Carbon Footprint Analysis for Wood & Agricultural Residue Sources of Pulp

FINAL REPORT

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1.0 INTRODUCTION & OVERVIEW

Background

In December 2010, HB Lanarc was engaged to compare the carbon footprints of wood and agricultural residue sources of fibre for pulp production. This work builds on earlier research into ecological footprint analyses (Kissinger , Fix and Rees, 2007), which found that wheat straw has a lower overall ecological load than aspen and spruce for purposes of pulp production. As such, wheat straw presumably offered the most promise in terms of minimizing carbon impacts associated with pulp production for paper-making.

Objectives

The objectives of this study, "Carbon Footprint Analysis for Wood and agricultural residue Sources of Pulp", are:

(1) to account for the existing and potential carbon footprint of pulp production from wood and agricultural sources for:
    a. Organic vs. Conventional (wheat);
    b. Zero-Tillage / Low-Tillage vs. Conventional Tillage (wheat);
    c. Conventional Fibre Processing Technology vs. New/Innovative Agriculture Fibre Processing Technology;
(2) to determine if and to what extent alternative agricultural residue sources can contribute to carbon emission reduction in the Canadian pulp industry; and
(3) to briefly address the required policy implications of alternative sources for pulp production.

This Report

This report provides an overview of energy inputs and corresponding greenhouse gas emissions (i.e. carbon footprints) associated with the production of pulp using wood and agricultural residue sources of fiber. Wood sources include aspen and spruce species, while agricultural residue sources focus on wheat straw.

For the wheat straw production component, the report explores organic versus conventional management systems, and zero/low (i.e. conservation) tillage versus conventional tillage management systems. Data obtained from the literature indicate that crop rotation has a larger influence on energy consumption than tillage management, so we also included crop rotation in our data collection and analysis.

Although the focus is placed on the carbon footprint as determined by energy inputs (fuel and electricity) it is also highly important to compare to the effect of land-use change, such as the conversion of unmanaged forested land to managed/harvested lands. This indirect component of the carbon footprint is large, and is included for reference within the report.

The research framework/methodology (including assumptions, calculations, etc) is outlined in more detail – along with research findings – in the main body of the report.

Summary of Findings

The focus of this research is on energy inputs, which indicates that conventional wheat straw performs the poorest, with organic wheat straw being somewhat comparable to spruce and aspen. However, while beyond the scope of this research, it appears that significantly more stored carbon is emitted by managed forests than undisturbed forests, and that this would impact the relative carbon benefits of wood-based paper compared to straw-based papers. This is explored at a high-level in this paper.

2.0 LAND USE CHANGE IMPACTS: CARBON STORAGE

All organic materials include a substantial amount of carbon. Plants remove carbon dioxide from the air and store carbon through photosynthesis. This carbon is effectively stored in the organic material until it is released, such as through decomposition or burning.[1] While this carbon footprint analysis focuses primarily on greenhouse gas emissions associated with energy inputs/consumption during production (agriculture, logging, chipping) and processing of wheat straw and woods, it is important to keep this in perspective with the effect of the conversion of land from unmanaged to managed and harvested states.

WHEAT STRAW

Straw residue is a byproduct of existing agricultural practices. In virtually no cases is it likely that land would be converted from non-agricultural to agricultural use based solely on the need for pulp production. Therefore, there is no estimate of the impact of land-use change for wheat-straw residue provided within the context of this document, which focuses on the carbon footprint of pulp production, not of agriculture in and of itself.

WOOD

Unlike wheat-straw, land-conversion from unmanaged (i.e. intact natural forests) to managed forest lands is common in wood-pulp production, and this conversion is driven by the industrial process. While replanting is common practice, undisturbed forests store significantly more carbon than harvested forests. The amount of carbon stored in managed forest land depends highly on forest management practices, including the tree type, location, and the amount of time between harvests. For example, re-planting trees and approximately 100 years before re-harvesting will likely result in a replacement of carbon in many areas (Ford, 2009). However, on a shorter (e.g. 60 year) crop rotation, stored carbon will simply not return to pre-harvest levels (Seely et al., 2002; Peng et al., 2002).

There is substantial disagreement within the literature as to how much carbon is actually stored in managed vs. unmanaged forests, and this differs substantially by species type and locality. For the purposes of this document, only a rough value is provided. Based on the work of Peng *et al* (2002), it appears that approximately 50% of carbon storage capacity will be lost from the conversion from unmanaged to managed and harvested forests. This equates to approximately 190 tonnes of carbon storage lost for every hectare of forest used to produce pulp.[2]

It is also important to note that reducing greenhouse gas emissions is considered to be time-sensitive: the Intergovernmental Panel on Climate Change targets for carbon emissions reduction

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[1] http://www.gcrio.org/ipcc/techrepI/forest.html

[2] Assumes a 100 year crop rotation and conventional harvesting methods.

focus on the years 2020 and 2050, therefore looking at stored carbon over time frames exceeding 100 years is not necessarily valuable in addressing global climate change priorities.

