Assessment of Alternative Fibers for Pulp Production

Public Version

by
Valerie M. Thomas
Wenman Liu
School of Industrial and Systems Engineering, and
School of Public Policy
Georgia Institute of Technology
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Executive Summary: Assessment of Alternative Fibers for Pulp Production

Background. Kimberly-Clark (K-C) positions itself as a leader in responsible fiber sourcing. As such, the company incorporates sustainability considerations into its decision making. It is committed to both responsible forestry and recycled fiber and has stated commitments to use increasing levels of environmentally preferred fiber. At the same time, global trends are putting pressure on supply and price on several fiber sources important to the company. For example, Northern softwood pulp and recycled fiber are both used in the production of the company's tissue products. Forecasts point to supply pressure on both fiber types over time. Moreover, environmental concerns have been raised regarding the sourcing of certain fiber types or from certain locations. For example, sourcing of northern softwood from Canada has raised concerns particularly regarding impact to biodiversity and carbon storage in forests. Due to these and other factors the company is interested in exploring a range of alternative fiber sources that could provide increased flexibility in fiber choice for any number of its products. Kimberly-Clark wants to understand the environmental, social, and economic impacts of such opportunities so that it may weigh these factors in its decisions. Kimberly-Clark commissioned this study in order to better understand some of the areas of impact and potential concern for a set of fiber types they are exploring.

Goal and Scope. This study considers the environmental implications of bamboo kraft pulp as a substitute for northern softwood Kraft pulp, and mechanically pulped *Arundo donax*, kenaf or wheat straw as substitutes for recycled deinked pulp. The analysis compares current production and delivery of Canadian northern softwood kraft pulp with potential production of bamboo Kraft pulp in the southeast of the United States, and compares current production of deinked recycled fiber pulp with potential production of *Arundo donax*, kenaf or wheat straw mechanical pulp in the US southeast. This study is not intended to make comparative assertion between fibers. The comparison sets and study were established due to their ability to inform Kimberly-Clark and its stakeholders as it considers potential use of alternative fibers. They should not be interpreted as actual fiber substitution plans as the company is still in early stages of research.

Data and Assumptions. The analysis for northern softwood Kraft pulp is based on data from K-C suppliers; the analysis of recycled fibers is based on current K-C recycled fiber operations and data. The analysis for the alternative fibers is based on data from prospective suppliers, supplemented by literature values and databases, as well as on pilot scale pulping studies at K-C. Uncertainty and data quality are evaluated throughout, and are reflected in error bars and data quality assessment.

Results. Production of northern softwood requires more land and more time than production of bamboo (Figure 3.5); as a result northern softwood pulp has greater potential for impacts on carbon storage in forests (Section 3.5 and Figure 3.8) and on ecosystems (Section 4.2).

Pulp made from the alternative fibers *Arundo donax*, kenaf and wheat straw generally have somewhat larger impacts than those of recycled fiber (Figures 3.1, 3.6, and 3.8-

3.15). Wheat straw, because it is an agricultural residue, has the lowest agricultural impact of the alternative fibers considered.

In the environmental assessment, we find that some environmental impacts are dominated by the pulping process; these include impacts from fossil fuel use (Figure 3.1). For these impacts, even though pulping processes differ by fiber, the environmental impacts are broadly similar across fiber types and can potentially be addressed by alterations in the pulping process, the energy systems, and other associated inputs and processes.

Other environmental impacts are dominated by the production of the fiber itself; these include most ecosystem impacts, and the climate change impacts of harvesting forest products. Of these fiber-dominated impacts, northern softwood is notable for its potential climate change impacts. Because the trees used for northern softwood production grow slowly, it takes a long time – as much as 70 years or more – for forests to regain the carbon that is released from harvesting trees. This results in a higher climate change impact for northern softwood than for bamboo (Figure 3.8). This full carbon accounting has often not been included in previous environmental assessments of pulp and paper products.

This study reinforces the importance of location, technology and management practices as key determinants of environmental impacts. Management and forest certification programs that protect areas of high conservation value and high carbon storage potential may be able to limit the carbon and ecosystem impacts of fiber sourcing.

The significant environmental issues of kenaf, *Arundo donax*, wheat straw and bamboo are a consequence of the type of plant and the scenario for its production. Kenaf is an annual plant; planting, fertilization, herbicide use, irrigation, and harvesting occurs annually. Wheat is also an annual plant, with similar inputs, but wheat straw is an agricultural residue. Even though we allocate to wheat straw some of the overall inputs for wheat production, the residue nature of wheat straw results in an overall lower environmental profile than for kenaf. In this assessment, kenaf has relatively high use of fertilizer, water, and herbicides, and correspondingly higher associated impacts. These and other data and assumptions are summarized in Chapter 2. The figures in Chapter 3 show results for each environmental impact category; Sections 4.1 and 4.2 address overall impacts on human health and species, respectively.

Limitations. The alternative fiber pulps have not yet been produced at commercial scale in the United States, and have not been produced anywhere at commercial scale with the conditions and technologies considered here, so the results presented are necessarily provisional (see Chapter 4 for further discussion). This study focuses on the direct effects that can be attributed to the six fibers; a supplemental consequential analysis, in Section 4.3, indicates that indirect effects may be of similar magnitude as direct effects; these effects could be more fully addressed as data and scenarios become more fully characterized.

There are data gaps that limit the completeness of the analysis, including data on waterborne emissions from pulp mills and the environmental fate of agricultural inputs used in fiber production; this limits the completeness of toxicity-related analysis.

A key limitation of this study is in the interpretation of land use impacts. Ecosystem impacts depend on site-specific details of land management and on landscape scale characteristics. The analysis of potential land use impacts on biodiversity uses generic characterization factors from studies in Europe and, in the absence of detailed local data from the varying forest regions of Canada and the agricultural areas of the US southeast, provides more of a qualitative than quantitative evaluation of land use impacts. A further assessment of northern softwood production and of the production of alternative fibers in the southeast of the United States would go beyond lifecycle analysis to measure and evaluate impacts on a range of environmental and ecosystem endpoints.

List of Acronyms and Abbreviations

1,4 DB	1,4 dichlorobenzene
AOX	Adsorbable organic halides
BOD	Biological oxygen demand
C	Carbon
CO	Carbon monoxide
CO_2e	Carbon dioxide equivalents
COD	Chemical oxygen demand
DALY	Disability adjusted life year
EPA	U.S. Environmental Protection Agency
ha	hectare
ISO	International Standards Organization
KC	Kimberly-Clark Corporation
kg	kilogram
kWh	kilowatt-hour
LCA	Life Cycle Assessment
m	meters
man-Sv	man-Sievert
MJ	megajoules
MRF	materials recovery facility
N	Nitrogen
N_2O	Nitrous oxide
NOx	Nitrogen oxides
P	Phosphorus
PAH	Polycyclic aromatic hydrocarbons
PCDD	Polychlorinated dibenzo-dioxins
ppt	parts per trillion
SETAC	Society of Environmental Toxicology and Chemistry
SOx	Sulfur oxides
t	metric ton
TSP	Total suspended particulates
UNEP	United Nations Environment Program
VOC	Volatile organic compounds
W	Watt
y	year

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Critical Review

<u>Note About Shortened Report</u>

This is a shortened version of the original research report. The primary change is the removal of any information considered to be potentially a confidentiality risk for Kimberly-Clark to disclose publicly. Where data has been removed or added, orange highlighting is used to alert the reader to such changes.

Chapter 1: LCA Goal and Scope

Study Goal: This LCA assesses the environmental impacts of alternative fibers for pulp production. Kimberly-Clark Corporation (K-C) is considering use of alternative fibers in its products; this study is intended to inform K-C and its stakeholders as it considers use of alternative fibers. The study is developed as an environmental lifecycle assessment, conducted under the requirements of ISO 14040 and 14044 (ISO 2006a, 2006b). In addition, the study is carried out in the context of broader consideration of sustainability questions; these issues include the scale of land use and impacts on biodiversity.

1.1 Study Scope

The alternative fibers considered are *Arundo donax*, wheat straw, kenaf, and bamboo, all grown in the United States. The currently-used fibers, with which the alternative fibers are compared, are northern softwood from Canada, and recycled fiber. These fibers are specified based on current K-C products and processes, and the LCA for the currently-used fibers is based on existing K-C LCAs, supplemented with additional data and information to support evaluation in areas such as biodiversity and carbon cycles.

1.2 Functional Unit

The functional unit is one metric ton of pulp, air-dried, as delivered to the paper mill gate. This pulp functions as a component of tissue papers, including toilet tissue for home use and paper towels for commercial use. Three types of pulp are studied: Kraft pulp made from bamboo or northern softwood, mechanical pulp made from wheat straw, kenaf, or *Arundo donax*, and de-inked pulp made from recycled paper. K-C’s tissue papers used for toilet paper and bathroom paper towels are generally made with a mix of fiber types. Northern softwood Kraft pulp has long fibers that provide strength to the paper; Kraft-processed bamboo fiber can potentially provide the same function. De-inked recycled fiber is a lower strength fiber that is extensively used as a component in tissue paper production; potentially mechanically pulp wheat straw, kenaf, or *Arundo donax* can provide this same function in tissue papers. In addition, other fibers, such as eucalyptus, are often used in tissue paper production; these fibers provide softness; neither these fibers nor potential substitutes for them are considered in this study. Because the kraft pulps have somewhat different characteristics from de-inked pulp and mechanical pulp, the study comparisons were set up between the two types of Kraft pulp – bamboo versus northern softwood – and between the mechanical pulps and the de-inked fiber – made from wheat straw, kenaf, *Arundo donax* and recycled paper. However, because different products could potentially use different mixes of fibers and actual fiber substitution opportunities are still being explored, this study generally shows results across all fibers.

Even within a functional use and for similar pulping processes, each fiber may function somewhat differently, both in terms of manufacturing performance and in terms of paper features such as softness and strength. For example, although mechanically pulped *Arundo donax*, kenaf and wheat straw are all undergoing pilot testing as alternatives for recycled fiber, a complete picture regarding the suitability of each as a recycled fiber substitute or if they may be substituted for other fiber types is not yet clear. Additionally, these alternative fibers could be substituted across a varying range of offset proportions to recycled fiber or even in combination with each other. In such cases, their functional performance would only be understood once developed and tested. Testing on the ability to use these three fiber sources for substitution of virgin fibers such as northern softwood, southern hardwood, or eucalyptus has yet to be explored extensively. This study is focused on the environmental and sustainability impacts of fibers and does not address the other types of differences between fibers; these other characteristics could be a factor in decisions regarding alternative fiber utilization.

1.2 System Boundary and Cut-off Criteria

The system boundary encompasses the lifecycle stages of

- fiber production, including agricultural and forestry inputs of chemicals, water, other materials, energy, and land,

- transportation to the pulp mill,
- pulp production, and
- transportation to the paper mill gate.

These lifecycle stages are illustrated in Figure 1.1. Included within the system boundary are both inputs from human activities – materials and energy – and inputs from nature – water and land.

The selection and definition of the system boundary is important both to ensure that the system boundaries are consistent between products that might be compared, and also to seek to include the main sources of environmental impacts. In this analysis we have set our system boundary using a process-based approach, including all primary production processes of fiber production and fiber processing as well as the production of the chemicals and fuels used in production and processing. Background processes, such as the lifecycle inventories of the infrastructure, are included when ecoinvent data sets are used (Ecoinvent 2012). This includes the road and rail infrastructure used for transport, the electricity and fuel system infrastructure, and the infrastructure used for production of the chemicals used in fiber production and pulping.

The time frame of the study is immediate and near-term production of alternative fibers, with 2012 as the base year; the study considers current technology and infrastructure. The production of the infrastructure, including farm and forestry machinery, roads, railways, vehicles, and pulp mills is excluded from the analysis; the study assumes use of existing pulp mills and existing infrastructure. Also, the lifecycle of the paper that becomes recycled fiber has been excluded.

These system boundary decisions imply *de facto* cut-off criteria. Our cut-off criteria goals are 2% for mass inputs, 2% for energy inputs, and 5% for environmental significance. One way to evaluate the cut-off criteria is to use economic input-output tables to evaluate the economy-wide impact of pulp mills on other sectors of the economy. Hybrid approaches to lifecycle analysis have been developed (Suh et al. 2004) which use economic input-output analysis to address the implications of cut-off criteria. While we do not extend this assessment to a full hybrid lifecycle assessment, we do use economic input-output lifecycle assessment (EIOLCA) data to evaluate the cut-off criteria for the pulp production process.

