CARBON STORAGE IN LANDSCAPES AFFECTED BY OIL SANDS MINING IN ALBERTA'S NORTHERN BOREAL FOREST[1]

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Abstract: The objective of reclamation of surface mined lands in the Athabasca Oil Sands Region in northern Alberta is to return the land to an equivalent land capability. The native soils disturbed by surface mining must be salvaged and replaced during reclamation in accordance with the current provincial legislation, consequently, the topsoil (LFH or Ah, Ahe, Ae, Oa, Oi, Oe horizons) and subsoil (B and C horizons) or upper two meters of organic soil are removed and stockpiled during overburden and resource extraction activities and are replaced over tailings sand or overburden during reclamation. The objective of this research was to assess the carbon (C) balance within the reclaimed landscape by monitoring the soil, biomass and dead organic matter carbon pools from the time of initial reclamation forward at the operations of Syncrude Canada Ltd. To achieve this objective C losses and gains were monitored through respiration and biometric assessments, respectively. These methods were then used to evaluate the C dynamics of various reclamation strategies and soil prescriptions compared to targeted natural undisturbed ecosites. Net C accumulation was determined using biometric measurement techniques for three years at several long-term-monitoring sites representing six soil cover prescriptions and three of the most common natural soil types. Measurements of the annual production of above and below ground C biomass and soil respiration were used to develop biometric estimates of net ecosystem productivity. The soil component comprised a substantially larger proportion of the total C pools in the reclaimed areas. The soil C pool was larger for all reconstructed sites with a peat-mix or LFH cap than for the natural sites, especially sites with mature tree stands 70 years of age or greater which had substantially more C stored in the above ground biomass than in the soil. Measurement of inputs to and output (losses) from the total C pool for reclaimed sites with different soil covers indicated that losses were nearly balanced by inputs in the early years following revegetation.

Key words: carbon pools, soil covers, soil respiration, biometric, measurement, biomass carbon

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Introduction

Production from Syncrude Canada Ltd. surface mining operations in the Athabasca oil sands region north of Fort McMurray, Alberta began in 1978 (Macyk and Drozdowski 2008). Reclamation research has been ongoing since the early 1970's (Macyk et al. 1998) and has addressed issues associated with soil reconstruction and revegetation including the type and thickness of soil materials required and the evaluation of the suitability of a variety of introduced and native species including grasses, legumes, trees and shrubs. Soil capping research to achieve a level of soil quality that will assist in achieving equivalent land capability has been a major focus for Syncrude's reclamation activities.

One indicator of soil quality is its bioactivity, which is often characterized by the soil organic matter (SOM) or soil organic carbon (SOC) content (Molina et al. 1994). Soil OC is recognized as an important component of soil quality through its influence on soil physical properties and the cycling of nutrients. Interest in SOM has expanded to include its role in the worldwide C budget and climate change (Elliott et al. 1994).

The goal of placement of soil covers in the reclamation sequence is to provide a suitable root zone for the target forest ecosystem. From a biological standpoint, the soil cap must provide a sufficient pool of nutrients to sustain the developing vegetation community until natural patterns of nutrient cycling are re-established (Barbour et al. 2007). Proper replacement of SOM is one of the most important steps in reclamation, and one of the key indicators of successful reclamation (Barbour et al. 2007). Measuring the C stored in the soil and above- and below-ground biomass can be a useful tool used to assess the success of the various soil capping prescriptions.

Changes in ecosystem C stocks occur predominantly through CO_2 exchange between the land surface and the atmosphere. Plant biomass, including the above- and below-ground components, is the main conduit for CO_2 removal from the atmosphere (IPCC 2006). Large amounts of CO_2 are transferred between the atmosphere and terrestrial ecosystems, primarily through photosynthesis and respiration. Approximately half of the CO_2 taken up by plants through photosynthesis (referred to as gross primary production) is respired and returned to the atmosphere, with the remainder constituting net primary production (NPP). Net primary productivity; which is the total production of biomass and dead organic matter in a year, minus losses from heterotrophic respiration (decomposition of organic matter in litter, dead wood and soils) is equal to the net C stock change in an ecosystem (net ecosystem productivity (NEP)) (Curtis et al. 2002, Gough et al. 2008).

Land use and management influence NPP through a variety of anthropogenic actions such as deforestation, fertilization, soil handling practices and revegetation strategies. The objective of this research was to compare the change in C stocks in a reclaimed landscape to undisturbed natural areas at the operations of Syncrude Canada Ltd., and to develop and recommend reclamation strategies aimed to achieve post-mining equivalent land capability (Macyk et al. 2009a). A necessary tool for understanding the flow of C within ecosystems is biomass. Methods for quantifying the flow of C focus on stock changes in biomass associated with woody plants and trees which can accumulate large amounts of C over their lifespan. Biomass associated with non-woody herbaceous plants is relatively ephemeral, i.e., it decays and regenerates annually or every few years, therefore emissions from decay are balanced by removals due to re-growth making overall net C stocks in biomass rather stable in the long term. In forest ecosystems, biomass is located in five major pools (Table 1). Net ecosystem productivity can be estimated by measurements of above- and below-ground C biomass and soil respiratory losses.

Table 1. Definitions of Carbon Pools.