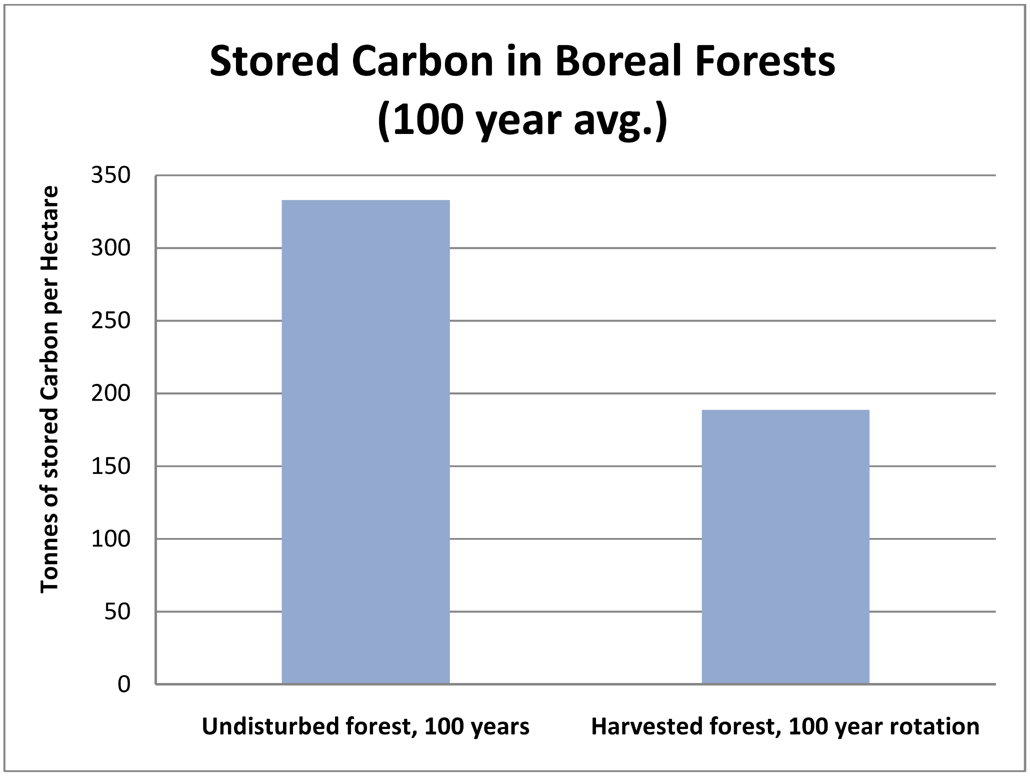

Chart 1: Stored Carbon in Boreal Forests under Different Management Practices. Data adapted from Peng *et al*. 2002.

Pre-harvest forests will include a mix of tree types and other non-tree species. Post-harvest levels are assumed to be closer to a monocrop of desired tree species (i.e. Aspen or Spruce). [3]

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[3] Peng et al. 2002

Table 1: Carbon Storage Loss of Previously Unmanaged Boreal Forests Assuming a 100 Year Crop Rotation and a 500 Year Timescale[4]

Location	Carbon Stored unmanaged land (tonnes CO_2e/ha)	Carbon storage 100 year harvest (tonnes CO_2e/ha)	Carbon storage loss 100 year harvest (tonnes CO_2e/ha)
Prince Albert, **Saskatchewan (largely Aspen)**	304	90	215
Thompson, **Manitoba** (largely Black **Spruce)**	362	199	163
Average	**333**	**144**	**189**

Table 2: Biomass Yield of Forested Lands – Previously Unmanaged at Time of Harvest, Replanted with Monocrops, Assuming a 100 Year Crop Rotation[5]

Region	Initial Biomass Yield (first harvest) (tonnes/ha)	MAI (tonnes/ha)	Total Biomass Available for Pulping (100 years) (tonnes)
Manitoba Spruce	750	80	415
Saskatchewan Aspen	750	200	475
Average	**750**	**140**	**445**

In order to calculate carbon storage loss on a per tonne of pulp basis, the productivity of the land over a 100 year timescale needs to be taken into account. This estimate uses Mean Annual Increment (MAI) method based on the work of Siemens and Kulsherestha (1996). These yield estimates are then converted to tonnes of pulp on a 100 year time-scale and added to an estimate of original biomass density (pre-harvest). The carbon storage capacity loss per hectare is then divided by the number of tonnes of pulp produced per hectare.

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4 Adapted from Peng et al. 2002

5 Adapted from Peng et al. 2002

Table 3: Carbon Storage Loss of Previously Unmanaged Boreal Forests Assuming a 100 Year Crop Rotation and a 500 Year Timescale[6]

Region	Pulp Production Potential (100 year cycle) (tonnes/ha)	Carbon Storage Reduction per Tonne Pulp (100 year cycle) (tonnes CO_2e/ha)
Manitoba	177	0.9
Saskatchewan	186	1.2
Average	**181**	**1.0**

Approximately 1 tonne of forest carbon storage capacity is removed from the ecosystem for every tonne of pulp produced in the Boreal. It is notable that this number more than offsets the carbon footprints of pulp production (i.e. from inputs / energy consumption) on a per tonne of pulp basis. However, it is also important to note that this carbon storage loss is not necessarily emitted immediately. For example, much of the carbon embedded in the wood itself (i.e. above-ground carbon) will be embedded in the pulp, which will later be turned into paper, and its status at end-of-life (disposal, recycling, etc.) is unknown and outside of the scope of this analysis. A large portion will also be burned to fuel the pulping process. Processing is discussed further in Section 5 of this document.

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[6] Adapted from Peng et al. 2002

3.0 PRODUCTION: AGRICULTURAL RESIDUE SOURCES OF PULP

This section is divided into three production scenarios: treatment (organic and conventional); tillage management; and rotation. Each scenario includes values for energy inputs and corresponding CO_2, which are translated into carbon footprints based on removable straw yields (described below).

Several sources were used, with nearly all data coming from the Canadian Prairies. Two U.S. studies were used to translate primary energy coefficients into greenhouse gas equivalents, and to supplement/support Canadian literature that identify proportions of N-based and P-based fertilizers as inputs (kg/ha) into conventional systems. Other international studies were reviewed to supplement and support Canadian research.

Note that all values presented in the tables are based on annual values, derived from averages of several years' worth of data.

ORGANIC & CONVENTIONAL TREATMENT

Data below in Table 4 are drawn and synthesized from a long-term experiment at the University of Manitoba Glenlea research station, which included two four-year rotations of wheat-pea-wheat-flax and wheat-alfalfa-alfalfa-flax in both conventional and organic systems. The conventionally-managed system included pesticide and fertilizer applications according to standard recommendations, and organically-managed systems included neither. Animal manure[7] was not applied to the organic systems, which took advantage of growing legumes that added N to the soil system biologically. Weeds were controlled in the conventional treatments with herbicides and tillage, and in the organic treatments with light harrowing. All field operations were performed using commercial farm equipment (Hoeppner et al, 2005).