The system boundary is developed to consider the production of pulp from alternative fibers to the point of delivery to the paper mill gate. After that point, the pulps made from different fibers are assumed to have the same function, subject to the distinctions between kraft pulp, mechanical pulp, and deinked pulps discussed previously. However, our analysis of the inventory and impacts of the carbon that is contained in the pulp has indicated that the fate of pulp through its entire lifecycle to disposal and degradation is important to the overall comparison between fibers. Accordingly, in consideration of climate impacts, we extend the system boundary so as to complete the analysis of the carbon cycle. In that analysis we show the results to the main system boundary at the paper mill gate, and also the additional results for this specific inventory flow for the end-of-life stage. This is indicated with the additional dotted line in Figure 1.1.

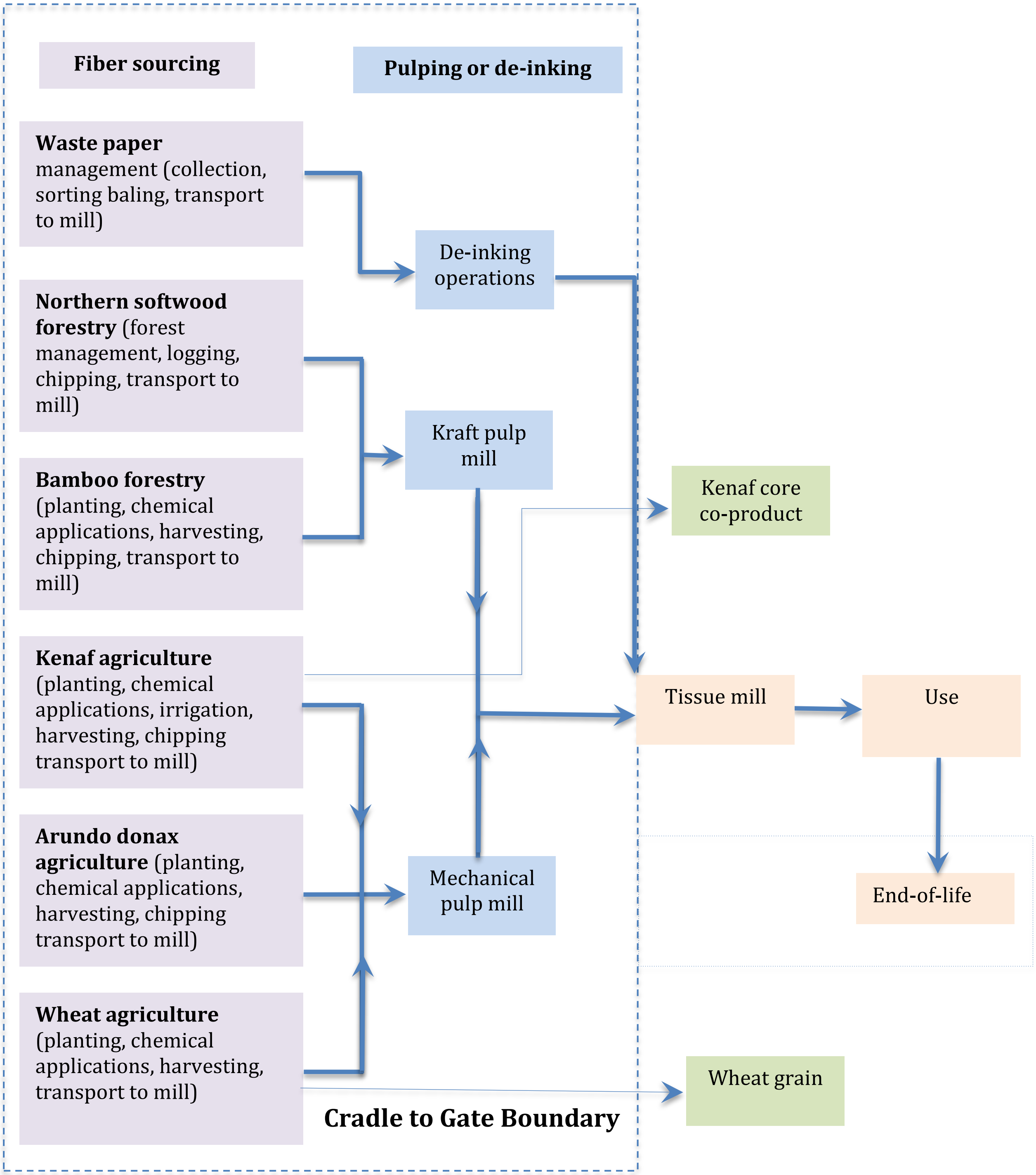

Figure 1.1 System boundaries for alternative fiber assessment. The baseline analysis is for the cradle to gate boundary to the tissue mill gate, including the processes shown within the dashed line; note that the tissue mill is outside the dashed line. The co-products kenaf core and wheat grain are also outside the dashed line system boundary, as is produce use. A supplementary analysis of end-of-life greenhouse gas emissions is also developed, indicated by the additional dotted line.

1.3 Allocation Procedures

Of the fibers considered in this study, some issues of allocation arise. Wheat straw is a co-product of the production of wheat, which suggests that some of the inputs for wheat production should be allocated to the wheat straw. Similarly, kenaf has both bast (bark) and core (pith); the bast is what is used for fiber production, while the core can have other uses, particularly as an absorbent.

The ISO guidelines for lifecycle assessment call for avoiding allocation if possible, with disaggregation or system boundary expansion being preferred (ISO 2006b). Taking a system boundary expansion approach, fully incorporating the lifecycle of wheat grain products and products made from kenaf core is beyond the scope of this study. So here we do take an allocation approach. To allocate the inputs between co-products, a basis for the allocation needs to be selected. In principle we would like to allocate based on the economic return to the grower - that is, on the net profit to the grower for each co-product – because this would reflect the extent to which each co-product is driving the decisions for production. In practice, however, we have limited or no data on the relative profitability of wheat straw and kenaf core. Our allocation approach, therefore, is to carry out the analysis for two different allocation values that span the potential range of economic allocations; comparison of the results for different allocations can provide insight into how markets for co-products can affect the results.

For wheat straw, we allocate 10% of the fiber production inventory to wheat straw in our baseline analysis, and we also evaluate the results for a 20% allocation, to represent a situation with a higher relative value of wheat straw compared to wheat grain. For kenaf we allocate 30% of the fiber production inventory to the kenaf bast in the baseline analysis, and we also evaluate the results for 100% allocation to kenaf bast, to represent a situation in which there was no market for the kenaf core co-product. For northern softwood, tall oil is produced as a co-product and provides 1.5% of pulp mill revenue

(Stenius 2000); this is below the 5% environmental significance cut-off criterion for this study and so no allocation is made for tall oil.

1.4 Data Sources

Evaluation of alternative fiber production draws on data provided to K-C from potential growers and providers (GTP 2011 for *Arundo donax* and wheat straw; Kengro 2012 for kenaf; K-C 2012a for bamboo). We compare these values with data from the published peer-reviewed literature, when available, to inform the evaluation of data quality. Evaluation of pulp production processes for northern softwood Kraft pulp uses data provided to K-C from a northern softwood Kraft pulp supplier; these data have been used in previous K-C LCAs. Data for production of de-inked fiber from recycled paper are from K-C's facility in [LOCATION REMOVED]; these data also have been used in previous K-C LCAs. Data on pulping of wheat straw, kenaf, and *Arundo donax* are based on estimates from K-C engineers who are conducting pilot studies with these fibers at the K-C facility in [LOCATION REMOVED]. Data on Kraft pulping of bamboo are also based on estimates from K-C engineering, and draw on data from production of eucalyptus Kraft pulp and northern softwood Kraft pulp.

The pulping processes for the alternative fibers wheat straw, kenaf, *Arundo donax*, and bamboo, as they would be carried out by K-C, are still being developed. K-C engineers provided best estimates data for energy use, chemical inputs, and air and water emissions, based on their professional experience and judgment and their ongoing investigations of alternative fibers. For the pulping of recycled fiber and northern softwood, site specific data from K-C suppliers are used.

There is limited experience in the large-scale production of kenaf, *Arundo donax*, and bamboo in the US southeast. We use data provided by prospective K-C suppliers of these fibers, for yield and for chemical, energy, and water inputs. For wheat straw production we draw on data from the US southeast and the US as a whole.

For electricity production, the mechanical pulping and de-inked pulp analysis uses site-specific data from the electricity generated on-site at the K-C facility in [LOCATION REMOVED], where mechanical pulping and recycled fiber de-inking would be carried out. The Kraft pulping process uses predominantly on-site generated electricity; the small amount of off-site sourcing of electricity is modeled as the US national grid mix.

Background data are drawn from the ecoinvent database, version 2.2, as needed (Ecoinvent 2012). These data are not used for mill operations; they are used for the production of some chemical inputs and for transportation emissions and infrastructure. The broad base of data available via this source enables the use of a single consistent source for all background data, minimizing the potential for differences in data sources to distort system comparisons. In addition, the ecoinvent database has been used in previous K-C LCA studies and enables more direct comparison of results with previous findings. These data are largely derived from technology and operating conditions in Europe; the potential disparity between the data sources for the ecoinvent data and the actual situation for US and Canadian pulp production are reflected in relatively low data quality scores.

The specific datapoints used to represent the systems are not disclosed in this shortened version of the report to be sure to protect confidential business knowledge.

1.5 Data Quality Approach

Data quality can be addressed with the following indicators: time-related coverage, geographical coverage, technology coverage, precision, completeness, representativeness, consistency, reproducibility, data sources, and uncertainty (ISO 2006b). We use a semi-qualitative matrix pedigree method that scores the data for each quality indicator (Weidema and Wesnaes 1996). The matrix is intended to provide a qualitative determination of the quality of data used for each unit process, giving insight into areas where sensitivity analysis or additional data collection might be required. Table 1.1 shows the data quality evaluation system that we use; data are evaluated with a six-number score, corresponding to the six categories shown in Table 1.1. This scoring system is nearly identical to that used in the ecoinvent database (Pré, 2010), with the exception that the last indicator, precision and variability, replaces the ecoinvent indicator called sample size. The indicators in Table 1.1 explicitly match the ISO 14044 data quality aspects of completeness, time, geography, technology, and precision in indicators 2, 3, 4, 5, and 6 respectively. The evaluation of reliability in indicator 1 is a partial indicator of uncertainty; additional aspects of uncertainty are addressed qualitatively in the data quality discussions and in the sensitivity analysis. Representativeness is addressed through the combination of the time, geography and technology metrics - indicators 2, 3, and 4. Consistency, reproducibility, and the implications of the sources of the data are addressed in the data quality assessment discussions.

The data quality for all unit processes was evaluated to assess the uncertainty introduced by data quality. Data quality scores of 1, 2, or 3 are considered to fully meet the data quality requirements. This does include some data based partly on qualified estimates, without full coverage of all sites, and with some extrapolation across fiber types and technologies. These data limitations are expected for a study such as this, which is considering the environmental impacts of processes before they have been implemented at commercial scale. Data quality scores of 4 or 5 are considered to indicate substantial data limitations.

To assess the implications of data quality on our results, we estimate the variability indicated by the data quality scores (Pré, 2010), and use Monte Carlo simulation to develop an uncertainty analysis that reflects the data quality. These uncertainty analysis results are presented as error bars in the lifecycle impact results.

To assess the sensitivity of the result to key assumptions of yield and allocation, we calculate the results for our baseline assumptions, and for different yield and allocation choices; we present and discuss these results in comparison with the baseline results. The sensitivity analysis addresses the potential for lower bamboo yield, higher allocation to (e.g. greater production impact from) wheat straw and kenaf fiber, and higher yield for northern softwood.

Table 1.1. Data quality indicators used for the pedigree matrix evaluation.