Biomass	Above Ground Biomass	All biomass of living vegetation, both woody and herbaceous, above the soil including stems, stumps, branches, bark, seeds and foliage.
	Below Ground Biomass	All biomass of live roots. Fine roots less than 2 mm diameter are often excluded because these often cannot be empirically distinguished from SOM or litter.
Dead Organic Matter	Dead Wood	Includes all non-living woody biomass not contained in the litter, either standing, lying on the ground, or in the soil. Dead wood includes woody lying on the surface, dead roots, and stumps larger than or equal to 10 cm in diameter.
	Litter	Includes all non-living biomass with a size greater than the limit for SOM and less than the minimum for dead wood, lying dead, in various states of decomposition above or within the mineral or organic soil.
Soils	Soil Organic Matter	Includes organic carbon in mineral soils to a specified depth (1 meter for this paper). Live and dead fine roots and dead organic matter within the soil that are less than the minimum diameter for roots and dead organic matter are included with SOM where they cannot be empirically distinguished.

Soil C refers to the total C in soil and it includes both inorganic and organic forms. Inorganic soil C is largely ignored when discussing changes in C stocks due to the long timescale required for inorganic forms of C to change and interact with atmospheric C. The OC content of mineral forest soils (to 1 m depth) typically varies between 20 to over 300 Mg C ha^{-1} depending on the forest type and climatic conditions (Jobbagy and Jackson 2000). Organic C pools are not static due to differences between C inputs and outputs over time. Inputs are largely determined by forest productivity, the decomposition of litter and its incorporation into the mineral soil and subsequent loss through mineralization and respiration (Pregitzer 2003). Soil respiration can be used as a parameter to compare the quality of the various reclaimed soil covers with the natural soils in the area as it is a basic indicator of soil quality or soil health (Doran and Parkin 1994).

The bulk of biomass production (NPP) contained in living plant material is eventually transferred to dead organic matter (DOM) pools (i.e., dead wood and litter) therefore SOM tends to concentrate in the upper soil horizons, with roughly half of the SOC in the upper 30 cm layer. Estimating the C dynamics of DOM pools allows for increased accuracy in the reporting of where and when C emissions and removals occur. Some DOM decomposes quickly, returning C to the atmosphere, but a portion is retained for months to years to decades. Dead organic matter and SOM stocks are influenced by land use and management activities that affect litter input rates and decomposition and SOM loss rates. Reclamation strategies that include the establishment and maintenance of a healthy vegetation cover will result in continued addition of C to the system.

This paper describes the research undertaken by the Alberta Research Council on behalf of and funded by Syncrude Canada Ltd. to assess the C balance within the reclaimed landscape and undisturbed natural areas using the methodologies described in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories wherever possible.

Materials and Methods

Study Area

Syncrude Canada Ltd. is located approximately 40 km north of Fort McMurray, Alberta. The area is characterized by a cool temperate climate with a mean annual air temperature of 1.1°C and a mean annual precipitation of approximately 342 mm of rainfall and 156 mm of snowfall (Macyk et al. 2009b). Monthly mean air temperatures range from 17.7°C in July to -

18.1°C in January (Macyk et al. 2009b). The average growing season with temperatures greater than 10°C from May to September is approximately 143 days.

Most of the area is underlain by Cretaceous shales and sandstones. The typical mineral soils in the area are Luvisolic (Boralfs) soils developed under mixed deciduous and coniferous vegetation (Turchenek and Lindsay 1982). The vegetation is characteristic of the Boreal forest region. The principle tree species of the area are white spruce (*Picea glauca* (Moench) Voss), black spruce (*Picea mariana* (Mill.) B.S.P.), trembling aspen (*Populus tremuloides* Michx.), balsam poplar (*Populus balsamifera* L.), and white birch (*Betula papyrifera* Marsh). Jack pine (*Pinus banksiana* Lamb.) is dominant on well-drained sandy areas, but also occurs with other tree species on drier glacial till soils and in mixes with black spruce in the uplands.

Study Sites

Permanent sampling plots (10 x 10 m) were established at 13 reclaimed locations at the Southwest Sand Storage Facility (SWSS), Mildred Lake Settling Basin (MLSB), South Bison Hill (SBH) and overburden dump 5 (South) and nine undisturbed reference locations adjacent to the MLSB and SWSS in 2007 (Macyk et al. 2009a) to conduct the required annual measurements (Table 2).

The sites selected for this project represent the various soil capping prescriptions used for reclamation at Syncrude (Table 3). The peat-mix (PM) used for reclamation is a mixture of peat and mineral materials, resulting in a mineral soil with less than 17% OC by weight. The mineral component of the peat mix layer in the soil covers studied in this project range from sandy loam to sandy clay loam. The LFH material used for reclamation is a combination of upland forest floor material composed of lithic, fibric and/or humic materials and the underlying mineral horizon. The secondary material (Sec) is comprised of sandy clay loam to clay loam subsoil or parent material primarily of glacial origin. The tailings sand (TS) is the sand resulting from the extraction of bitumen from the McMurray oil sand formation and is comprised of a total sand content >90% with dominantly fine sand fractions (0.25 to 0.10 mm). Soil reclamation prescriptions at Syncrude have included various depths of PM applied over or incorporated into secondary material over tailings sand or overburden and various depths of LFH material applied over PM or Sec over tailings sand or overburden. Table 2 provides the names/numbers and descriptions for the reclaimed and natural sites evaluated in this study. Site names will appear in italics for the remainder of this paper.

Table 2. Study Sites at Syncrude's Southwest Sand Storage Facility, Mildred Lake Settling Basin and South Bison Hill locations.