The energy inputs associated with conventional systems include fuel for all field operations, fertilizers, and pesticides (refer below to Table 4). The energy inputs associated with organic systems include just fuel for all field operations.

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[7] Adding manure to an organic wheat system would involve 16.5 kg CO_2 equivalents per hectare, assuming 3.3 kg of manure are applied per hectare, and each kg of manure is equivalent to 5 kg CO_2 equivalents (Meisterling et al, 2009).

Table 4[8]: Energy Inputs for Wheat Production (Conventional and Organic Treatment)

Treatment[9]	Fuel (MJ/ha)	Fertilizers (MJ/ha)	Pesticides (MJ/ha)	Total Energy Inputs (MJ/ha)
Conventional[10]	1430	2349	442	4221
Organic	1268	0[11]	0	1268

Greenhouse gas emissions per unit of energy inputs are based on primary energy coefficients and greenhouse gas equivalents,[12] and are as follows:

- Fuel (gasoline): 0.06856 kg CO_2 / MJ
- Fertilizers [13] (i.e. N[14] and P): 0.05572 kg CO_2 / MJ
- Pesticides (active ingredients): 0.07500 kg CO_2 / MJ

The carbon footprints associated with wheat production (below in Table 5) were developed by applying the values associated with CO_2 emissions per unit of energy (as per above) to the values in Table 4.

Table 5: Carbon Footprint for Wheat Production (Conventional and Organic Treatment)

Treatment	Fuel & Lube (kg CO_2/ha)	Fertilizers (kg CO_2/ha)	Pesticides (kg CO_2/ha)	Total CO_2 (kg CO_2/ha)
Conventional	98	131	33	262
Organic	87	0[15]	0	87

Based on assumptions about removable straw yields, the carbon footprints for wheat production are translated below in Table 6 into carbon footprints for wheat straw production *only*. This is an

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[8] Information in this table was synthesized from Hoeppner et al, 2005 and is comparable to data in other literature.

[9] Both conventional and organic data represent averages for grain-based and integrated rotations.

[10] Conventional energy inputs are based on recommended application rates on the Canadian prairies.

[11] Adding manure to this treatment would result in this value being 16.5 kg CO_2/ha, increasing the total carbon footprint for the organic treatment to 103.5 CO_2/ha, which is a marginal increase relative to the significantly larger carbon footprint of the conventional treatment (Table 5). Refer to footnote 6 for how this is calculated.

[12] Primary energy coefficients (MJ per unit) and GHG emissions (kg CO_2 equivalent per unit) are from Meisterling et al., 2009 and are generally consistent across the literature.

[13] Nitrogen and phosphorus-based fertilizers comprise the bulk of fertilizer inputs into wheat production (Piringer and Steinberg, 2006; Manitoba Agriculture, 2011; Meisterling et al, 2009). As such, only their GHG equivalents are accounted for here. (i.e. Sulphur and potassium-based fertilizers are relatively marginal and therefore not accounted for in GHG equivalents).

[14] Based on their relative application proportions during wheat production (Piringer and Steinberg, 2006; Manitoba Agriculture, 2011), a combined GHG equivalent value was determined for N fertilizer: O.05111 kg CO_2 / MJ; and P fertilizer: 0.06957 kg CO_2 / MJ.

[15] Refer to footnotes 7 and 11.

important step as only the proportion of the total carbon dioxide emissions associated with the biomass of straw used in the pulping process is relevant for purposes of this study. Straw removal in organic systems could be a challenge as the organic system is based on cycling nutrients through organic matter, natural cycles, etc. This drives home the point that straw removal may not be a responsible choice for organic producers, or at least warrants further study.

Table 6: Carbon Footprint for Wheat Straw Production (Conventional and Organic Treatment)

Treatment	Removable Straw Yield (kg straw/ha) [16]	Total CO_2 (Straw) (kg CO_2/tonne straw)[17]	Total CO_2 (Straw required for one tonne pulp)[18] (kg CO_2/tonne pulp)
Conventional	983	154	**368**
Organic	961[19]	52	**125**

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[16] These values are derived from the average grain (i.e. seed) yield (2287 kg/ha) in the three prairie provinces for 10 years (Statistics Canada, 2001). The organic grain yield (1601 kg/ha) was obtained by multiplying the approximate ratio (0.7) of organic yields to conventional yields (Entz et al, 2011; Malhi and Lemke, 2007). The removable straw yields presented in Table 6 – which accounts for straw left on the soil for nutrient recycling, as well as losses during combining and baling – is approximately 0.43 of the grain yield for the conventional treatment, and 0.6 of the grain yield for the organic treatment (McConkey, 2011). These ratios were obtained from personal correspondence with Agriculture and Agri-Food Canada (McConkey, 2011), and it is consistent with Saskatchewan-based research (Lafond et al, 2009). It is important to note that Agriculture and Agri-Food Canada researchers "have looked at large body of literature and conclude that there will be some loss of soil quality with straw harvest compared to situation without straw harvest. There may be conditions where loss is not easily detected and soils that have high initial quality so loss is not important to productive capacity. That is to say, with straw return we may be keeping soil at higher quality than necessary from a strictly production viewpoint" (McConkey, 2011).

Other research has shown that removing different quantities of straw (i.e. 50% and 95%) result in "likely" to "certain" detectable effects on soil carbon, respectively (Lemke et al, 200). They note: "Although it appears that a modest amount of residue may be safely removed from these Udic borolls (Black Chernozems) without a measurable effect on soil carbon, this would only be feasible if accompanied by appropriate soil management" (Lemke, 2009). According to a U.S. study on the effect of residue management on nutrient cycling for wheat and other small grains: "Straw removal will change the nutrient cycling dynamics of crop/soil systems compared with systems in which only grain is removed. Compared with grain, straw contains a lower proportion of P and N but a higher proportion of K…" (Tarkalson et al, 2009). As such, this will have impacts on fertilizer application (though it is worth noting that K-based fertilizers – from an energetic standpoint – are not as significant as N-based fertilizers.