Score	1	2	3	4	5
Reliability	Verified data based on measurements	Verified data partly based on assumptions OR non-verified data based on measurements	Non-verified data partly based on qualified estimates	Qualified estimate (e.g. by industrial expert); data derived from theoretical information (stoichiometry, enthalpy, etc.)	Non-qualified estimate
Completeness	Representative data from all sites relevant for the market considered over an adequate period to even out normal fluctuations	Data from >50% of the sites relevant for the market considered over an adequate period to even out normal fluctuations	Data from only some sites (<<50%) relevant for the market considered, OR some sites but from shorter periods	Data from only one site, or from sites but for shorter periods.	Representativeness unknown or from small number of sites AND from shorter periods
Time-related coverage	Less than 3 years difference to reference year	Less than 6 years difference to our reference year	Less than 10 years of difference to reference year	Less than 15 years of difference to reference year	Data age unknown or > 15 years from reference year.
Geographical coverage	Data from area under study	Average data from larger area in which the area under study is included	Data from smaller area than area under study, or similar areas		Data from unknown OR distinctly different area.
Technology coverage	Data from enterprises, processes, and materials under study		Data on related processes or materials but same technology, OR same processes and materials but different technology	Data on related processes or materials but different technology, OR data on laboratory scale processes and same technology	Data on related processes or materials but on laboratory scale of different technology
Precision and variability	< 10%	< 30%	< 50%	Order of magnitude	More than order of magnitude

1.6 Lifecycle Assessment Approach and Emphasis

The assessment addresses fiber scenarios for paper production that have not been considered before, using fibers for which there is not a lot of experience or data. For this reason, we restrict the analysis to an attributional basis, which means that we evaluate the environmental impacts of the fibers independent of larger-scale changes in markets that might be induced by fiber selection. Moreover, of necessity we make assumptions based on small amounts of data and in the absence of commercial-scale experience of alternative fiber production or pulp production with alternative fibers.

Environmental concerns related to northern softwood have focused on biodiversity and climate change (Armstrong 2009; Binkley 1999; CBFA 2012; Carlson et al. 2010; EPN 2012). Accordingly, for those topics we provide more background and detail.

The process lifecycle assessment calculations are carried out using SimaPro 7.4 software (PRé, 2010). We also use the 2002 input-output lifecycle assessment model EIOLCA to test system boundary and potential issues with cut-off criteria (Carnegie Mellon University Green Design Institute 2012). We use Microsoft Excel for supplemental calculations.

1.7 Supplemental approach to consequences of fiber choice

Another important aspect of understanding these potential changes is indirect land use change and the overall consequences of use of the alternative fibers. Although there may be scenarios in which indirect effects have substantial impacts, it is beyond the scope of this project to address them fully. However, to begin to address the implications of a transition from northern softwood to bamboo pulp on both northern forests and on the southern timberlands on which the bamboo would be grown, we supplement the analysis with additional discussion of biodiversity. And to consider the implications of production of kenaf and *Arundo donax* on cropland, we supplement the kenaf and *Arundo donax* LCA with some assessment of potential crop displacement.

Alternative fiber development may be simultaneous with developments in biofuel feedstock production and policy. Large-scale US production of biofuel, mandated by the US Renewable Fuel Standard (RFS2), could increase demand for the same types of cropland and timberland on which alternative fibers could be produced. This could affect overall environmental impacts; while most parts of the LCA are independent of scale, both indirect land use change and ecosystem impacts are scale-dependent.

1.8 Impact Assessment Methodology

Impact categories are selected to focus on the key impacts expected to be of concern for alternative fibers. We use the ReCiPe method of impact assessment, global version 1.06 (Goedkoop et al. 2012). ReCiPe is a follow-on updated method that builds on the Eco-indicator99 and CML methods; we chose it because it has broad coverage, is widely used, is generally well regarded, and convenient (Huppes and van Oers 2011). The list below shows the mid-point impact categories that we examine, along with the units and characterization factor names:

Fossil resource depletion (MJ): fossil depletion potential
Water depletion (m^3): water depletion potential
Agricultural land occupation (m^2-y): agricultural land occupation potential
Urban land occupation (m^2-y): urban land occupation potential
Natural land transformation (m^2): natural land transformation potential
Climate change (kg CO_2 equivalent): global warming potential
Human toxicity (kg 1,4 DB equivalent): human toxicity potential
Particulate matter (kg): particulate matter formation potential
Freshwater eutrophication (kg P equivalent): freshwater eutrophication potential
Marine eutrophication (kg N equivalent): marine eutrophication potential
Terrestrial, freshwater, marine, toxicity (kg 1,4 DB equivalent): terrestrial freshwater and marine ecotoxicity potential
Terrestrial acidification (kg SO_2 eq): terrestrial acidification potential
Ozone depletion (kg CFC-11-equivalent): ozone depletion potential
Photochemical oxidant formation (kg NMVOC): photochemical oxidant formation potential
Ionizing radiation (kg U235 equivalent): ionizing radiation potential
Mineral resource depletion (kg oil equivalent): mineral resource depletion potential

The above list is the entire set of mid-point indicators included in the ReCiPe method; these metrics are internationally accepted measures of environmental impact. Of these, there are several impact categories for which the endpoint analysis indicated an endpoint contribution much smaller than those of other impact categories; these are addressed in the appendix.

For climate change, we evaluate the global warming potential of biogenic carbon – that is, all the plant-based and soil carbon involved in fiber production – using the method of Guest et al. (2012); this method provides values that are used within the ReCiPe methodology. For water depletion we developed additional analysis beyond the ReCiPe water depletion assessment, by considering a local characterization of water availability using the method of Pfister et al. (2009).

Midpoint indicators, as described above, are used in lifecycle and other environmental assessments because their scientific and technical validity are clear; their values are relatively straightforward to measure and evaluate, and they correspond to environmentally relevant emissions.

We also consider the following endpoint categories, shown below with their units and categorization factor names:

Damage to human health (y): disability adjusted life years

Damage to ecosystem diversity (y): loss of species during a year

The endpoint modeling combines midpoint results (Goedkoop et al. 2012; Thompson et al. 1990) and provides an approach to understanding the relative magnitude of the environmental impacts. Disability adjusted life years (DALYs) are a widely used metric for health impacts; a limitation however is that the values can be expected to depend on health care availability, progress, and quality (Murray and Lopez 1996). DALYs are used in the ReCiPe methodology with no discounting or age-weighting.

For the category of damage to ecosystem diversity, the measure is in terms of damage to species. This metric is a measure of the disappearance of species or stress on species in a certain region during a certain time. Species density is calculated based on data from the

GEO 2000 survey from the United Nations Environment Program's World Conservation Monitoring Center (Goedkoop et al. 2008; WCMC 1992).[1]

In the midpoint and endpoint evaluations there are some choices to be made for the time-horizon of various environmental impacts, and the range and extent of the health and ecosystem impacts considered for each category. In ReCiPe these choices are grouped into three basic categories, called individualist, hierarchist, and egalitarian, with the individualist choices emphasizing short-term and more certain impacts and technological optimism, hierarchist choices taking the most common policy principles, and egalitarian taking a long-term precautionary approach (Goedkoop et al. 2008). We have selected the hierarchist perspective; this is the intermediate choice in terms of time frames and other issues and uses, for example, the 100-year time frame for global warming potentials. This approach was also used in the earlier Eco-indicator methodology, and is internationally accepted among life cycle practitioners.

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[1] The analysis is based on known species of insects, fungi, arachnids, nematodes, viruses, bacteria, plants, protozoans, algae, molluscs, crustaceans, and vertebrates (Goedkoop et al. 2012).

Chapter 2: Summary of Data and Assumptions

This chapter summarizes the data and assumptions for the alternative fiber assessment. K-C requests life cycle inventory data from its suppliers; we used data from these questionnaires as the primary sources of data. Questionnaire responses provided to K-C from suppliers include data on production of kenaf, wheat straw, *Arundo donax*, and bamboo, and on the pulping of northern softwood. Data on the pulping of recycled fiber, wheat straw, kenaf, and *Arudno donax* come directly from K-C commercial and pilot scale operations.

In cases of missing data, we searched the technical and research literature to find data to fill the gaps. This includes estimates for the fate of agricultural chemicals, the application rates of herbicides, and the air emissions from bamboo pulping. The uncertainty in these data values is reflected in their low data quality scores.

2.1 Fiber Production

The alternative fibers under consideration are *Arundo donax*, kenaf, wheat straw and bamboo. The standard fibers considered for comparison are recycled fiber and northern softwood. These are discussed in turn below, with key fiber production data summarized in Table 2.1.

2.1.1 *Arundo donax*

Arundo donax is a perennial reed (see Figure 2.2). The expected yield is 25 t/ha-y, based on one year of data (GTP 2011). Reported annual fertilizer application rates for nitrogen (N), phosphor (P) and potassium (K) are 37, 5.4 and 20.5 kg per hectare, respectively (GTP 2011). Other studies report a range of *Arundo donax* yields. One grower reports 60 air-dried tons per hectare per year, in South Carolina, with use of fertilizer in year 1 only (Reiser and Gafford 2012). In Italy, *Arundo donax*, grown without irrigation but with application of 100-100-100 kg N, P_2O5, and K_2O per hectare each year, has a reported yield of 38 air-dried tons per hectare per year on average for years 2 through 12 (Angelini et al. 2009). In other studies, mean yields of 11 t/ha and 22 t/ha in the first and the second year of growth respectively were recorded (Cosentino et al. 2005). Energy for planting and harvesting were 10,000 MJ/ha for year 1 and 4000 MJ/ha in years 2 through 12 (Angelini et al. 2009). Ninety percent of this energy consumption was direct diesel fuel consumption during agricultural operations; the additional 10% incorporates the energy for agricultural machinery production and repair, assuming a 10-year machinery lifetime, using data from Boehmel et al. (2008). Another study from Italy (Monti et al. 2009) reported a yield of 21 t/ha and a harvesting energy use of 2000 MJ/ha.

In the absence of U.S. data on the energy used in farming *Arundo donax*, we draw on the Angelini et al. study, adjusting for the yield differences, for an agricultural energy use of 2700 MJ/ha/yr. There are reports of irrigating *Arundo donax* when it is grown in semi-arid regions (Mantineo et al. 2009) but we have found no reports of *Arundo donax* irrigation outside of semi-arid regions. Following the Angelini et al. study and conversations with a US supplier, we assume no irrigation is used.

Figure 2.2 *Arundo donax*

Chipping: Chipping of *Arundo donax* is reported to be difficult and similar to bamboo (Reiser and Gafford 2012). Chipping can be accomplished using mobile diesel chippers or using fixed location electric chippers. Drawing on data from several sources (Nati et al. 2010) and discussions with chipper operators, we estimate 90 MJ of diesel fuel per ton of chipped fiber.

Invasiveness: Invasiveness may be a concern for *Arundo donax* (Breed 2012). It spreads through vegetative propagation. One grower reports that *Arundo donax* can be eradicated by cutting it and spraying with glyphosate (Reiser and Gafford 2012); glyphosate is also reported in the literature as the most common herbicidal treatment for *Arundo donax* (Dudley 2000). Potentially, glyphosate could be used around the edges of fields to control invasiveness. An *Arundo donax* supplier reports that stands can be productive for up to thirty years. In the absence of field reports of the extent of herbicide use, we assume glyphosate use to eradicate *Arundo donax* once every ten years, at an application rate commonly used in forestry before replanting, of 2 lb/acre, corresponding to 0.22 kg/ha-y; this value is a placeholder that should be adjusted as more data become available.

2.1.2 Kenaf

Kenaf is an annual (see Figure 2.3). It is comprised of about 35% bast (bark) and 65% core (wood) fibers. It has a reported yield of 7-15 t/ha-y at 7% moisture (KenGro 2012). It is the bast that will be used for pulp production; correspondingly, the average net bast yield is about 3.9 t/ha-y. Kenaf core is used as an absorbent in the oil industry and other applications. In the absence of economic data on profits from kenaf bast and core production, we evaluate two different allocations. The baseline is a mass allocation which attributes 35% to the bast fiber; this may underestimate its relative economic value since core fiber may be the market driver. In order to span the range of allocations, the second allocation is 100% to bast; this would be appropriate if the market for core provides little or no return to the farmer. If there is a profitable market for both core and bast, the appropriate allocation would be in between the first and second allocation values; if production ramps up this issue could be resolved in future studies.

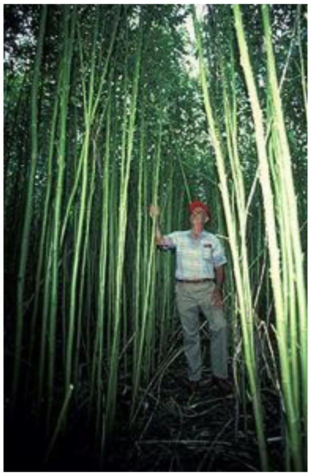

Figure 2.3 Kenaf

Because it is an annual, kenaf may be grown in rotation with soy, cotton or other crops. At the current time there is no information on any effect of kenaf on agricultural practices for other crops, and no allocation or system expansion is developed for crop rotation in this analysis.