Site No.	Age or Year of Reclamation	Location	# of Plots	Soil Prescription	Vegetation Cover
Undisturbed					
16	70+	-	2	Luvisol†; medium to fine textured	trembling aspen, white spruce, lowbush cranberry, gooseberry, bearberry, dogwood
17	100+	-	2		
18	17	-	1		
29	70+	-	1	Sphagnum Peat Organic	black spruce, labrador tea, mosses, lichens
30	70+	-	2	Luvisol; medium to fine textured	trembling aspen, white spruce, lowbush cranberry, gooseberry, bearberry, dogwood
31	70+	-	2		
32	15	-	1		
35	70+	-	1	Brunisol‡; coarse textured	jackpine, bearberry, blueberry, pincherry
Reclaimed					
Cultivar	1985	MLSB*	3	5 to 10 cm windblown TS** / Secondary / TS	white spruce, aspen, dogwood, caragana, vetch, dandelion, sweet clover, grasses
Lower Pine	1980	MLSB	2	20 to 30 cm peat mix / TS	jack pine, aspen, saskatoon, raspberry, strawberry, sweetclover
Upper Pine	1985	MLSB	2	10 cm windblown TS / 30 cm peat mix / TS	jack pine, aspen, dogwood, dandelion, vetch, grasses
SWSS§ Lower slope	1997	SWSS	3	80 cm secondary / TS	larch, balsam poplar, willow, dogwood, buffaloberry, dandelion
SWSS Mid Slope	1997	SWSS	2		white spruce, aspen, balsam poplar, willow, dogwood, gooseberry, dandelion
Cabin	1991	MLSB	3	40 to 50 cm peat mix / TS	jack pine, balsam poplar, willow, wild rose, buffaloberry, strawberry, bearberry
Native Species	1997	MLSB	-	20 cm peat mix and secondary incorporated / 40 cm secondary / TS	native grasses and pasture grasses
Cabin Slope	1996	MLSB	3	15 cm peat mix / 20 cm secondary / TS	white spruce, jack pine, aspen, willow, dogwood, strawberry, sweet clover, grasses
LFH†† Beach	1997	MLSB	3	15 cm LFH / 20 cm secondary / TS	white spruce, aspen, honeysuckle, raspeberry, bluebell, strawberry
SBH***	1998	SBH	3	15 cm peat mix / secondary / overburden	white spruce, aspen, willow, fireweed, horsetail, mosses, grasses
SBH Slope	1998	SBH	9	15 cm peat mix / 20 to 80 cm secondary / overburden	white spruce, aspen, willow, fireweed, grasses
Fibric Peat	2005	Dump 5	4	15 to 25 cm peat mix / secondary / overburden	aspen, willow, white spruce, mosses, grasses

†Luvisol - fine textured soil; ‡Brunisol - coarse textured soil; *MLSB - Mildred Lake Settling Basin; **TS - Tailing Sand; §SWSS - Southwest Sand Storage Facility; ***SBH - South Bison Hill; ††LFH - soil layer containing lithic, fibric and humic materials

Table 3. Various soil capping prescriptions used for reclamation at Syncrude Canada Ltd.

Material	Texture	Description
Tailings Sand (TS)	>90% Sand	Sand resulting from the extraction of bitumen from the McMurray oil sand formation; dominantly fine sand fractions (0.25 to 0.10 mm).
Overburden (OB)	Sandy clay loam to Clay	Geologic materials overlying the oil sand layer that are removed and stored in-pit and in out of pit 'dumps'.
Secondary (Sec)	Sandy clay loam to Clay	Salvaged subsoil or parent material (usually surficial geologic material of glacial origin); dominantly mineral material (i.e., organic matter content typically low).
Peat-Mix (PM)	Mineral material in mix - Sandy loam to Sandy clay loam	A mixture of peat and mineral materials resulting in a mineral soil with <17% organic carbon by weight.
LFH†	-	An LFH horizon is a designation commonly applied to upland organic soil horizons. In the context of reclaimed soil covers it refers to the replaced surface layer which contains LFH, LF, LH materials combined with some of the underlying mineral (Ae, AB, B) horizon material incorporated during the pre-mining soil salvage operations.

† LFH - Lithic, Fibric Humic

At each of the sites evaluated, efforts were made to derive biometric estimates of annual C storage by measurement of major C pools and fluxes as presented in Table 4.

Biometric Measurements

Changes in C storage can be assessed based on a number of factors relating to above- and below-ground biomass, DOM and SOM (IPCC 2006). The fundamental basis for the methodology assumes that the flux of CO_2 to or from the atmosphere is assumed to be equal to changes in C stocks in existing biomass and soils. The changes in C stocks relative to the different C pools can be determined using the equation provided below.

$$\Delta C_{LU} = \Delta C_{AB} + \Delta C_{BB} + \Delta C_{DOC} + \Delta C_{SOC}$$

where:

ΔC_{LU} = carbon stock changes for a specific soil capping prescription or undisturbed natural soil

AB = above-ground biomass carbon = $\Delta C_{trees} + \Delta C_{shrubs}$

BB = below-ground biomass root carbon

DOC = deadwood and litter carbon

SOC = soil organic carbon

Table 4. Components of net primary productivity, ecosystem respiration and soil carbon dynamics measured to derive a biometric estimate of net ecosystem productivity.