[17] These two values were calculated by multiplying total kg CO_2/ha by the proportion of straw yield to overall above-ground biomass yield (average of 0.5757 across different management systems, which all share similar values) (Malhi and Lemke, 2009). These numbers are 151 kg CO_2/ha for conventional wheat straw and 50 kg CO_2/ha for organic wheat straw. This calculation ensures that only the proportion of total carbon dioxide emissions associated with straw biomass is considered. These numbers are then converted into kg CO2/tonne straw by dividing by removable straw yields.

[18] These values were calculated by multiplying the wheat straw to pulp yield – which is 40-45%, for an average of 2.4 MT wheat straw: 1.0 MT pulp – with CO_2 associated with one tonne of wheat straw. This number is similar to the previous study but updated to reflect numbers obtained by the Alberta Research Council (Chute, 2011).

[19] While perhaps counter-intuitive, removable organic straw yields are larger than conventional straw yields in terms of proportion. According to a researcher at Agriculture and Agri-Food Canada: "The low rate has a lot to do with stubble height. Conventional production will leave stubble tall to improve moisture conservation and reduce erosion risk… In an organic system, they need tillage to control weeds so they don't have same opportunity for either moisture or soil conservation and thus have less incentive to leave tall stubble… Plus… I expect slightly lower grain to residue ratio on organic systems" (McConkey, 2011). He also noted that straw removal in organic systems could be a challenge as the organic system is based on cycling nutrients through organic matter, natural cycles, etc. This drives home the point that straw removal may not be a responsible choice for organic producers, or at least warrants further study.

CONSERVATION (ZERO AND MINIMUM) & CONVENTIONAL TILLAGE SYSTEMS

According to 10-year research undertaken on the Canadian Prairies[20], “the use of conservation tillage management enhanced overall energy use efficiency for the two mixed rotations, but not for the monoculture cereal rotation. We concluded that adopting diversified crop rotations, together with minimum and zero tillage management practices, will enhance non-renewable energy use efficiency of annual grain production in this sub-humid region.” Specifically:

- Conservation tillage practices used to manage summerfallow significantly reduced non-renewable energy inputs, with energy savings averaging 11% with minimum tillage (MT) and 16% with zero tillage (ZT) relative to conventional tillage (CT); and
- While the substitution of herbicides for some or all of the mechanical tillage used in summerfallow preparation increased herbicide energy inputs, these increases were more than offset by energy savings in fuel (as well as machinery repair and maintenance).

The following table illustrates these energy trade-offs:

Table 7: Effect of Tillage Method[21] on Non-Renewable Energy Inputs for Summerfallow Preparation (1987-1998)

	Conventional Tillage[22] (MJ/ha)	**Minimum Tillage[23] (MJ/ha)**	**Zero Tillage[24] (MJ/ha)**
Herbicides	152	682	805
Fuel and Lubricants	1200	554	366
Machinery Overhead	229	174	161
TOTAL	1581	1410	1332

Source: Zentner et al, 2003.

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[20] For thin Black Chernozem soils.

[21] Refer to detailed descriptions about tillage methods for the study in the following three footnotes, which seem generally consistent with the Alberta Government’s definitions of tillage activity for the Dry Prairie in the Tillage Management protocol (Alberta Government, 2008).

[22] In this study, “CT management practices received one or two tillage operations in fall for crop residue management and weed control, plus one tillage operation in spring to prepare the seedbed…On CT fallow areas, weeds were controlled by tillage alone, and this generally involved an average of 4.9 (range of 2-6) operations over the 20-month fallow period…” (Zentner et al, 2003).

[23] In this study, “under MT management, cropped areas received a phenoxy-type herbicide by one pre-seed tillage operation in spring… For MT fallow areas, weeds were controlled using a combination of tillage and herbicides. A phenoxy-type herbicide was applied in fall to control of winter annual weeds, followed by one or two non-selective herbicide applications in mid- to late-spring, and this was followed by one or two tillage operations, as required during summer and early fall” (Zentner et all, 2003).

[24] In this study, “under ZT management, weeds were controlled by herbicides alone and crops were planted without seedbed preparation. Areas being cropped received phenoxy herbicide in fall, followed by a non-selective herbicide in spring prior to planting. On ZT fallow areas, a phenoxy-type herbicide was applied each fall, followed by an average of 3 (range 2-5) applications of non-selective herbicide (used alone or in combination) in spring and summer periods, as required based on pre-spray observations of weed density and diversity in the affected plots” (Zentner et al, 2003).

Similarly, tillage had no effect on straw yield in a Saskatchewan study (Mahli and Lemke, 2007). However, while substituting herbicides for tillage may be offset by fuel energy savings, some research shows tillage impacting soil organic carbon and nitrogen (Dolan et al, 2006) which may have implications for fertilizer application over time.

Impact of Tillage Method on Soil Carbon

While this section accounts for and quantifies the carbon footprints associated with energy inputs, soil carbon is impacted by tillage method and plays an important role in storage of atmospheric carbon (i.e. in the form of soil carbon organic matter), as conservation tillage methods sequestering more atmospheric carbon than conventional tillage methods (Baig and Gamache, 2009). While empirical data comparing carbon change between conventional tillage and zero-tillage practices are highly variable (VandenBygaart et al, 2007), a study conducted for the Alberta Government shows that increasing conservation tillage (i.e. minimum and zero tillage) between 1990 and 2006 on the Canadian Prairies resulted in an annual carbon gain of 1220 kg of CO_2 equivalents per hectare. Compared with the smaller carbon footprints associated with energy inputs for wheat production (i.e. averaging approximately 215 kg of CO_2 equivalents per hectare across the different management systems, as per Tables 5 and 9), this carbon gain value is significant.