Inputs: Fertilizer application of 112 kg nitrogen, 22.4 kg phosphorus and 33.6 kg potash per hectare (100, 20, 30 pounds per acre) is reported. Reported fuel use is 15 gallons of diesel fuel per hectare (6 gallons per acre), which at 150 MJ/gal corresponds to diesel fuel use of approximately 2300 MJ/ha-y. The reported irrigation rate is 6100 cubic meters per hectare (24 acre inches per acre) (Kengro 2012). This is about 60% of kenaf's evapotranspiration rate (Bañuelos et al. 2002). We assume that 60% of the water used for irrigation is consumed – that is, leaves the watershed through evapotranspiration or with the kenaf harvest, and that 40% is retained within the watershed; this is consistent with estimates of average irrigation water consumption fraction in the US (Brown 1999). Given the lack of site-specific data on the fraction of irrigation water lost to the watershed, we consider an uncertainty range from 10% loss to 90% loss of irrigation water from the watershed.

Kenaf can be grown without irrigation. In central California, kenaf grown without irrigation had lower yield (Bañuelos et al. 2002). The extent to which the yield of kenaf grown in the southeast would be affected by a change in the irrigation quantity has not been evaluated, but can be expected to depend on the amount of rainfall and other factors.

For chipping and separating of kenaf bast and core, we assume diesel energy use of 90 MJ per ton, as for *Arundo donax*. Use of the herbicide treflan (trifluralin) is reported, at a rate of 0.2 gallon per hectare (GTP 2011). Glyphosate can be used to kill the crop to allow for a November harvest; alternatively the crop can be harvested later without glyphosate by waiting for frost to kill the plants (K-C 2012c). We assume glyphosate use at a rate of 2 lb per acre, based on general glyphosate application rate data from the US Department of Agriculture (USDA 1997).

A separate source in the US southeast reports an expected yield of 9-11 tons per hectare (8,000 -10,000 pounds per acre), with 8-12% moisture (GTP 2011). Reported fertilizer application is 69 kg/ha nitrogen, 9 kg/ha P, and 29 kg/ha K. In Italy, Amaducci et al.

(2000) report nitrogen fertilizer application at a rate of 100 kg/ha. All of these values are of similar order of magnitude to that reported by the data from a prospective supplier (KenGro 2012), providing some assurance to the data quality.

Invasiveness: Invasiveness is not a reported concern for kenaf.

2.1.3 Wheat straw

Wheat is widely grown in the United States. For every ton of wheat approximately 1.3 tons of wheat straw is available (NREL 2011). Average U.S. wheat yields are 3 t/ha (USDA 2011), which implies a wheat straw yield of 3.9 t/ha. A potential K-C wheat straw supplier in Georgia reports a harvested wheat straw yield of 5.6 t/ha (GTP 2011); this appears to be higher than average and is in the range reported as exceptional in another source (Rankin 2012). Given the limited data, we assume a wheat straw yield of 3.9 t/ha. We assume one wheat crop per year.

Wheat straw is a residue of wheat production; wheat straw would be produced regardless of whether it is used for pulp or other products. And, to the extent that wheat straw is procured for pulp production with no extra profit or cost savings to the farmer, then it might be reasonable to allocate all of the farming inputs to the wheat grain, and consider wheat straw production to have zero environmental impacts. However, if the farmer is able to sell both wheat and wheat straw, so that selling wheat straw becomes part of the economics of wheat production, then wheat and wheat straw can be considered as co-products; a portion of the inputs for wheat production can be allocated to the wheat straw. With the current low market utilization of wheat straw there are no data available on the relative returns to farmers of wheat grain versus wheat straw. Previous studies have made 10% (Jungbluth and Busser 2011) and 13% (Li et al. 2012) allocations to wheat straw based on

Figure 2.4 Wheat straw

economic valuation. Rounding to one significant figure, we draw on both of these references and use 10% as our baseline allocation choice. Noting, however, that the returns from wheat production in the southeast are low (USDA 2012), it is plausible that sales of wheat straw could become a larger portion of wheat profits in the southeast than elsewhere, and we use a second allocation value of 20% for comparison.

Inputs: US production of wheat has been reported to use 66 kg N, 8.7 kg P, 41 kg diesel and 9.3 kg gasoline per hectare (NREL 2011; Meisterling et al. 2009), corresponding to a total fuel use of about 2500 MJ/ha-y. Some portion of the straw is left on the land for maintenance of fertility and soil carbon. Even so, the removal of wheat straw may result in additional fertilizer requirements; these have been estimated to be an additional 2.2 kg N and 0.67 kg P per hectare; these values are included here (NREL 2011). Wheat production is assumed to be non-irrigated; the US southeast is generally has plentiful rainfall and Alabama has a low irrigation rate even compared to neighboring Georgia and Mississippi (Martin 2012). As of 2012, however, a tax credit is being provided to encourage installation of irrigation equipment in Alabama (Martin 2012); future analyses could take into account changes in irrigation practices.

Herbicides: Lifecycle inventory data on the use of pesticides in wheat production, and the emissions to air and water, are available in the U.S. Lifecycle Inventory Database (NREL 2011); we use these values.[2]

Invasiveness: Invasiveness is not a concern for wheat.

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[2] These include 2,4-D, bromoxynil, carbaryl, carbofuran, chlorpyrifos, dicamba, disolfoton, diuron, glyphosate, malathion, MMCPA, metribuzin, paraquat, parathion, permethrin, phorate, triallate, and trifluralin (NREL 2011: wheat at field).

2.1.4 Bamboo

Although bamboo is widely grown in China, commercial production of bamboo has not yet been established in the United States and thus the characterization of bamboo is based on projections from prospective suppliers, supplemented by information on characteristics of bamboo grown elsewhere. Bamboo is assumed to be grown on land currently used for softwood timber production in the US southeast. Data on bamboo production were developed by K-C engineers based on information from the prospective supplier (K-C 2012a). The bamboo life span is considered to be 100 years; one-third is harvested each year (K-C 2012a). Plantings include *Phyllostachys edulis* (Moso) and *Phyllostachys nigra* (Henon). Site preparation will begin with wood harvested and sold within the forest products industry as usual. No stump or root removal takes place following harvest of the wooded land.

Figure 2.5 Bamboo (www.booshoot.com)

The herbicide atrazine is applied 6-12 weeks prior to planting, which is reported to be normal softwood forestry practice (K-C 2012a). An application rate of 3 lb per acre is reported for southeastern forestry management (Nelson and Cantrell 2002); we use this application rate in our analysis. In addition, we note that softwood timber growers in the southeast use insecticide to control termites; we assume no insecticide use for bamboo or any other fiber.

No fertilizer was applied during pilot tests; some fertilizer application is possible in the future (K-C 2012a). In other studies of bamboo, an annual fertilizer application rate of 90 kg/ha of 10-30-10 is reported; this corresponds to masses of nitrogen (N), phosphor (P) and potassium (K) of 9, 11.5, and 7.5 kg per hectare respectively (Lugt et al. 2009). Some hand planting has been used for pilot plots. Some mechanical planting, similar to softwood forestry, may be used at commercial scale. No fully automated planting is envisioned. No specific thinning activities are expected for bamboo plantations; the short harvest cycle provides some thinning. No pesticide applications are planned after the initial planting. Plots are not irrigated. One third of the culms are harvested every year after three years of growth. Plants regrow from the rhizome. Harvesting is done with conventional mechanical (diesel) softwood harvesting equipment. Multiple culms are harvested in a single cut. Approximately 20% of the plant mass (culm top and branches/leaves) is cut and left in the field (K-C 2012a).

No source-specific information on the amount of diesel fuel used by the harvesting equipment or other activities in growing and harvesting the bamboo has been provided. Based on data from the U.S. Lifecycle Inventory Database (NREL 2011) for the diesel energy use in forestry, we provisionally assume 0.8 kg diesel per dry ton of bamboo for harvesting, corresponding to about 40 MJ per dry ton of bamboo, or about 2000 MJ/ha-y for a 46 t/ha-y yield. In addition, we assume 90 MJ per ton for chipping, as for other fibers.

Bamboo Yield: The data supplied to K-C on domestic US bamboo sourcing indicates an expected yield [DATA REMOVED]. A Chinese supplier reports a yield of 30 t/ha-y for Chinese-grown bamboo used for pulp (Spitzley 2011). Scurlock et al. report *Phyllostachys* species with annual yields of 2.0–5.8 t/ha-y, including up to 21% in the form of branches (Scurlock, 2000); this is, however, for a different species of bamboo. Lugt et al. (2009) report that Moso has a density of 0.7 t/m^3 and annual yield of about 4.6 m^3/ha, corresponding to about 3.2 t/ha-y. For our baseline analysis we use [DATA REMOVED], as reported by the prospective supplier, and in the sensitivity analysis we also show results for a yield of 30 t/ha-yr corresponding to the yield achieved by K-C's bamboo supplier in China (Sptizley 2011).

Invasiveness: Invasiveness may be a concern for bamboo. Although no actions to address invasiveness have been reported, we provisionally assume glyphosate use at a rate of 2 lb per acre every 10 years, as for *Arundo donax*.

Biodiversity significance: Southeastern forests support highly diverse ecosystems, both terrestrial and aquatic, that provide substantial ecosystem services (Hanson et al. 2010). Some southeastern watersheds contain substantial numbers of aquatic species at risk; these include the Upper Clinch River on the Virginia-Tennessee border, the Green River in Kentucky, and Cahaba River in Alabama, the Conasauga River on the Georgia-Tennessee border, and the Altamaha River in Georgia (Master et al. 1998). Historical practices of intensive logging have resulted in habitat loss and degradation (WWF 2012).

2.1.5 Northern Softwood

Yield: In quantifying the land used to produce northern softwood, we consider the land needed to support the continuing supply of pulp. That is, we consider not only the land needed to supply pulp in a given year, but the entire forest area that might be considered to be "in rotation" for the production of pulp. For northern softwood, the regeneration times[3] are long – 60 to 100 years – and much of the harvested softwood is from primary forest. Defining this yield is not based on a single measurement, but rather is an estimate made in Canada at the provincial level; the annual allowable yield is often controversial and the measurements and considerations that go in to developing these estimates are not published. Thus the "yield" of northern softwood has uncertainties that are different than for the yields of agricultural fibers. Kissinger et al. (2007) report spruce yields of 1.3, 2.0 and 1.6 m^3/ha-y in Manitoba, Saskatchewan and Alberta, respectively,

Figure 2.6 Spruce forest, British Columbia

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[3] Regeneration time, as used in this report, means the time required for the tree or other biomass to grow back after harvest. In the LCA literature, the term regeneration time is used to refer to the time for an ecosystem to recover to its original state after transformation to a new land occupation process; this is not the meaning used here.

whereas aspen in those same regions has a reported yield of 2.5, 2.4 and 2.9 m^3/ha-y, respectively. With spruce as the baseline species for pulp production, provisionally we use the value of 1.6±0.4 m^3/ha-y, which is the average of the 1.3, 2 and 1.6 values for spruce yield in three provinces; the ± spans the range. With an estimated dry coniferous pulpwood density of 0.65 t/m^3 (FAO 2012), 1.6 m^3/ha corresponds to 1±0.2 t/ha-y. We use this value, 1 t/ha-y, for all northern softwood in our analysis.

A northern softwood yield of 1 t/ha-y is somewhat lower than US reports. Sendak et al. (2003) report harvest yields of northern softwoods in the range of 27-32 ft^3/acre-year, corresponding to 1.4 t/ha-y. As of the late 1990s, average US timber yields were 3 m^3/ha-year, corresponding to 2 t/ha-y (Wernick and Ausubel 1997). Canadian forest yield may be lower due to both low intensity management and northern growing conditions.

Higher northern softwood yields can be achieved; 8.3 m^3/ha-y, corresponding to 5.4 t/ha-y, has been achieved in British Columbia with intensive management (Binkley, C. S. 1999). However, these values would be for intensively managed plantations that might be established in the future, which may have very different management practices and are not representative of pulp feedstock currently available. In our sensitivity analyses we use a 25% yield increase for northern softwood, corresponding to the far end of the range of yield estimates for boreal northern softwood provided by Kissinger et al. (2007).

<u>Inputs:</u> While much of the logging in Canada is from natural forests, after logging the forests will generally be replanted. Herbicides are assumed to be used before re-planting. Provisionally we assume that the herbicide is glyphosate, commonly known as Roundup, and that it is applied once every 70 years (Mance, 2012). Application rates are reported to range from 0.3 to 4 lbs of active ingredient per acre (USDA 1997). We provisionally assume two pounds of active ingredient per acre, applied once every 70 years.