Item	**Measured/ Estimated**	**Method**	**Application**
Above Ground Net Primary Productivity Components			
Tree volume	Measured	Allometry	All Sites
Shrub volume	Measured	Allometry	All Sites
Leaf Area Index	Measured	LAI 2000†	All Sites
Canopy cover	Measured	WINCANOPY‡	All Sites (Semi-annual)
Below Ground Net Primary Productivity Components			
Root Production	Estimated	Expansion factors based on above-ground biomass	All Sites
Dead Organic Matter Net Primary Productivity Components			
Dead Wood	n/a	n/a	n/a
Litter	Measured	Litter plots and/or traps	Cabin, SBH*, Lower Pine, 17, 18, 35, SWSS**
Respiration			
Total soil respiration	Measured	LICOR chambers and multiplexers	2008 - cabin, SBH, native species, fibric peat 2009 - cabin, SBH, 18
Soil Carbon			
Soil surface	Measured	soil collar/bulk density sampling	All Sites (several reps)
Sub-surface	Measured	soil collar/bulk density sampling to 1 m	All Sites (1 rep)

† Licor instrument used to measure Leaf Area Index; ‡ Regent Instruments Inc. instrument used to measure canopy closure; * South Bison Hill; ** Southwest Sand Storage Facility

Above- and below-ground biomass

Above-ground C stored in wood was assessed annually at all sites using allometric equations relating breast height and basal tree diameters measured in the sampling plots and species specific density and expansion factors for branch and leaf/needles developed for Alberta species (Table 4) (Alberta Environment 2007).

Biomass C associated with the lower canopy vegetation includes trees and shrubs that are <1 m in height and excludes the non-woody herbaceous ground cover. Below-ground C stored in roots was estimated using allometric equations relating above-ground woody mass to below ground woody mass for specific species (Table 5) (Alberta Environment 2007).

Table 5. Stand Level Biomass Expansion Factors Used in Carbon Determinations for Different Species (Alberta Environment 2007).

Species	**Expansion Factor**	**Root to Shoot Ratio**	**Density (t/m^3)**
Spruce	1.2	0.133	0.35
Jack Pine	1.05	0.116	0.42
Balsam Poplar	1.08	0.141	0.6
Birch	1.26	0.155	0.51
Willow	1.26	0.155	0.39
Aspen	1.26	0.155	0.37

Dead Organic Matter

Dead wood has not been evaluated at the monitoring sites; however, it will be assessed in 2010. Litter plots were established at seven plots in 2009 to evaluate annual litter accumulation according to a method described in Rezende et al. (1999). The total accumulated litter in 0.5 m^2 plots was collected and dried and subsequently weighed. To evaluate annual deposited litter, an area of 25 cm around the 0.5 m^2 plots was cleared of litter to avoid entry of litter into the cleared plot by wind or animals. Litter traps were also installed at these locations to compare the methods however, due to a late fall litter in these traps was not collected in 2009.

Respiration

Licor LI-8100 Automated Soil CO_2 Flux Systems equipped with LI-8150 Multiplexer units were used to make short-term survey and long term unattended measurements of soil CO_2 flux. Short term measurements of one minute duration were completed every four hours between May and October at the cabin, native species, south bison hill and fibric peat sites in 2008 and at the cabin, south bison hill sites and site 18 in 2009.

At each of the sites a soil sample equivalent to the volume occupied by the cylindrical chamber collar (8.9 x 20 cm) was extracted at the conclusion of monitoring in October. Total C and nitrogen (N) were determined in a LECO® CN-2000 CNS Analyzer (Leco 1993).

Soils

Surface SOC was determined at each of the reconstructed and natural sites by extracting a soil plug equivalent to the volume occupied by a retrofitted cylindrical collar (20.3 x 10.8 cm). In addition, core samples (8.9 x 10 cm) were obtained to approximately 1 m at each reclaimed and undisturbed location. Samples were obtained in 10 cm intervals down to 1 m and stored in plastic bags at 4°C until delivered to the laboratory for analyses. The samples were collected in a manner that resulted in complete characterization of the soil cap and at least one interval of the underlying tailings sand at the reclaimed sites.

Results and Discussion

Carbon Reservoir

The above-ground biomass, below-ground biomass, DOM (litter) and soil C pools combined constitute the C reservoir for the natural and reclaimed sites evaluated. Figure 1 illustrates the biomass (above- and below-ground biomass combined), DOM and SOC pools (upper 15 cm) for the sites evaluated in 2007, 2008 and 2009. These results illustrate the trends and relationships associated with the C pools of reclaimed and natural sites.

The highest total C stock values reported in 2007, 2008 and 2009 were associated with the older stand natural sites (70+ years). In 2009, values for sites 70 years and older ranged from 53 to 257 Mg C ha^{-1}. The natural sites in the 18 to 26 year old stand range had values of 40 to 55 Mg C ha^{-1}, which is a better reference for comparison with the reclaimed sites. For the older stands the above- and below-ground C stocks comprised of the trees, shrubs, and associated roots were in a few instances twice to three times the size of the DOM and surface soil (0 to 15 cm interval) C pools. For the younger stands the total vegetation cover and roots accounted for 15 to 40% of the total C present. The soil component comprised a substantially larger component of the total C pools or reservoir at the reclaimed sites. The proportion varied for the different sites based on soil reconstruction technique, vegetation cover established, and age of the site.