ROTATION (GRAIN-BASED & INTEGRATED[25])

The research methodology used in Section 3.0 (i.e. for treatment system), including CO_2 equivalents, removable straw yields, etc, applies here (i.e. rotation system).

The energy inputs associated with both grain-based and integrated rotations include fuel for all field operations, fertilizers, and pesticides. Fewer fertilizer and pesticide inputs in the integrated rotation are due to legumes biologically adding N to the soil system and suppressing certain insects, diseases, and weed pests (Hoeppner et al, 2005; Nemecek et al, 2001; Sustainable Agriculture Research and Education, 2001).

Table 8[26]: Energy Inputs Wheat Production (Grain-Based and Integrated Rotations)

Rotation	Fuel (MJ/ha)	Fertilizers (MJ/ha)	Pesticides (MJ/ha)	Total Energy Inputs (MJ/ha)
Grain-Based	1265	2915	593	4773
Integrated	1433	1783	292	3508

Table 9: Carbon Footprint for Wheat Production (Grain-Based and Integrated Rotations)

Rotation	Fuel & Lube (kg CO_2/ha)	Fertilizers (kg CO_2/ha)	Pesticides (kg CO_2/ha)	Total CO_2 (kg CO_2/ha)
Grain-Based	87	162	45	294
Integrated	98	99	22	219

Table 10: Carbon Footprint for Wheat Straw Production (Grain-Based and Integrated Rotations)

Rotation	Removable Straw Yield (kg straw/ha)[27]	Total CO_2 (Straw) (kg CO_2/tonne straw)	Total CO_2 (Straw required for one tonne pulp) (kg CO_2/tonne pulp)
Grain-Based	1464	116	**278**
Integrated	1464	86	**207**

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[25] Both grain-based and integrated data represent averages for organic and conventional treatments. The grain-based rotation includes wheat-pea-wheat-flax and the integrated rotation includes wheat-alfalfa-alfalfa-flax.

[26] Information in this table was synthesized from Hoeppner et al, 2005. Energy input values are comparable with those found across the literature.

[27] This is calculated as above (Table 6), except also averaging organic and conventional values.

SUMMARY: WHEAT STRAW PRODUCTION CARBON FOOTPRINT

What follows is a carbon footprint summary of all the scenarios. Note that the conventional and organic treatment values include data from both grain-based and integrated rotations (averages), and the grain-based and integrated rotation values include data from both conventional and organic treatment systems (averages).

Table 11: Carbon Footprints for All Agricultural Residue (Wheat Straw) Production Scenarios

	Conventional Treatment	Organic Treatment	Grain-Based Rotation	Integrated Rotation
Carbon Footprint (kg CO_2/tonne pulp)	**368**	**125**	**278**	**207**

While the grain-based rotation value obtained through this research is comparable to the values found in the energy component of the previous study (Kissinger et al, 2007), there are indeed differences in the other numbers due to reduced energy inputs associated with organic treatment and integrated rotation scenarios.

4.0 PRODUCTION: WOOD SOURCES OF PULP

This section deals with the two major pre-pulping stages of wood production: logging and chipping. Logging data is broken down by region (based on research areas in the studies) but is not specific to tree species. The chipping process is broken down by species (i.e. aspen and spruce).

As the purpose of the research was to explore various agricultural and pulping scenarios, and research into aspen and spruce has already been undertaken as part of the earlier work (Kissinger et al. 2007), less detail is provided below.

LOGGING

Four studies on fuel and greenhouse gas emissions from forestry operations were reviewed (Sambo 2002; Sonne 2006; Klvac and Skoupy, 2009; Garcia et al., 2009) and the equivalent CO_2 per m^3 of wood was extracted. The following table presents a summary of the results:

Table 12: Greenhouse Gas Emissions from Forestry Operations

Region	Logging[28] **(kg CO_2/ M^3 of wood)** [29]	Total - Spruce **(kg CO_2 / tonne of pulp**[30]	Total - Aspen **(kg CO_2 / tonne of pulp**
British Columbia, Canada	9.4	48.8	41.1
Spain	14.2	74.0	62.2
Sweden	12.6	65.7	55.2
Washington State (U.S.)	8.3	43.2	36.4
Europe	9.6	50.0	42.1
Average		**66**	**47**

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[28] Energy values for hauling are not included as transportation is not accounted for in the agricultural component of the carbon footprint. Transportation is not included because it is entirely dependent on mill location, and this study does not select a hypothetical location for a pulp mill.

[29] The energy inputs are from fuel (diesel).

[30] This assumes a chemical pulping process (refer to Section 4.0 of this report). The equivalent wood required for the production of one tonne of pulp is as follows: Chemical pulp made of spruce requires 5.21 m^3 and chemical pulp made of aspen requires 4.38 m^3 (FAO, 2009; Nielson et al, 1985). These values are multiplied with the kg CO_2/m^3 of wood to determine kg CO_2/tonne of pulp.

CHIPPING

The next step in the wood carbon footprint accounting is the chipping process. As is the case in straw production, this process results in some losses of fibre. The chipping yield (i.e. the proportion of feedstock round wood actually converted to chips, including losses) is approximately 44% for Canadian spruce and 36% for Canadian aspen[31] (i.e. one tonne of chips requires 2.25 tonnes of spruce logs and 2.8 tonnes of aspen logs (Nielson et al., 1985)).

In the chipping stage, consumption of electricity and diesel fuel are represented by their corresponding greenhouse gas emissions (Araki 2003; Statistics Canada, 2003; Environment Canada, 2003). CO_2 emissions per unit energy differ provincially due to different sources of electricity, and it is assumed that the electricity supply for chipping comes from the provincial grid[32].