Diesel energy use for planting and harvesting of northern softwoods is expected to be comparable to southern timber energy use; provisionally we use 40 MJ/t (NREL 2011).

Biodiversity significance: In Canada there is a wide diversity in forests, both boreal and non-boreal. Both boreal and non-boreal forests have significant environmental and cultural value. The coastal temperate rain forest of British Columbia is non-boreal forest with very high biodiversity, including some of the world's largest remaining wild salmon runs and carbon storage (Ecotrust 1992; DellaSala 2010). Canada's boreal forest, the world's largest intact forest, provides critical habitat for threatened woodland caribou (COSEWIC 2002) and other species, and large-scale carbon storage.

Of the total northern softwood pulp currently purchased by K-C, 38% is considered to be boreal. The boreal pulp is sourced from Alberta, Ontario, and Quebec; 30% of this is Forest Stewardship Council (FSC) certified. The non-boreal northern softwood fiber is sourced from Nova Scotia, British Columbia, and Washington State. Of the total northern softwood procured, 20.6% is FSC certified, 28.8% is certified by the Canadian Standards Association (CSA), 43.9% is Sustainable Forestry Initiative (SFI) certified, and 6.7% meets the FSC Controlled Wood standard (K-C 2012). Both the location and the forest management practice are expected to affect the ecosystem impacts and other environmental impacts. These refinements could be incorporated in future analyses. Figure 2.7 shows a map of the forest regions of Canada and the forest certification in place at the end of 2011. An interactive online version of this map, with detailed information at finer scale is available (FPAC 2012).

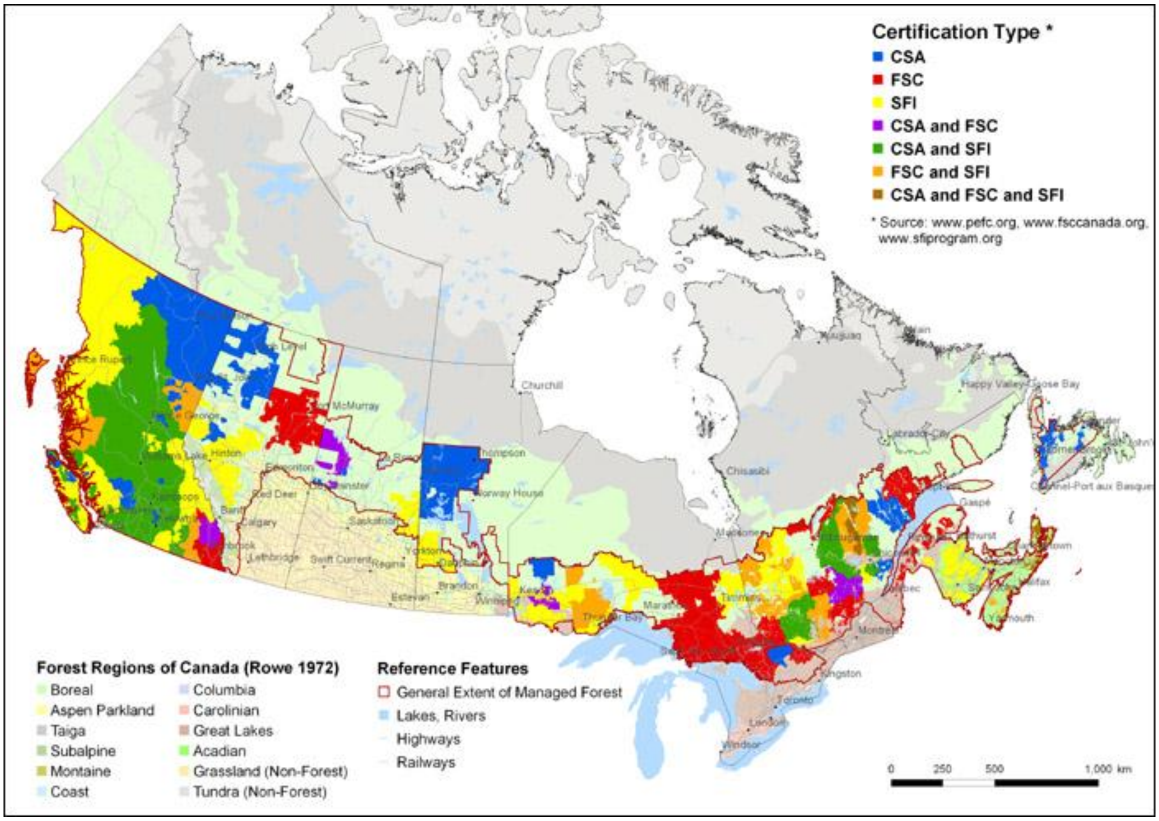

Figure 2.7 Forest regions of Canada and the forest certifications in place at year-end 2011 (FPAC 2012).

Key fiber production data are summarized in Table 2.1. As noted above, recycled fiber is considered starting from the paper collection process and due to the large transportation component of recycled paper collection that process is addressed in section 2.2.2, on transport.

Table 2.1 Selected fiber production assumptions

Fiber	Yield (t/ha-y)	Irrigation (m^3/ha-y)	Fertilizer N, P, K (kg/ha-y)	Herbicide	Energy (MJ/ha-y)
Arundo donax	25[a]	0[a]	37, 5.4, 20.5[a]	Glyphosate: 0.22 kg/ha-y[n]	Harvest 2700 MJ/ha-y[b]; Chipping 90 MJ/t[c]
Kenaf bast	3.9[e]	6100[e]	112, 22.4, 33.6[e]	Trifluralin: 0.76 kg/ha-y[a]; Glyphosate: 2.2 kg/ha-y[n,o]	Planting and harvest 2300 MJ/ha-y[e]; Chipping 90 MJ/t[c]
Wheat Straw	5.6[a]	0[a]	66[f]	2,4 D: 1.1 kg/ha-y[h]	Harvest 2500 MJ/ha-y[f]
Bamboo	DATA REMOVED[i]	0[i]	9, 11.5, 7.5[k]	Glyphosate: 0.22 kg/ha-y[n] Atrazine: 0.014 kg/ha-y[i]	Harvest 2000 MJ/ha-y[l] Chipping 90 MJ/t[c]
Northern Softwood	1±0.2[m]	0[d]	0[d]	Glyphosate: 0.032 kg/ha-y[n]	Harvest 40 MJ/ha-y[l]

Sources (bold indicates direct K-C supplier): [a]**GTP 2011**. [b]Angelini et al. 2009. [c]Nati et al. 2010. [d]Author estimates. [e]**Kengro 2012**. [f]Meisterling et al. 2009. [h]Johnson and Nice 2011. [i]**K-C 2012a**. [k]Lugt et al. 2009. [l]NREL. [m]Kissinger et al. 2007. [n]USDA 1997. [o]K-C 2012c.

2.1.6. Fate of Agricultural Chemicals

For nitrogen fertilizer applications, we assume 12% loss to water, and air emissions of nitrogen oxide (NO and NO_2) of 10% of the amount of applied nitrogen; these are the values used in the US Lifecycle Inventory Database (NREL 2011: wheat at field) and are derived using US EPA methods (US EPA 2012b). Nitrogen fertilizer applications also result in a release of nitrous oxide, N_2O; here we follow the IPCC guidance and use 1% of applied nitrogen, corresponding to 0.0157 kg per kg of nitrogen (IPCC 2006, Chp. 11, Table 11.2). For phosphate fertilizer applications, we assume that 1.3% of applied phosphorus is released to water as phosphate, again based on estimates from NREL (2011) and US EPA (2012b).

For atrazine we use 2% loss to water and 0.1% air emissions (Cal EPA 2001).
For other pesticides we use NREL and EPA data and models (US EPA 2012b, NREL 2011: wheat at field), with the following values: glyphosate 1% to water, 3% to air; 2,4-D 10% to air, 0.05% to water.

2.1.7 Data Quality Assessment for Fiber Production

Table 2.2 summarizes the data quality for fiber production. The quality of data for the inputs and yields for all fibers are similar: all are based on measured current data and the sources are the enterprises under study in the US southeast, although the data do not represent all enterprises that might produce these fibers, and there is considerable expected variability in the values for yield and chemical inputs. Moreover, because the data are from different suppliers, there may be some issues with the consistency in reporting of inputs to the production processes. The data and assumptions regarding the emissions to air, soil, and water from fiber production are of lower quality, based on qualified estimates of chemical fate and transport rather than on measured data from the sites. In terms of reproducibility of these results in future studies, there could be differences in the modeling of the fate of agricultural chemicals; these uncertainties are reflected in the sensitivity analysis that is developed as part of the impact analysis.

Table 2.2 Fiber Production Data Quality Indicators
(Specific data sources are shown in Table 2.1.)

Process	**Data Source**	**Data Quality**
Production Inputs and Yields		
Arundo donax	K-C supplier data	1,3,1,2,1,3
Kenaf	K-C supplier data	1,3,1,1,1,2
Wheat Straw	K-C supplier data for yield and USDA data for inputs	1,3,1,1,1,2
Bamboo	K-C supplier data	2,3,1,4,1,2
Northern Softwood	Canadian government data for yield and NREL data for inputs	2,3,1,1,1,2
Emissions of Agricultural Chemicals to Air, Water, Soil		
Arundo donax	literature estimates	4,3,1,3,4,3
Kenaf	literature estimates	4,3,1,3,4,3
Wheat Straw	literature estimates	4,3,1,3,4,3
Bamboo	literature estimates	4,3,1,3,4,3
Northern Softwood	literature estimates	4,3,1,3,4,3

2.2. Fiber Transport

The system boundary for this study includes transport to the pulp mill and transport from the pulp mill to the paper mill. Both transport stages are addressed in this section.

2.2.1 Transport to the mill

K-C's purchases of alternative fibers are still at the pilot scale; the specific locations for full-scale production are not yet identified. K-C engineers indicate that alternative fibers would be sourced from within 100 km, so we assume a 100 km transport distance by truck for *Arundo donax*, wheat straw, bamboo, and kenaf. For northern softwood, transport distances have increased as close-in wood has been harvested, and 150 km is reported as an average transport distance (Canadian Bioenergy Association 2007). Some northern softwood may be transported over larger distances, as may some of the other fibers; the implication of larger transport distances is discussed in the interpretation section. As more information becomes available, travel distances could be modeled more specifically. For kenaf, for example, one supplier indicated that transport from Florida to Location Removed could be 40 km by ship and 340 km by truck (GTP 2011).

For northern softwood transport, we use the US LCI Database for *Softwood logs with bark, harvested at high intensity site, at mill, US PNW* (NREL 2011), which consumes a total 0.014 liters of diesel fuel and 0.22 g of lubricants per t-km of transport. For *Arundo donax*, wheat straw, kenaf and bamboo we use short-haul combination freight truck data from the ecoinvent database, which incorporates an assumed 70% weight loading of the trucks. Because the fibers are being transported from agricultural areas, we assume that essentially all of the backhauls will be empty. Previous studies have assumed that backhaul for trucks is 30-68% of energy use for fronthaul (Cooper et al. 2008); we assume that the backhauls have 50% of the fuel consumption and correspondingly 50% of the emissions of the loaded trucks.

2.2.2 Recycled fiber collection and transport to the de-inking pulp mill

The collection, sorting, baling and transport of recycled fiber to the de-inking pulp mill is addressed here as one "unit process", in accordance with how it has been addressed in other studies. K-C sources mixed office paper from a number of sources. Mixed office paper is collected from office locations and transported to a "materials recovery facility," or MRF, where it is sorted and baled, and from there the baled paper is transported by a combination of truck and rail to the K-C de-inking pulp mill in [LOCATION REMOVED], which is served by a rail line. Detailed data on office paper collection and transport to K-C were not available, so we use data from other sources as discussed below.

The Environmental Defense Fund (EDF 2002) reported that the collection and transport, processing at the MRF, and residuals disposal for recycled office paper in the United States requires 1150 MJ/t, 329 MJ/t, and 49 MJ/t, respectively, for a total of 1500 MJ/t of mixed office paper collection and delivery. The U.S. EPA has developed a Waste Reduction Model, WARM, to help solid waste managers and organizations to report greenhouse gas reductions from recycling and other waste management activities; that model reports an overall total of 510 MJ/t for the collection, sorting and delivery of mixed office paper to de-inking pulp mills (US EPA 2006), which is lower than the value reported by EDF. In the ecoinvent database, Hischier (2007) has provided European data on recycled fiber collection, sorting and delivery to the pulp mill based (Pre 2007); these data show a good match to the energy data reported by EDF (2002) and have the benefit of including full inventory data and being somewhat more recent; we use the Hischier data from ecoinvent in this study.