The lowest C pool values for reclaimed sites occurred at the *Cultivar Site*[1] with values ranging from 35 to 44 Mg C ha^{-1}. The soil component had relatively low levels because the area is characterized by a layer of windblown tailings sand over secondary material. The values were slightly higher for *SWSS Lower- and Mid-slope Sites* where the reconstructed soil is comprised of a layer of secondary material over tailings sand. The total C values at the *South Bison Hill (SBH) Slope Sites* which range from 59 to 99 Mg C ha^{-1} are higher primarily due to the increased above-ground carbon component. The *LFH Beach Site* had a mean value of 93 Mg C ha^{-1} based on a range of 71 to 114 Mg C ha^{-1}. The *Lower Pine Site* which at 27 years is the oldest reclaimed site monitored had values ranging from 84 to 97 Mg C ha^{-1}. The *Upper Pine Site*

[1] See Table 2 for descriptions of sites evaluated

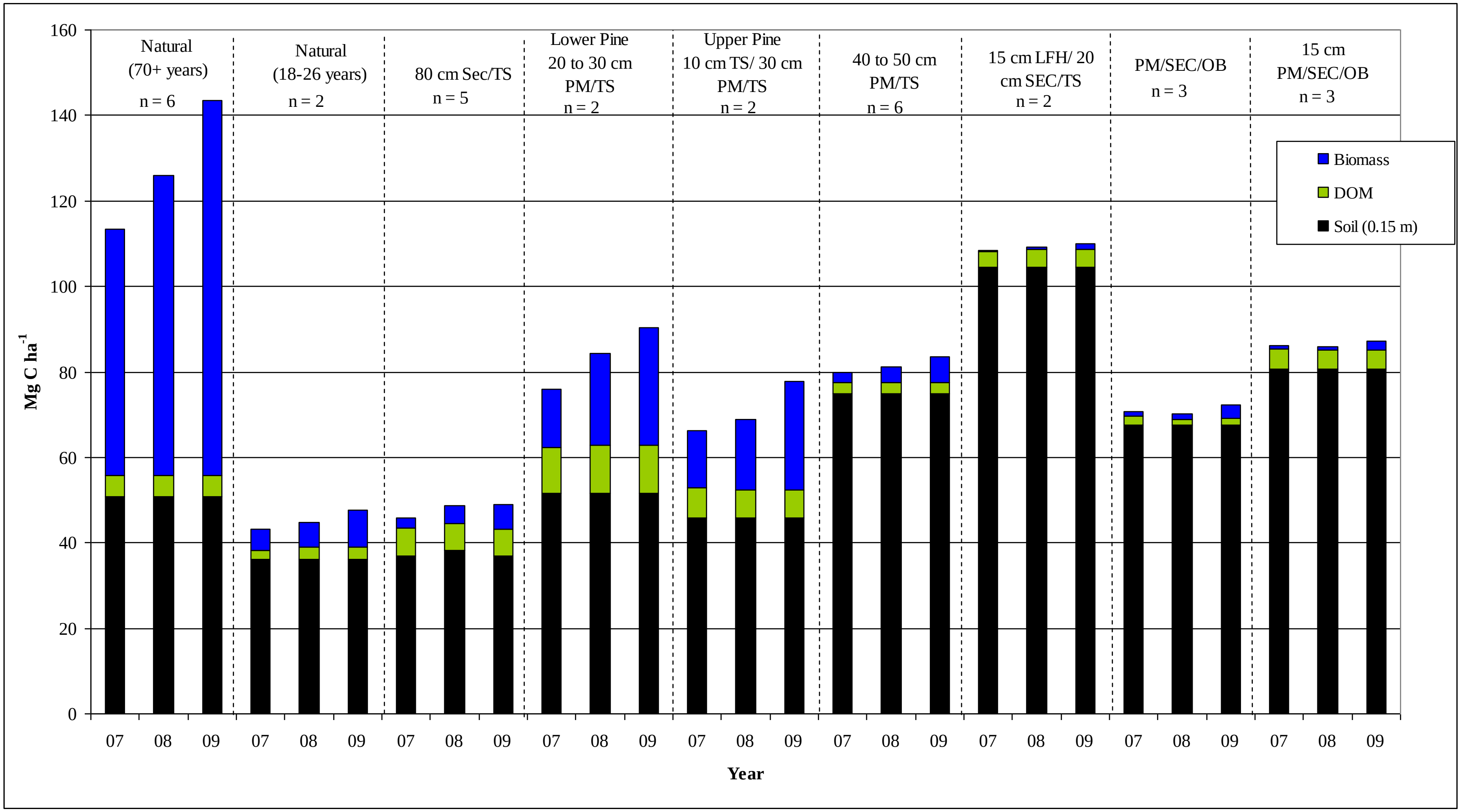

Figure 1. Comparison of the Components of the Carbon Pools at the Natural and Reclaimed Sites *(Sec – Secondary soil material; TS – Tailings Sand; PM – peat mix soil material; LFH – upland forest floor material; OB – overburden material; DOM – Dead Organic Matter).*

which is 22 years old had values ranging from 57 to 99 Mg C ha^{-1}. It is interesting to note that a substantial portion of the above-ground C pool at the *upper pine site* can be attributed to the shrub cover.

The data indicate that there was a wider range in above-ground shrub biomass values at the reclaimed sites than at the natural sites (Figure 2). With the exception of the *Natural Peat Bog Site 29*, the lowest value reported for the natural sites was 0.380 Mg C ha^{-1} for *Natural Site 30*. The values ranged from 0.88 to 3.34 Mg C ha^{-1} for the remaining natural sites demonstrating the extent of the shrub cover at these "mature" sites. The reclaimed sites were extremely variable. For example, one of the plots at the *Cultivar Site* had a value of 0.073 Mg C ha^{-1} while another plot had 3.4 Mg C ha^{-1}. Similarly two of the plots at the *SBH Slope Site* had values of 0.065 and 0.132 Mg C ha^{-1} while the remaining plots had values ranging from 0.459 to 1.4 Mg C ha^{-1}. The shrub component at the *SWSS Lower Slope* and *Upper Pine Sites* increased the above-ground biomass component to 2.1 Mg C ha^{-1} and 2.2 Mg C ha^{-1} respectively. The values for the remaining sites ranged from 0.0014 to 2.0 Mg C ha^{-1}. These values reflect the age of the site and the species planted.