The following table applies the energy coefficients for energy inputs (electricity and fuel) for spruce and aspen, and calculates total CO_2 associated with one tonne of chips using the chipping yields described above. The total CO_2 associated with one tonne of pulp – for the chipping component only – is then calculated by multiplying kg CO_2 /tonne of chips by the pulping yield. According to a pulping specialist at Alberta Innovates Technology Futures, the pulping yields for spruce and aspen are 45% and 48% respectively (Chute, 2011). This means that one tonne of spruce pulp requires 2.2 tonnes of spruce chips, and one tonne of aspen pulp requires 2.1 tonnes of aspen chips.

Table 13: Greenhouse Gas Emissions from Chipping Operations

Tree Species & Region	Energy Inputs **(for one tonne of chips)**	Total – Chips **(kg CO_2 / tonne of chips)**	Total **(kg CO_2 / tonne of pulp)**
Spruce (Canada)	42.4 kwh | 3.3 L diesel	19	42
Spruce (Central Europe)	n/a[33]	12	26
Aspen (Canada)	31.9 kwh | 2.5 L diesel	14	29
Aspen (Central Europe)	n/a	11	23

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[31] This includes an average chip recovery of 75% for spruce and 72% for aspen. Losses result from parts of the log, such as fines and bark, that are not chipped. It also accounts for an average moisture content of 40% for spruce and 48% for aspen (Araki, 2003).

[32] The energy coefficients for electricity assume the Alberta grid. The energy coefficient for diesel is 2.73 kg CO_2/1 liter of diesel.

[33] Central Europe data for both spruce and aspen are presented in greenhouse gas emissions and therefore conversion of energy inputs into kg CO_2 / M^3 wood is not needed.

SUMMARY: WOOD PRODUCTION CARBON FOOTPRINT

The table below adds the average logging greenhouse gas emissions with the chipping greenhouse gas emissions in both Canadian and Central European contexts.

Table 14: Carbon Footprints for Wood Production Scenarios

	Spruce (Canada)	Spruce (Central Europe)	Aspen (Canada)	Aspen (Central Europe)
Carbon Footprint (kg CO_2/tonne pulp)	**89**	**73**	**76**	**65**

5.0 PULP PROCESSING

There are many different pulping processes available for pulping both wood and wheat. The best approach depends both on the material used (e.g. wood vs. straw, type of wood or straw, etc) and the intended use of the pulp (e.g. high-grade paper, paperboard, etc). For the purposes of this analysis, the concentration was placed on pulp suited for high-quality paper making.

The dominant pulping process used to produce high-quality paper is chemical pulping (IEA, 2007). There is significant agreement in both academic literature and government reports that improvements in energy efficiency (and therefore emissions) can still be made for Kraft pulp mills (i.e. existing practices), therefore this analysis focuses on the ideal pulp mill based on best available technology (BAT) and "model" mills. Key data sources include one academic and two government publications, covering Canadian, European, and global best practices.

The essential goal of the chemical pulping process is to remove lignin and other undesirable elements from the cellulose. These impurities are removed through a combination of chemicals and "cooking" at a high temperature, which is an energy intensive process. The footprint analysis methodology is focused on the quantity, type, and source of energy used directly at each stage in the process.[34] These steps are detailed in Table 15 below.

Table 15: Summary of Major Steps in Chemical Pulp Production

Step #	Major Step	Description
1	Grinding and Mixing	Wood or straw is ground and mixed with chemicals at medium temperature. This step is also called "impregnation".
2	Cooking	Mixed fibre is cooked at high temperature along with chemicals to separate out lignin and other impurities.
3a	Washing and Bleaching	Pulp is screened, washed, and bleached.
3b	Recovery	While the pulp is washed and bleached, the waste residues, called "black liquor", enter the recovery stage. Chemicals and water are recovered for re-use, and energy is generated from the combustion of remaining byproducts (e.g. lignin).
4	Drying	Pulp is dried, "packaged" and transported. In an integrated mill which includes paper production, this stage may not apply to the pulping process. Since assumptions are not made around location of mills in this analysis, this step was included in calculating the carbon footprint.

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[34] Embodied energy in the equipment and processing chemicals are not considered in the analysis.

This analysis focuses on best available technology (BAT) for both conventional pulp from wood and wheat straw, although reference is also made to existing practices. The rationale for focusing on BAT is as follows:

- Significant technological advances made over recent years imply a much lower emissions footprint than would traditionally be the case; and
- Data for existing mills are often based on integrated mills (i.e. mills that produce both pulp *and* paper on-site), and separate data for the pulping-only process is either unavailable and/or inaccurate.[35] In addition, different countries may use different system boundaries, or may have made decisions based on factors which are specific to each country (IEA, 2007).

Assigning emission values to the pulping process is somewhat complicated by the use of biomass for energy production in most pulp mills. In keeping with currently accepted but controversial practices related to greenhouse gas accounting, the emissions associated with the combustion of biomass are not included in the main body of this analysis.

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[35] For example, this is the case for data available in the Canadian Pulp and Paper industry (Nyober, 2011).

PROCESSING: WOOD SOURCES OF PULP

At this step in the pulp production process, the type of wood (aspen and spruce) could not be drawn out of available data on pulp production, and none of the sources studied in the course of this analysis have specifically listed wood-type as a component of the energy analysis.

Despite the substantial energy use in the chemical pulping process, all three of the model mills described above produce some combination of excess heat, excess electricity, or a combination of the two (i.e. "combined heat and power") through the combustion of biomass. According to the International Energy Association: "A large modern chemical pulp mill is self-sufficient in energy terms, using only biomass and delivering surplus electricity to the grid" (IEA 2007). The largest determinant of whether this type of equipment is installed or not is the discretion of the mill, and it may largely be influenced by the price of electricity, fuel, cost, and perceptions regarding reliability of equipment (Klugman et al., 2007). Table 16 below shows the net energy consumption of pulping wood.