For recycled fiber, the system boundary starts at paper collection. Other studies have adopted a larger system boundary, including a portion of the inputs for the initial production of the paper; system boundary expansion would increase the environmental impacts attributed to recycled fiber (Hohenthal and Behm 2009).

2.2.3 Transport from the pulp mill to the paper mill

The pulping of *Arundo donax*, kenaf, and wheat straw, and the de-inking of recycled fiber, are expected to be co-located with the tissue production facility. However, northern softwood kraft pulp will be transported from the pulp mill in Canada to the gate of the paper mill, which we take to be the K-C mill in Beech Island, South Carolina; we estimate a travel distance of 4000 km by train. Bamboo will be pulped at an unspecified kraft pulp mill in the southeast US and then sent by train to the same Beech Island paper mill; we estimate transport distance of 500 km by train. Although previous studies have indicated that rail empty backhaul could use 30% of the energy of front haul, we assumed that most backhauls will not be empty and we do not include backhaul for the rail transport (Cooper et al. 2008). Data on the fuel consumption and emissions from freight train transport are from the ecoinvent database.

2.2.4 Data Quality Assessment for Fiber Transport

The data source type and data quality indicators for fiber transport are shown in Table 2.4. The first part of the table refers to the data on transport distances and modes (truck and rail); the second part of the table refers to the data on the emissions, efficiency, and inventories associated with the transport.

Table 2.3 Fiber Transport Data Quality Indicators

Process	**Data Source Type**	**Data Quality**
Transport distances and modes		
Arundo donax	K-C	1,3,1,1,1,3
Kenaf	K-C	1,3,1,1,1,3
Wheat Straw	K-C	1,3,1,1,1,3
Recycled Fiber	ecoinvent	1,3,2,2,1,3
Bamboo	K-C	1,3,1,1,1,3
Northern Softwood	K-C	1,3,1,1,1,3
Transport emissions, efficiency, and inventories		
Arundo donax	ecoinvent	1,2,1,2,3,3
Kenaf	ecoinvent	1,2,1,2,3,3
Wheat Straw	ecoinvent	1,2,1,2,3,3
Recycled Fiber	ecoinvent	1,5,2,2,1,3
Bamboo	ecoinvent	1,2,1,2,3,3
Northern Softwood	ecoinvent	1,2,1,2,3,3

In terms of the sources of the data, there is some inconsistency between sources for distance traveled and for the emissions, efficiency, and inventories associated with transportation. In terms of reproducibility, different studies of these same fibers might include different transportation distances and different transportation modes and efficiencies, which could affect the transportation inventories. In addition, in the specific scenarios considered, the paper mill is co-located with the pulping for *Arundo donax*, kenaf, wheat straw and de-inked pulp; in other studies the pulping may not be co-located with the paper mill; transportation inventories may differ for different scenarios.

2.3. Fiber Pulping

This study considers two different pulping processes for the alternative fibers. Mechanical pulping is considered for the *Arundo donax*, kenaf, and wheat straw, and Kraft pulping is considered for the bamboo. As discussed in the goal and scope chapter, pulps made with these different processes have somewhat different functions. The fibers undergoing mechanical pulping are expected to function similarly to recycled fiber, which is pulped with the de-inking process; the fiber undergoing Kraft pulping – bamboo – is expected to function similarly to northern softwood Kraft pulp.

Features of the pulping technology, fiber efficiency, and energy consumption are highlighted in Tables 2.4.a and 2.4.b. All of the technologies included in Table 2.4 include the entire pulping process: mechanical pulping, Kraft pulping, and deinking are all complete processes, including pulping and bleaching. Table 2.4.a shows the mechanical pulping and recycled fiber deinking pulping, all of which would be carried out at the K-C mill in [LOCATION REMOVED]; for these processes the electricity data show total electricity consumed in the pulping process. Table 2.4.b shows the Kraft pulping processes for northern softwood and bamboo; for these processes the electricity data show the amount of external electricity drawn from the grid; in addition the natural gas, fuel oil and biomass wastes are used to generate both process heat and electricity used internally. The tables show that mechanical pulping is more efficient than Kraft pulping, in terms of the amount of pulp that is produced per ton of input fiber. Northern softwood is shown as being the least efficient. The value of 2.6 tons of fiber per ton of pulp is derived from data supplied by a Canadian mill (K-C 2007).[4] Kraft pulp mills have been reported to have yields in the range of 1.8-2.2 tons of wood chips per ton of pulp (Briggs 1994, Table 8.1), more efficient that what we assume here.

The data on the mechanical pulping of *Arundo donax*, kenaf, and wheat straw are based on pilot testing at K-C. This process involves fiberization [SPECIFICS REMOVED], conveyance to and agitation in a peroxide (non-chlorine) bleach tower, refining and screening, followed by processing through a wet-lap machine which produces a pulp of approximately 50% moisture. Because the pulp production at K-C is co-located with tissue production, further drying is not needed. [DATA REMOVED]

While the amount of electricity required mechanical pulping is similar for *Arundo donax*, kenaf, and wheat straw, they are not exactly the same. While some of these differences can reflect how difficult it is to grind each kind of fiber, a key factor is the difference in the pulping efficiency – that is, the amount of input fiber needed to produce a ton of pulp.

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[4] The plant reports input of 4.15 tons of wood chips for production of 1 air dried ton of pulp. Here wood chips are assumed to have a 37% moisture content to arrive at a pulp yield of 2.6 tons of wood chips per ton of pulp.

Kenaf requires less input fiber per ton of pulp than does wheat, and the electricity requirement is correspondingly smaller.

[TABLE 2.4.a REMOVED]

Table 2.4.b Process, pulping efficiency and energy assumptions for Kraft pulping

Fiber	Efficiency (t fiber/t pulp)	External Electricity (kWh/t pulp)	Natural Gas (MJ/t pulp)	Fuel oil (MJ/t pulp)
Bamboo	Data Removed	Data Removed	Data Removed	Data Removed
Northern Softwood	2.6[f]	39[f]	0[f]	3070[f]

Sources (bold indicates K-C data or direct K-C supplier data): [d]**K-C 2012a**. [f]**K-C 2007a**.

The carbon dioxide emissions data from electricity for mechanical pulping and deinking are from the US EPA eGRID database (US EPA 2012), for the years 2004 and 2005, for the power plant located at the K-C [LOCATION REMOVED] mill; this plant is powered by a combination of natural gas and biomass waste from pulp and paper production and for this reason has a low carbon dioxide emission factor. To model the full inventory of consumption and emissions from this electricity system, we used a combination of ecoinvent databases for electricity provided by natural gas and by biomass.

K-C is currently in the pilot testing stage of alternative fiber mechanical pulping. Although the data in Table 2.4.a reflect K-C engineers' current understanding of the pulp process, these estimates should be revisited as more data become available. In particular, at the [LOCATION REMOVED] mill, the biomass wastes used in the power plant come from recycled fiber production wastes and from tissue production wastes. However the pulping liquors from mechanical pulping of wheat straw, kenaf, and *Arundo donax* may not be suitable for combustion in the power plant and may need to be disposed separately; moreover the pulping equipment requires more aggressive clean-outs than for other fibers. Any major change in power plant operations or additional disposal of the mechanical pulping wastes should be incorporated into future analyses.

Tables 2.5 and 2.6 summarize the chemical pulping inputs for all the fibers. K-C engineers developed the estimates in Table 2.5 for kenaf, wheat straw and recycled fiber.

We estimate *Arundo donax* pulping requirements assuming proportionality to the pulping efficiency.

[TABLE 2.5 REMOVED]

Table 2.5 shows use of peroxide, H_2O_2, for the mechanical and deinking pulping processes; peroxide is a bleaching agent. For recycled fiber, borol is used as an additional bleaching agent; borol is a mixture of sodium borohydride ($NaBH_4$) and sodium hydroxide (NaOH), and is modeled as a 50-50 mix using ecoinvent databases. The chelant is used to remove metals ions in the recycled fiber system; we model this as EDTA (ethylenediaminetetraacetic acid) using process data from ecoinvent. [DATA REMOVED] For *Arundo donax*, the estimate is based on extrapolation from kenaf and wheat straw rather than on direct measurement, so the estimated peroxide use is shown to one significant figure only.

Table 2.6 Estimated chemical inputs for bamboo and northern softwood Kraft pulp production per air dried metric ton of pulp.

Input	Bamboo (kg/t)[a]	Northern Softwood (kg/t)[b]	Notes
Fiber chips	Data Removed	2600	air dried
NaOH	Data Removed	49.2	facility total including process and water treatment
H_2O_2	Data Removed	4.4	bleaching agent
HCl			pH control
O_2	Data Removed	5.7	bleaching agent
Sulphur			ClO_2 residual elimination
Na_2ClO_4	Data Removed	59.7	ClO_2 production
H_2SO_4	Data Removed	44	ClO_2 production
CH_3OH	Data Removed	5.4	ClO_2 production
NaOCl			water treatment
Polyelectrolyte			water treatment (modeled as acrylonitrile)
$Al_2(SO_4)_3$			water treatment
Talc			pitch control
Defoamer			pitch control (modeled as silicon tetrahydride)

Sources (bold indicates K-C data or direct K-C supplier data): **[a]K-C 2012a**. **[b]K-C 2007a**.

Based on pulping trials, bamboo pulping is assumed to have requirements similar to Kraft pulping of eucalyptus, which is one of the fastest growing hardwood species. Most Kraft pulp mills use bark and waste wood as fuel for boiler operation. Bamboo has no bark available as boiler fuel, but bamboo wood waste from screening continues to be available; this is similar to the situation with eucalyptus, which has little bark. K-C engineers estimate that the required electricity can be primarily generated from wood waste and the additional natural gas, with 7.3 kWh/t pulp imported from the grid; in addition the natural gas input shown in Table 2.4 compensates for reduced bark availability. Silica must be removed to prevent evaporator scaling and filtering problems. Table 2.6 provides process data for production of bamboo Kraft pulp provided by K-C engineers, based on available data from K-C research partners on the eucalyptus hardwood Kraft process with adjustments as noted above. [DATA REMOVED]

The estimated water emissions for pulp production are summarized in Table 2.7. The emissions included in the table are biological oxygen demand (BOD), chemical oxygen demand (COD), suspended solids, adsorbable organic halides (AOX), nitrogen, phosphorus, and polycyclic aromatic hydrocarbons (PAH). The mechanical pulping of *Arundo donax*, kenaf, and wheat straw is similar to the process used for bleached chemi-thermo-mechanical pulp (BCTMP) and water emissions values based on K-C data from BCTMP processes are used (K-C 2007b). These values could be revised in future analyses, when any process differences or differences due to specific properties of the non-wood fibers are more fully understood. K-C recycled fiber deinking occurs in an integrated mill and consequently direct data on deinking water emissions are not available; here we cite values for typical deinking mills (EC 2001, Table 5-11).

BOD, COD, and AOX are all combined measures of water emissions, rather than specific molecules. Within the ReCiPe methodology, these measures are not included in the calculation of midpoint or endpoint impacts. As a result, the impact results underestimate the impacts of emissions to water. Development of more specific data on wastewater emissions from the pulping facilities will allow for more complete assessment of water emissions in future studies.

Table 2.7 Estimated water emissions for pulp production (kg/t pulp)

Water emission	Bamboo[a]	Northern Softwood[b]	Kenaf, *Arundo donax*, wheat straw[c]	Recycled fiber deinking[d]
BOD	1.46	1.9	0.68	
COD	14.6	57.9	18	20
Suspended solids	1.32	1.8	1.01	
AOX	0.1	0.25	0	
Nitrogen	0.275	0.65	0.15	0.35
Phosphorus	0.052	0.13	0.07	
PAH		0.002		

Sources (bold indicates K-C or K-C supplier data): **[a]K-C 2012a**. **[b]K-C 2007a**. **[c]K-C 2007b**. [d] EC 2001.

We draw on ecoinvent inventory data for each of the pulping chemicals. Water is used for cooling in electric power plants. In the absence of site-specific data on cooling water evaporation from the electricity used by the various pulp mills we use the US average for thermoelectric power plants of 1.8 liters of freshwater evaporated per kWh of electricity consumed (Torcellini et al. 2003). A more recent estimate, which includes evaporation from hydroelectric power plants, puts the US weighted average for all power production at 3.27 liters per kWh (Pfister et al. 2011).