The differences in C stock between 2007, 2008 and 2009 can be seen in Figure 1. The results demonstrate an increase in total C values from 2007 to 2009 for all sites. The substantial difference in the biomass contribution to the total C pool for older (70+ years) natural sites than younger (18 to 26 years) natural sites is evident. The soil C pool is supporting a substantial C pool in the vegetation cover at the older natural sites.

In general the reclaimed sites with a peat mix cap at the surface had the highest total soil C concentrations. The highest SOC mass value (197.1 Mg C ha^{-1}) for reclaimed sites at the 0 to 15 cm depth was reported for one of the plots at the *Cabin Slope Site* in 2008. The values for the remaining two plots were 104 and 105 Mg C ha^{-1} (Figure 1). The lowest value (2.3 Mg C ha^{-1}) was reported for the one of the plots at the *SWSS Mid-Slope Site* where secondary material was located at the surface. Sampling to depths of up to 1 m allowed for calculation of the mass of carbon stored to the 60 cm and 1 m depth at most of the sites (Figure 7). The C stock values in the upper meter ranged from 65 Mg C ha^{-1} at the *Natural Brunisolic Site 35* to 335 Mg C ha^{-1} for the *Cabin Slope Site (plot 1).*

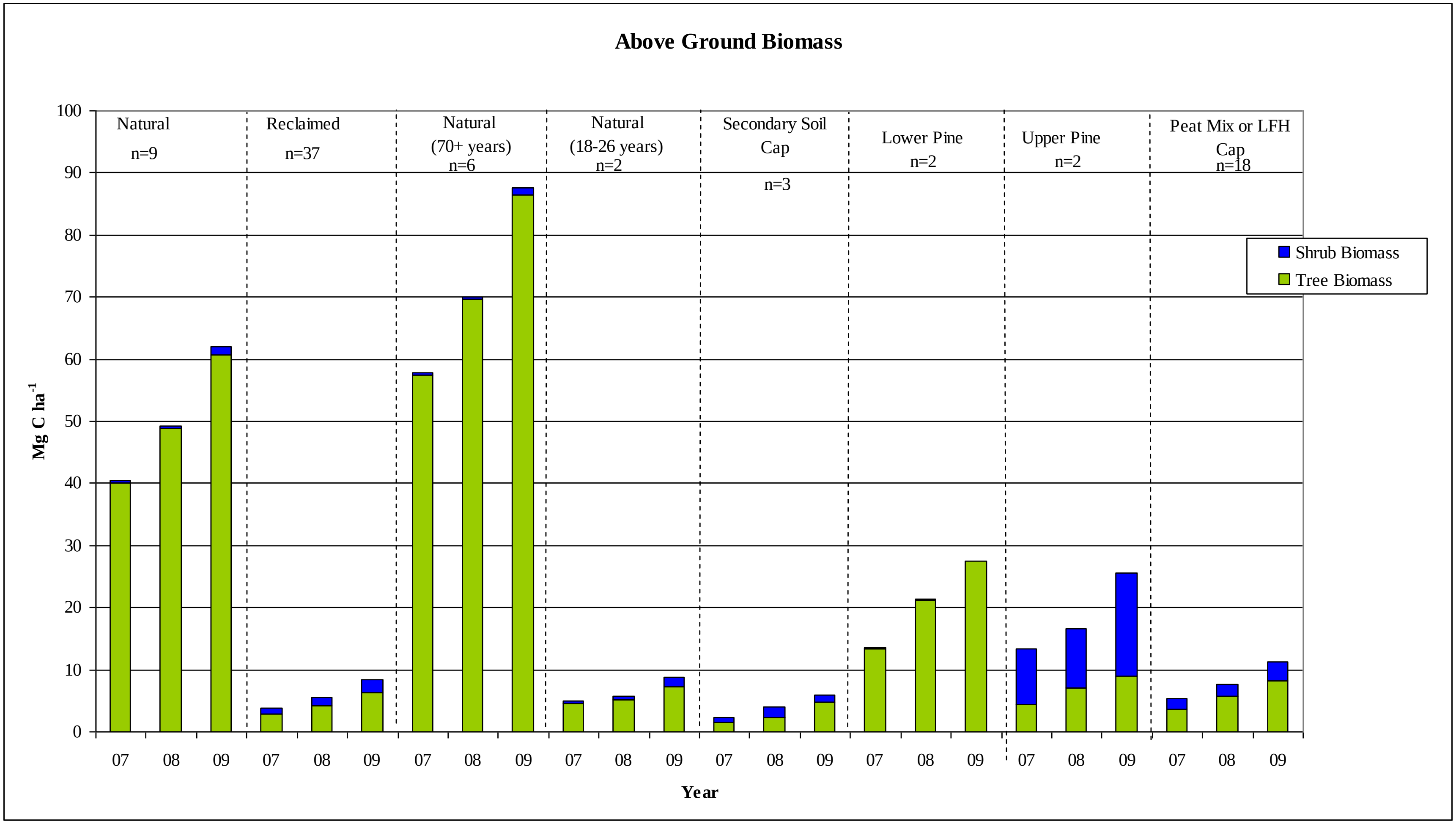

Figure 2. Comparison of the Tree and Shrub Biomass (Above- and Below-Ground) at the Natural and Reclaimed Sites *(LFH – upland forest floor material*

In general, the soil C pool is larger for all reconstructed sites with a PM or LFH cap than for the natural sites. The reconstructed soils with the secondary material cap or with windblown tailings sand at the surface have SOC values slightly lower than the natural soils.