Table 16: Energy Use in Chemical (Kraft) Wood-Pulp Processing

Reference Case	Technology Reference Year	Heat Use **(GJ/Adt[36])**	Electricity Use **(GJ/Adt)**	Total Energy Use **(GJ/Adt)**	Notes
Model Mill - Sweden[37]	1998	10.8	2.7	13.5	
Model Mill - Canada[38]	2001	12.2	2.3	14.5	Many existing Scandinavian mills already outperform the Canadian model mill.
Best Available Technology - International[39]	2006	12.3	2.1	14.3	
Average	**2002**	**12**	**2**	**14**	This is around 50% more efficient than the average existing kraft mill in Canada.[40]

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[36] Adt refers to air dried tonne of pulp

[37] (Klugman et al., 2007)

[38] (Francis et al., 2002)

[39] (IEA, 2010)

[40] However, this is only an approximation due to difficulties in separating consumption data for pulp-only mills from consumption data for combined pulp and paper mills. In addition, available figures are aggregated across the industry, and are not provided by individual facilities within available literature.

While energy is used in the pulping processed, energy is also generated for use in surrounding buildings (i.e. for paper production processes in integrated facilities) or in the grid, resulting in net negative energy consumption values across the board:

Table 17: Net Energy Consumption in Wood-Pulp Processing

Country of Reference	Technology Reference Year	Net Heat Consumption	Net Electricity Consumption (GJ/Adt)	Total Energy Consumption
Model Mill - Sweden[41]	1998	-7.5	-2.3	-9.8
Model Mill - Canada[42]	2001	-3.6	-0.1	-3.7
Best Available Technology, International[43]	2006	Not specified	-1.9	-
Average	**2002**	**-4**	**-1**	**-5**

Note: negative numbers indicate excess energy available for either use in surrounding buildings (heat) or sale to the grid (electricity).

Table 18: Greenhouse Gas Emissions from Wood-Pulp Processing

Country of Reference	Technology Reference Year	Emissions (kg CO_2/Adt pulp)
Average	**Best Practices, averaged across several sources**	**N/A**

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[41] (Klugman et al., 2007)

[42] (Francis et al., 2002)

[43] (IEA, 2010.)

PROCESSING: WHEAT STRAW SOURCES OF PULP

Wheat pulp production can be done using chemical processes, including the Kraft process described above, or by using mechanical processes (EPA, 2010). As with wood, high quality paper making is generally accomplished through chemical pulping processes.[44]

Efforts were made to find information specific to wheat-straw. However, in some cases, reference will be made to other agricultural residue sources of pulp, such as hemp, flax, or kenaf, where applicable, as several documents group “non-woods” together when contrasting these to conventional wood-pulping.

The chemical composition of wheat straw residues complicates the energy requirements of the pulping process. In general, less lignin requires less energy and chemicals for pulping. Straw has about 1/3 less lignin than wood (EDF, 1996), implying a lower energy and emissions footprint. However, lower lignin content also reduces energy available through black liquor combustion, as much of the energy comes from combusting the lignin itself (EDF, 1996).[45] In addition, the high silica content in straw reduces the efficiency of black liquor combustion relative to lower-silica materials (Harris et al, 2008). There are methods to remove a significant portion of the silica before pulping, such as that developed by Alberta Innovates Technology Futures, but these processes also require energy.

A variety of promising technologies exist at the demonstration scale, but it does not appear that any of these have been constructed at full-scale facilities. Overall, there is somewhat less certainty regarding the analysis of energy and emissions associated with pulping wheat than there is with conventional wood-pulp.

The table below outlines energy use in wheat-pulp processing. It focuses on one demonstration mill, as detailed data from non-integrated processes (i.e. isolating pulping from paper production) are difficult to obtain[46]:

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[44] Mechanical processes may create pulp for use in lower quality applications, or for future mixing with other pulp types.

[45] Experiments with Kenaf, another agricultural residue fiber source, showed that the lower lignin content also reduced energy available through biomass combustion. Unfortunately, this leads to significantly more purchased energy (fossil fuels and grid electricity).

[46] Pulping specialist Wade Chute at Alberta Innovates Technology Futures confirmed that energy consumption differences between wood and agricultural residue pulping processes are minor.

Table 19: Energy Use in Chemical Wheat-Pulp Processing

Reference Case	Technology Reference Year	Heat Use (GJ/tonne)	Electricity Use (GJ/tonne)	Total Energy Use (GJ/tonne)	Notes
Bioregional **MiniMilll - UK**[47]	2008	Not available at this detail	Not available at this detail	14.5 adt	The energy consumption figures provided in the report do not include the breakdown of heat vs. electrical energy consumption.

Overall, energy consumption in existing and BAT pulp mills using wheat straw appears highly similar to wood-based processing, both in terms of energy used per tonne of output and energy recovery from biomass. It should be noted that the MiniMill would have the potential to generate electricity if constructed at a larger scale (i.e. no longer "mini").

Results for the Bioregional Mini Mill should be treated cautiously; although this technology has been piloted successfully in several locations, the full-scale production facility is not yet complete. However, other peer-reviewed articles have made similar claims about the potential for energy self-sufficiency using biomass from the pulping process (Rousu, 2002) using other technologies, and final agreements for full-scale plants of these types are in place in China (Chemopolis, 2011). At this stage of analysis, these claims are considered sufficient for assuming that the potential for on-site energy production from black liquor in wheat-pulping is likely comparable to energy requirements.

As with wood-based biomass combustion, it is assumed that any potential excess heat or electricity would be sold or used along with any associated carbon credits or offsets. Therefore, as with wood-based pulp production, the effective energy consumption and associated emissions for pulp processing from straw is assumed to be zero, or so close to zero that further analysis is unnecessary:

Table 20: Greenhouse Gas Emissions from Straw-Pulp Processing

Reference Case	Technology Reference Year	Emissions (kg CO_2/Adt pulp)
Bioregional Mini-Mill (UK)	2008	N/A

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[47] (Harris et al. 2008.)

SUMMARY: WHEAT STRAW & WOOD PROCESSING CARBON FOOTPRINT

Although pulping processes use a significant quantity of energy, modern mills using best available technology (BAT) appear to be net energy contributors. Chemical pulping processes do not significantly affect the greenhouse gas footprint relative to other processes.