Although we do not evaluate any co-products of northern softwood pulp, some northern softwood pulp mills receive wood chips from sawmills; thus sawtimber can be a co-product of northern softwood pulp. In the absence of information about the ratios of sawtimber and pulp production we do not include sawtimber as a coproduct. Another co-product of northern softwood kraft pulp is tall oil, which has a number of industrial applications including soaps, emulsifiers, and binders. In kraft pulping of northern softwood, tall oil is produced at a rate of approximately 40 kg/t pulp and to provide 1.5% of the mill's revenue (Stenius 2000). No tall oil is produced from the pulping of bamboo.

In evaluation of environmental impacts we draw on additional data regarding water scarcity, carbon in soils, biodiversity and other issues. These data are discussed as part of the impact assessment.

Table 2.8 Estimated air emissions for Kraft pulp production (kg/t pulp)

Air emissions	Bamboo[a]	Northern Softwood[b]
CO	18	18
CH_4	0.1	0.1
N_2O	0.07	0.07
NOx	2.4	2.4
SOx	0.09	0.09
VOC	1.9	1.9
TSP	2.5	2.5
PM10	2.1	2.1
PM2.5	1.6	1.6
PCDD	6.8E-06	1.7E-05
PAH	0.01	0.01

Sources (bold indicates K-C supplier data): [a]author extrapolations. [b]**K-C 2007a**.

The estimated air emissions from Kraft pulping of bamboo and northern softwood are shown in Table 2.8; these include carbon monoxide (CO), methane (CH_4), nitrous oxide (N2O), nitrogen oxides (NOx), sulfur oxides (SOx), volatile organic compounds (VOC), total suspended particulates (TSP), particulate matter smaller than 10 microns (PM10), particulate matter smaller than 2.5 microns, polychlorinated dibenzo-dioxins (PCDD), and polycyclic aromatic hydrocarbons (PAH). The values for northern softwood are from a K-C supplier. In the absence of other estimates for air emissions from kraft pulping of bamboo, we assume these emissions are the same as for Kraft pulping of northern softwood, with the exception that the emission of PCDD (chlorinated dioxins) is scaled by the relative water emissions of AOX (adsorbable organic halides, which includes chlorinated compounds) for bamboo versus northern softwood. For the mechanical pulping of *Arundo donax*, kenaf, and wheat straw and for the de-inking of recycled fiber, all air emissions are assumed to be from the electricity production process, because this in the only combustion process at the facility.

2.3.1 Data Quality Assessment for Fiber Pulping

The data sources and data quality for pulping are summarized in Table 2.9. The sources of all of the data are K-C, K-C suppliers, or K-C engineers; the result is that the assumptions and measurements underlying the data are fairly consistent, although the reproducibility may be limited because the extent of measurements is limited to the facilities of K-C and its suppliers.

Table 2.9 Fiber Pulping Data Quality Indicators

Process	**Data Source Type**	**Data Quality**
Energy, chemical inputs, efficiency		
Arundo donax	K-C	3,1,1,1,1,3
Kenaf	K-C	2,1,1,1,1,2
Wheat Straw	K-C	2,1,1,1,1,2
Recycled Fiber	K-C	1,1,1,1,1,2
Bamboo	K-C	2,5,2,5,3,3
Northern Softwood	K-C	1,4,2,1,1,2
Water, air, solid waste emissions		
Arundo donax	K-C	2,5,2,2,3,3
Kenaf	K-C	2,5,2,2,3,3
Wheat Straw	K-C	2,5,2,2,3,3
Recycled Fiber	K-C	2,5,4,2,3,3
Bamboo	K-C	2,5,3,5,3,3
Northern Softwood	K-C	1,4,2,1,1,2

In addition to the direct evaluation of the quality of the data, addressed above, we consider the implications of the system boundary on the completeness of the data. For agriculture, chemicals, energy, and transportation we make use of ecoinvent databases that include background data on infrastructure construction and maintenance. However, we model the pulp production facilities directly, and as a result the background inventory of the pulp mill infrastructure is not included. We test for the cut-off criteria implied by this system boundary choice through examination of an economic input-output lifecycle assessment model for the US pulp mill sector. This model of the entire pulp sector does not have the resolution for the detailed modeling of alternative fibers, but can provide information about the scale of activities across industrial sectors. Table 2.10 shows the energy use of the top contributors to the US pulp mill sector, using the CMU Green Design Institute's EIOLCA model for 2002. As a proxy for the building of pulp mill infrastructure, we consider the iron and steel mill input to the pulp mill sector. The table shows that iron and steel mill activities comprise 0.2% of the energy inventory of pulp mill activity. While the energy and other inventory implications of producing the specific pulp mills studied here could be more or less than 0.2%, we take the low value as a basis not to further expand the system boundary to include pulp mill production. All of the other industrial sectors represented in Table 2.10 are explicitly included in our analysis.

Economic Sector	Energy inventory (%)	Cradle to Gate Inventory (%)
Pulp mills	68.8	80.8
Paper mills	10.6	-
Power generation and supply	7.2	8.4
Paperboard mills	4.3	-
Other basic organic chemical manufacturing	1.1	1.2
Alkalies and chlorine manufacturing	0.7	0.8
Petroleum refineries	0.7	0.8
Sawmills and wood preservation	0.7	0.8
Truck transportation	0.6	0.8
Oil and gas extraction	0.6	0.7
All other basic inorganic chemical manufacturing	0.5	0.6
Pipeline transportation	0.4	0.5
Rail transportation	0.4	0.4
Wet corn milling	0.3	0.3
Logging	0.2	0.3
Plastics material and resin manufacturing	0.2	0.3
Iron and steel mills	0.2	0.2
Petrochemical manufacturing	0.2	0.2
Fertilizer Manufacturing	0.1	0.2
Cradle-to-gate percent represented		97.2
Total percent represented	97.6	

Table 2.10 Percentage of energy consumption across all sectors of the US economy induced by economic activity in the pulp mill sector. Table shows top 19 sectors. Data from CMU Green Design Institute (2012).

Chapter 3: Life Cycle Inventory and Midpoint Assessment Results

Results are presented for each environmental category. The focus is mainly on midpoint indicators; these are measures for a single category, such as total fossil fuel use, total greenhouse gas emissions, or freshwater eutrophication potential in terms of nitrogen released. The greatest level of detail is provided for water, climate, and biodiversity. Endpoint indicators are also discussed and evaluated; these are indicators of human health impact, ecosystem impact, or resource depletion.

3.1 Uncertainty Analysis and Sensitivity Analysis

There is uncertainty in the assessment of both the current fiber production systems and in the future alternative systems. This reflects both variability – different farmers, different forest management practices and different pulp mill practices can lead somewhat different environmental impacts – and it also reflects uncertainty in the overall inventory of current and future alternative systems.

To address uncertainty in the data, we use the data quality analysis as input into a probabilistic uncertainty analysis. We assign uncertainty ranges to the data quality scores, assuming a log-normal distribution, and we carry out a Monte Carlo statistical analysis of these uncertainties (Goedkoop 2012). We show the results of this uncertainty analysis as error bars on all of our results; these error bars show the 95% confidence interval for a geometric standard distribution.

We also address the sensitivity of the results to the baseline assumptions. These include different assumptions about the yield of fiber in the forest and agricultural systems, and different assumptions about allocation between kenaf bast and core, and wheat grain and wheat straw. The sensitivity of the result to these different situations are analyzed and presented as separate comparative analyses.

3.2 Energy and Fossil Fuel Depletion

Figure 3.1 shows the total fossil energy use for production of one air-dried ton of pulp. This includes all electricity use, all inputs of natural gas and fuel oil, and all use of petroleum transportation fuels, including the energy required for energy supply. The figure shows that the full pulping process, including both facility energy use and the energy used to manufacture and transport the chemicals used in pulping, is generally the lifecycle stage responsible for most of the fossil energy use. Transportation is significant for the northern softwood pulp because in this scenario it is transported, by train, from Canada to the tissue production plant in the southeast US.

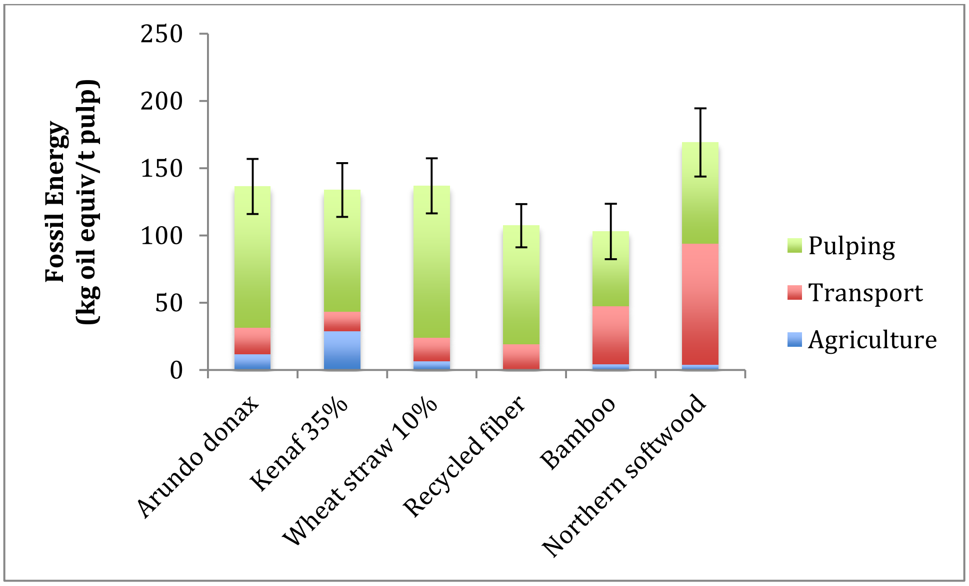

Figure 3.1 Total fossil energy use for production of one ton of pulp, with the baseline allocations for kenaf and wheat straw (kg oil equivalent per ton pulp)

Figure 3.2 shows total fossil energy with different allocations for kenaf and wheat straw; this would apply to a situation in which there was no market for the kenaf core material and in which wheat straw provided a larger percentage of the overall profit to farmers from growing wheat. In comparison with Figure 3.1, this allocation increases the agricultural portion of the energy for producing kenaf and wheat.

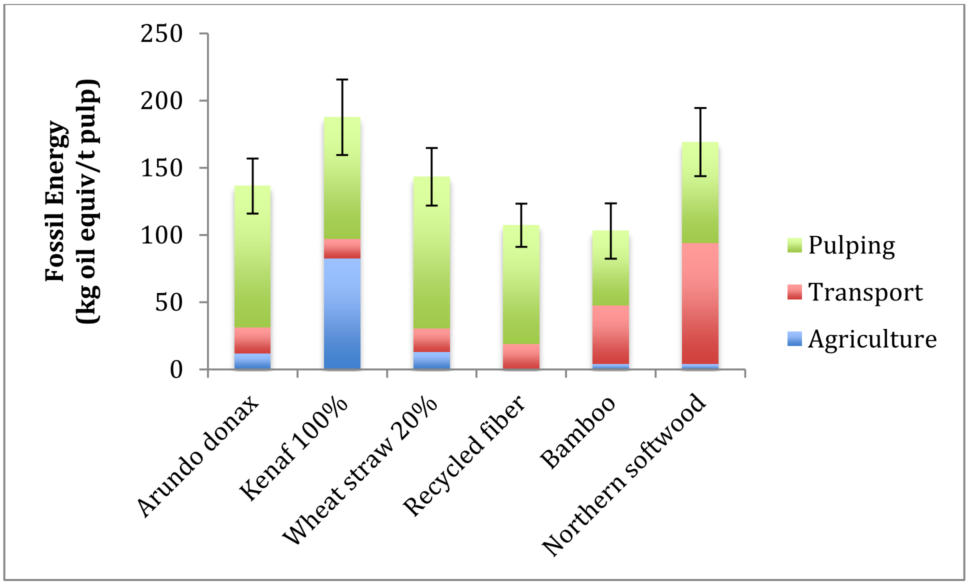

Figure 3.2 Total fossil energy use for production of one ton of pulp, with alternative allocations for kenaf and wheat straw (kg oil equivalent per ton pulp)

There could be situations in which the alternative pulps – *Arundo donax*, kenaf, wheat straw, and bamboo – could be pulped in facilities at which much less biomass was available for energy production. While the [LOCATION REMOVED] K-C U.S. mill at which the mechanical pulping would occur is an integrated mill with substantial biomass use in electricity production, in another situation, less biomass might be available so more fossil fuel might be used in pulping.