The fact that the reconstructed sites with a peat mix or LFH cap have high soil carbon pools suggests that the reconstructed sites have the ability to sustain productive plant communities in the long-term.

Table 6 provides the total biomass C levels from the litter layer at the sites in 2008. Overall the ranges in values for the reclaimed and natural sites were generally similar. The natural sites had values ranging from 0.7 to 7.4 Mg C ha^{-1} and the reclaimed sites had mean values of 0.5 to 8.5 Mg C ha^{-1} for the range of sites with the exception of the *Lower Pine Site* which had a mean value of 11.0 Mg C ha^{-1} and represents the oldest reclaimed site evaluated in 2008. The lowest values were reported for the younger sites that do not have well established vegetative covers.

Respiration

Total annual flux values (Mg CO_2 ha^{-1} yr^{-1}) were generated from the data obtained at the various sites in 2007, 2008 and 2009 (Table 7). Total C concentrations and mass of C were determined for the soils at each of the sites. Data obtained for a period of three years at the *Cabin Site* with a 40 cm PM/TS cap showed consistent values over the measurement period. The same was true for the two years of measurements at the *SBH Site*.

Annual respiration rates based on the soil carbon levels were slightly higher for the natural soils than the reclaimed soil covers. The results indicate that the replaced peat-mixes and LFH materials are breaking down and releasing nutrients for use by the developing ecosystem and functioning similar to the natural soils.

Table 6. Biomass Carbon from Litter (mean (standard deviation))at the Reclaimed and Natural Sites in 2008.

Site	Soil Prescription	Carbon Mg C ha^{-1}	Site	Soil	Carbon Mg C ha^{-1}
Reclaimed			**Natural**		
SWSS* Lower Slope	80 cm secondary / TS**	6.8	SWSS16	Luvisol[†]; medium to fine textured	6.6
SWSS Mid Slope-1		5.2 (1.6)	SWSS17		6.4
SWSS Mid Slope-2		8.5	SWSS18		2.3
Cultivar	5 to 10 cm windblown TS / Secondary / TS	2.9 (1.1)	SWSS29	Sphagnum Peat Organic	0.7
Upper Pine	20 to 30 cm peat mix / TS	6.5 (3.5)	SWSS30	Luvisol; medium to fine textured	6.7 (1.1)
Lower Pine	10 cm windblown TS / 30 cm peat mix / TS	11.4 (0.6)	SWSS31		5.0 (0.6)
Cabin	40 to 50 cm peat mix / TS	2.7 (1.0)	SWSS32		3.7
Cabin Slope	15 cm peat mix / 20 cm secondary / TS	2.4 (0.9)			
SBH[‡] Slope	15 cm peat mix / 20 to 80 cm secondary / overburden	1.6 (0.7)			
SBH	15 cm peat mix / secondary / overburden	4.3 (3.8)			
LFH[§] Beach-1	15 cm LFH / 20 cm secondary / TS	4.2 (0.2)			
LFH Beach -2	20 cm Peat / 20 cm secondary / TS	4.3			
Fibric Peat	15 to 25 cm peat mix / secondary / overburden	0.7 (0.4)			

*SWSS - Southwest Sand Storage Facility; **TS - Tailings Sand; [‡]SBH - South Bison Hill; [†]Luvisol - fine textured soil; [§]LFH - soil layer containing lithic, fibric and humic materials

Table 7. Carbon and Respiration Data for the Sites Monitored in 2007, 2008 and 2009.

Site	Mg C ha^{-1} (15 cm depth)			Total (Mg CO_2 ha^{-1} yr^{-1})			Annual Respiration (Mg CO_2/ha_{resp})/ (Mg C/ha)$_{soil}$		
	2007	2008	2009	2007	2008	2009	2007	2008	2009
LFH Beach*	70.00			23.00			0.33		
Cabin	69.00	60.95	55.46	26.60	25.26	21.84	0.39	0.41	0.39
SBH**	63.00	80.19	72.04	15.77	27.38	30.88	0.25	0.35	0.43
Fibric Peat		86.24			23.32			0.30	
SWSS 18§			45.49			48.81			1.07

*LFH Beach - soil presription = 15 cm LFH material/20 cm secondary/tailings sand (LFH - soil layer containing lithic, fibric and humic materials); **SBH - South Bison Hill; §SWSS 18 - Luvisol - fine textured natural soil

Biometric Estimates of NEP

The total C reservoir is based on inputs and outputs or losses from the system. Annual inputs and losses were calculated for the sites where respiration measurements were completed in 2008 and 2009 for the *Cabin* and *South Bison Hill Sites*.