Accordingly, since carbon footprints associated with pulp production for woods and straw are effectively zero (i.e. not applicable, as below), the production component of the carbon footprint – forestry and agricultural practices – reveals itself as being increasingly important.

Table 21: Carbon Footprints for Wood and Agricultural Residue Processing

	Wood	Agricultural Residue / Straw
Carbon Footprint (kg CO_2/tonne pulp)	**N/A**	**N/A**

On the other hand, while biomass is generally considered to be "carbon neutral", this assertion is increasingly questioned within both academic and non-academic literature (Johnson, 2009; Ford, 2009).[48] The table below summarizes some of the emissions factors associated with the combustion of black liquor from different types of biomass. Notably, there is only a small difference in the direct release of greenhouse gas emissions from different crop-types. This implies that whether or not emissions from biomass combustion are counted as carbon-neutral, the relevance of this to a comparison between straw and wood pulp is minor.

Table 22: Climate-neutral CO_2 Emission Factor for Biomass[49]

Type of Biomass	Sample crop	Emissions Factor (kg CO_2/GJ)
Kraft black liquor – North American hardwood	Aspen	93.5
Kraft black liquor – North American softwood	Spruce	94.2
Kraft black liquor – Straw residue	Straw	94.9

Adapted from (NCASI, 2008).

By contrast, this would not be the case with recycled paper, which generally does not combust biomass as part of its pulping process. If biomass combustion were counted as part of the emissions footprint, both wood and non-wood pulp would likely look considerably worse from a greenhouse gas perspective when compared to recycled paper. Please refer to the "conclusions" section for further discussion.

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[48] In addition, some existing GHG accounting protocols do provide biomass GHG emissions factors as a separate line-item (NCASI, 2008) even though they are not directly counted as part of the GHG footprint.

[49] Note: "dry" biomass such as woodbark- chips or agricultural residue maybe used as well.

6.0 CONCLUSIONS

The following table presents the total carbon footprints for each of the scenarios explored in this research. Conventional wheat straw performs the poorest, with organic wheat straw being somewhat comparable to spruce and aspen.

Table 23: Total Carbon Footprints

	Production (kg CO_2/tonne pulp)	Processing (kg CO_2/tonne pulp)	Carbon Footprint from Energy Inputs (kg CO_2/tonne pulp)	Potential Carbon Storage Loss from Land Use Conversion (kg CO_2/tonne pulp)
Spruce (Canada)	89	N/A*	89	~1,000**
Aspen (Canada)	76	N/A*	76	~1,000**
Wheat Straw: Conventional (i.e. non-organic)	368	N/A*	368	0
Wheat Straw: Organic	125	N/A*	125	0
Wheat Straw: Grain-Based Rotation	278	N/A*	278	0
Wheat Straw: Integrated Rotation	207	N/A*	207	0

*Best practices facilities use waste-biomass to heat and power the production process, and are virtually energy self-sufficient. The footprint of the biomass itself is difficult to determine, and would likely represent a portion of the Potential Carbon Storage Loss from Land Use Conversion.

**Potential Carbon Storage Loss from Land Use Conversion is a high level estimate provided for comparative purposes only. It assumes conversion from land that has never been harvested (i.e. old growth) to land that is harvested approximately every 100 years. A significant portion of this would be released to the atmosphere through biomass combustion (likely around half) with an additional portion embedded in the pulp itself.

POSSIBLE FUTURE AREAS OF IMPROVEMENT AND RESEARCH

RECYCLED PAPER

This analysis has focused on virgin wood and agricultural residue sources of pulp production. Opportunities for future research include exploration of energy savings associated with the use of recycled fiber (i.e. both wood and agricultural residue fibre-based paper).

CARBON STORAGE

Chart 1 (previous section) illustrates the enormous significance that boreal forest ecosystems play in carbon sequestration. Additional research that aims to quantify these values using a" per tonne of pulp" unit of measurement could prove useful. As shown in Section 3, tillage method also impacts carbon storage and resulting greenhouse gas emissions associated with wheat – and therefore – production.

UPGRADING PULPING/MILL STANDARDS, TECHNOLOGY, AND PROCESSES

The Canadian Industrial Energy End-use Data and Analysis Centre (CIEEDAC) publishes energy consumption and emissions data for the pulp and paper industry in Canada, based on a comprehensive survey of existing mills. Few of these mills represent best practices; in some cases fuel includes oil, coal, or even old tires are consumed for energy. In addition, there is a substantial gap between a "modern" mill and an average existing mill, demonstrated in benchmarking analysis completed by Natural Resources Canada (2006). It is also important to note that some of this aggregate data comes from integrated pulp and paper mills, and the data couldn't necessarily be accurately separated between pulping and paper production (Nboyer, 2011).

Table 24: Average Emissions from Existing Kraft Pulp Production in Canada, 2008 data, per unit output

Technology Reference Year	Energy (GJ/tonne pulp)	Emissions (kg CO_2/tonne pulp)
Most mills over 30 years old	33,056	225

Based on the average existing mill and the assumption that a new pulping mill can be self-sufficient in energy through waste-biomass combustion, the potential emissions savings of a major industry transition (e.g. to straw[50]) are massive. In other words, since most mills in Canada are using older technology/pulping processes, there is much room for improvement. The existing

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[50] This could be extended to wood mills as well.

1,700,000 tonnes of greenhouse gas emissions associated with chemical pulp production in Canada could result in enormous emissions savings, as shown below:

Table 25: Potential Industry-Wide Emissions Savings

Technology Reference Year	Technology Reference Year	Emissions Savings (tonnes CO_2)
Modern straw-mill[51], if applied on industry wide scale	Current	~1,700,000

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[51] This could be extended to wood mills as well.

7.0 LITERATURE REVIEW

What follows is a bibliography of reviewed literature for the collection and analysis of carbon footprint data in this study.

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