of a multiplier of four to approximate the conversion of wood biomass carbon (t) to volume (m^3)

Equation [3], which is derived from equations [1] and [2], was used to approximately convert wood biomass C (t) (an output from the CBM-CFS3) to wood volume (m^3). Equations [1] and [2] were used to estimate the conversion factor of 4 in equation [3]. Data used to estimate variables in the equations were for tree species common in the oil sands region.

$$\text{wood biomass (kg)} = \text{wood volume } (m^3) \times \text{bf (unitless)} \times \text{wd } (kg\ m^{-3}), \quad [1]$$

where bf is the mean bark fraction multiplier (1.174) and wd is the mean wood density (441.1).

$$\text{wood biomass C (t)} = \text{wood biomass (kg)} \times C_{prop} \times 1\ t\ C/1000\ kg\ C \quad [2]$$

where C_{prop} is the proportion of C in wood biomass (0.488).

$$\text{wood volume } (m^3) = \text{wood biomass C (t)} \times 4 \quad [3]$$

Estimation of mean wood density (wd) in kg m^{-3} used the data below taken from Singh (1984)

Species	Alberta
White spruce	410
Jack pine	452
Tamarack	507
Black spruce	465
Balsam poplar	405
Trembling aspen	408
Mean	441.1

Estimation of mean bark fraction for the Boreal Plains used the data below taken from Table 8 in Boudewyn et al. (2007).

Predominant genus	Bark (kg ha^{-1})	Wood (kg ha^{-1})	Bark fraction
Spruce	814	5968	0.136
Pine	565	2736	0.207
Poplar	2876	13769	0.209
Larch	1320	9023	0.146
Mean			0.175

Estimation of percent carbon in wood used the data below taken from Lamlon and Savage (2003)

Species	% C
Trembling aspen	47.1
White spruce	50.4
Larch	47.2
Jack pine	50.4
Mean	48.8

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