Inputs include the C added through biomass to the soil from maturity and decay of ground cover, litter, leaves and needles and root biomass. Additions from root production and leaf and needle shed were based on established turnover rates determined by species specific expansion factors (Alberta Environment 2007, Muukkonen 2007). Outputs or carbon losses are based on soil respiration values recorded. Figure 3 provides a generalized overview of the C pools measured and accounted for in terms of inputs and outputs. The vegetation growth and needles drop to form litter and contribute to SOM. The decomposition processes associated with this turnover contribute to C flux or soil respiration. For example, the *Cabin Site* which has a 17 year old jack pine cover had an input value of 5.83 Mg C ha^{-1} yr^{-1} and an output respiration value of 5.96 Mg C ha^{-1} yr^{-1} in 2009. The above- and below-ground biomass C pool contributed 3.18 Mg C ha^{-1} yr^{-1} which is comprised primarily of a well established jack pine cover. The DOM and SOC pools contributed 2.56 Mg C ha^{-1} yr^{-1}. These results indicate that the losses were almost balanced by the inputs. It should be noted that with time as the vegetation cover of trees and shrubs increases in size there will be an exponential increase in accumulation and storage in the above-ground C biomass pool which will result in increased annual needle, leaf, and root input to the soil pool, and organic matter cycling will shift from being largely based on the peat-mix or LFH cap to being driven primarily by the accumulated layer.

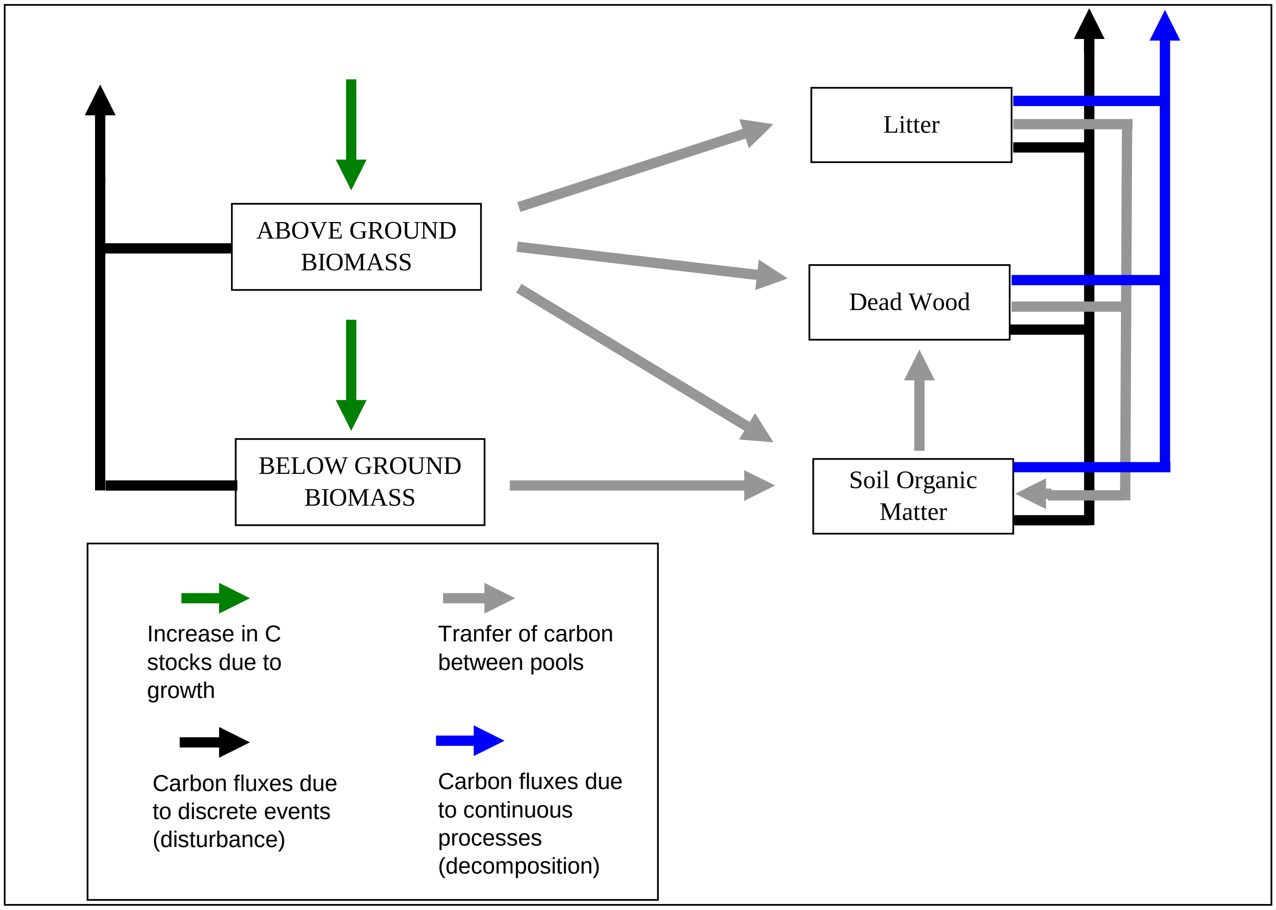

Figure 3. Generalized carbon cycle of terrestrial ecosystems showing the flows of carbon into and out of the system as well as between the five carbon pools within the system (Adapted from IPCC 2006).

Conclusions

The soil component comprised a substantially larger proportion of the total C reservoir in the reclamation soil covers. The proportion varied for the different sites based on soil reconstruction technique, vegetation cover established, and age of the site. The soil C pool was larger for all reconstructed sites with a peat-mix or LFH (forest floor) cap than for the natural sites, especially sites with mature tree stands 70 years of age or greater. These results demonstrate the importance of a peat-mix or replaced LFH (forest floor) layer in the placement of soil covers in reclaimed areas and suggest that reconstructed sites with these covers have the ability to sustain productive plant communities in the long-term. Measurement of inputs to and output (losses) from the total carbon pool for the reclaimed sites with different soil covers indicated that losses were almost balanced by inputs in the early years following reclamation and revegetation.

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