3.3 Water Depletion

Water use in the lifecycle of pulp production includes the water used to grow the trees or fiber plants, the water used for pulp production, the water used for external electricity production, and the water used for production of any chemical, fuels or other inputs. Current practice in environmental lifecycle assessment excludes consideration of water consumed by plants from precipitation or soil moisture, and focuses on water that is consumed – that is, removed from the watershed – as opposed to water that is withdrawn – taken for use and subsequently returned to the watershed.

Most plants considered as fiber sources for pulp and paper production are not irrigated. They draw their water from precipitation and from the soil, and the water required for growth of the plants is generally not considered in environmental lifecycle assessment. Nevertheless, there could be ecosystem impacts of growing plants with high water demand, and water requirements could potentially require irrigation in drought years or adversely affect yield or viability of some fiber options. For example, in Japan there has been speculation that the replacement of coniferous and broadleaved forests by bamboo could change the vegetation water cycle and affect water resources (Komatsu et al. 2010). In the US state of California, the high evapotranspiration of *Arundo donax* has raised concern about its impact on water resources.

Figure 3.3 shows evapotranspiration characteristics of the fibers. Evapotranspiration varies by location; the *Arundo donax* (Hendrickson and McGaugh 2005), kenaf (Banũelos et al. 2002), wheat (Mitchell 2001), bamboo, and loblolly pine values are for the US southeast. Although loblolly pine is not one of the fiber sources considered here, bamboo might be grown on land currently used for loblolly pine and so it is shown for comparison. The value for bamboo is from a study from Japan that compared coniferous forests and bamboo; the bamboo value shown in Figure 3.4 is estimated by scaling the coniferous forest values from the Japanese study to the loblolly pine values for the US southeast. The value for *Arundo donax* is highly uncertain and is drawn from the gray literature; studies and field experience indicate that *Arundo donax* does indeed have a high evapotranspiration value; it does however grow well in dry conditions; there is no report of *Arundo donax* ever needing irrigation. The value for Canadian central boreal forest does not have any direct comparative meaning *vis-a-vis* the US southeast values, but is shown for completeness.

Overall, Figure 3.3 indicates that evapotranspiration of *Arundo donax* may be high and warrants further investigation, and that the water requirements of kenaf, wheat, bamboo, and loblolly pine are similar. Evapotranspiration in the central Canadian boreal forest is considerably lower than that of the forests and croplands of the US southeast; however given the significant difference in these locations no implication should be drawn. The comparison here does not take into account the yield differences of the different fiber sources; the comparison is shown here without scaling by yield to emphasize the hydrological implications.

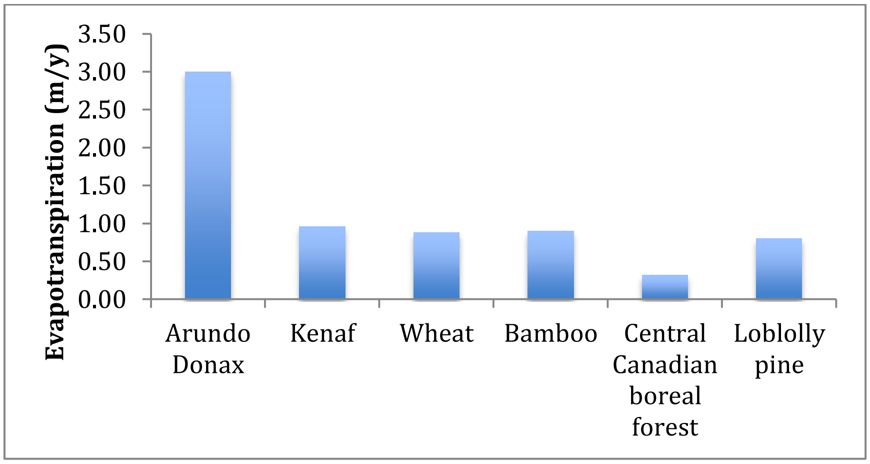

Figure 3.3 Evapotranspiration of land planted in each fiber. The value for *Arundo donax* is highly uncertain; although its evapotranspiration is always reported as high, its deep roots allow it to grow well without irrigation.

A midpoint, screening-level indicator is water deprivation, which can be characterized by a water stress index (Pfister et al. 2009), that takes into account that water is more scarce in some regions than in others. The water stress index is a value between 0 and 1, with 0.5 the threshold between moderate and severe water stress; the minimum value is set at 0.01 for low water stress and 1 representing high water stress. Water stress can occur at the locations in which the fibers are grown, and the locations of the mills in which the fibers might be pulped. Table 3.1 shows the water stress index for the location of the pulp mill in [LOCATION REMOVED], where the pulping of *Arundo donax*, wheat straw, kenaf and recycled fiber is modeled; wheat straw might also be sourced from nearby farms. The table also shows the water stress index from two different areas of Canada where northern softwood grows and is pulped. The table also shows the water stress index for locations where *Arundo donax* and kenaf might be grown. Also shown are the water stress indices for the locations of two other K-C mills, in [LOCATIONS REMOVED]; these pulp mill sites are shown for illustrative purposes only and are not modeled as pulping locations in this analysis. All locations shown in Table 3.1 have low water stress indices. There are, however, locations in the US with very high water stress indices; these include [LOCATIONS REMOVED].

Table 3.1. Water Stress Index for Fiber-Relevant Locations

Location	**Potential Activity**	**Water Stress Index**
[LOCATION REMOVED]	Pulp mill location and possible wheat production site	0.016
[LOCATION REMOVED]	Northern softwood production and pulping	0.015
[LOCATION REMOVED]	Northern softwood production and pulping	0.010
[LOCATION REMOVED]	Possible *Arundo donax* production site	0.022
[LOCATION REMOVED]	Possible kenaf production site	0.016
[LOCATION REMOVED]	Pulp mill location	0.025
[LOCATION REMOVED]	Pulp mill location	0.025

Multiplying the water stress index values by the location-specific water consumption per ton of pulp provides a water deprivation value per ton of pulp, as shown in Figure 3.4. Since the irrigation water dominates water consumption, the water depletion midpoint indicator again shows irrigation of kenaf as the dominant water impact.

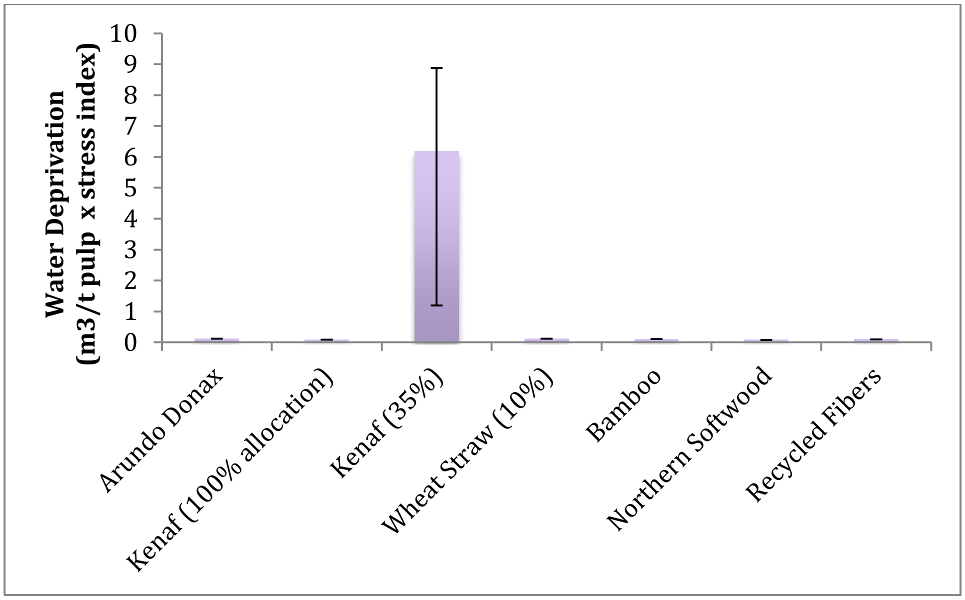

Figure 3.4 Water deprivation values based on the water stress index at the locations of fiber production and pulp production. Water used in production of the chemicals used in pulping is not included. The kenaf error bar indicates uncertainty in the portion of irrigation water lost from the watershed.

3.4 Land Occupation and Natural Land Transformation

The production of fiber involves use of agricultural or forest land for fiber production. The specific characteristics of the land used for each fiber will differ, and the overall environmental impacts of the land use will differ, but at the midpoint level all these land uses are evaluated in terms of area used. In lifecycle assessment methodology, land occupation and land transformation are often distinguished, and the time scale of the activity is also often included in the assessment. In the fiber production systems considered in this study, there is some room for interpretation regarding the extent to which land is being occupied versus transformed, and for how long. For *Arundo donax*, kenaf and wheat straw production, the agricultural activities fall clearly within the category of agricultural land occupation, although *Arundo donax* and kenaf could be produced entirely or primarily for fiber whereas wheat straw is a necessary residue of wheat grain production. For bamboo production, the baseline scenario is that managed plantation forest land would be used; however since bamboo is also a type of plantation we consider this to be land occupation as well, as opposed to land transformation. For northern softwood production, from a large-scale forestry perspective the land is in continued use even though there is abrupt land use change for the areas that are harvested each year. Moreover, some of the northern softwood harvesting is in areas that have not been previously logged, whereas other northern softwood harvesting is in areas that have been previously logged. Although in a more site-specific analysis some areas and practices of northern softwood harvesting might be classified as land transformation and other areas and practices of northern softwood harvesting might be classified as land occupation, in this analysis we categorize all of the northern softwood harvesting. Here we evaluate all the land used to produce fiber on an area basis, in terms of the functional unit of one ton of pulp; this implicitly includes the time required for each type of fiber to grow.

Figure 3.5 shows the land required for production of one ton of pulp, incorporating both the amount of land needed to produce a ton of fiber, and the amount of fiber needed to produce a ton of pulp. The figure shows that more land is affected by production of a ton of northern softwood Kraft pulp than by production of any of the other fibers. In the figure, kenaf is allocated between bast (35%) and core, and wheat is allocated between wheat straw (10%) and wheat grain. For northern softwood, 70 or more years are need for forest to regenerate after it is logged; the value shown is the amount of land needed for sustained on-going production of northern softwood.

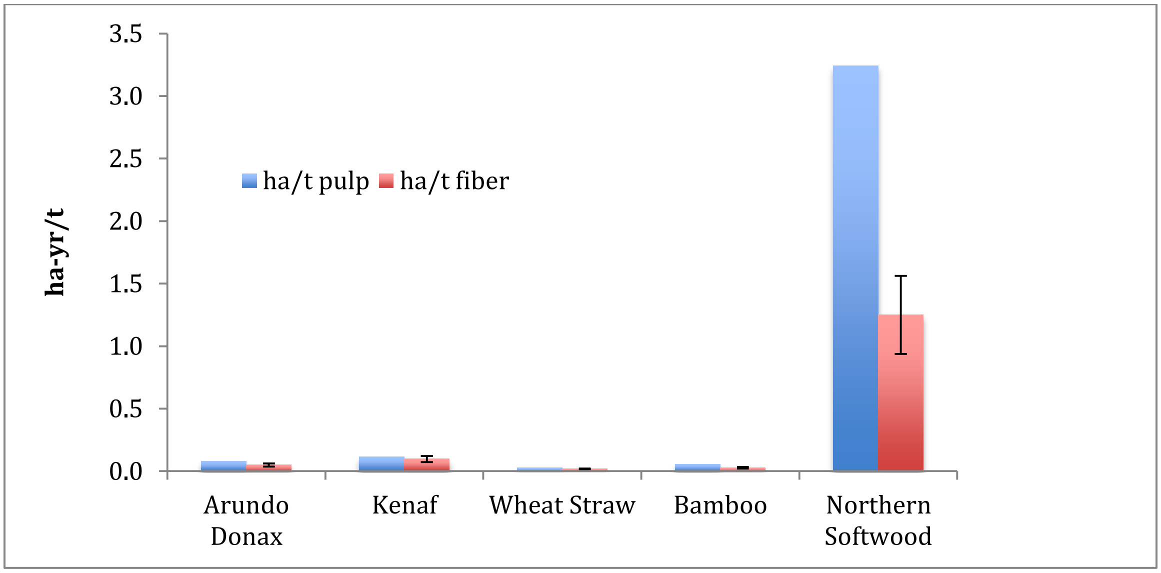

Figure 3.5.a Land occupation for production of one ton of pulp (blue) and fiber (red).

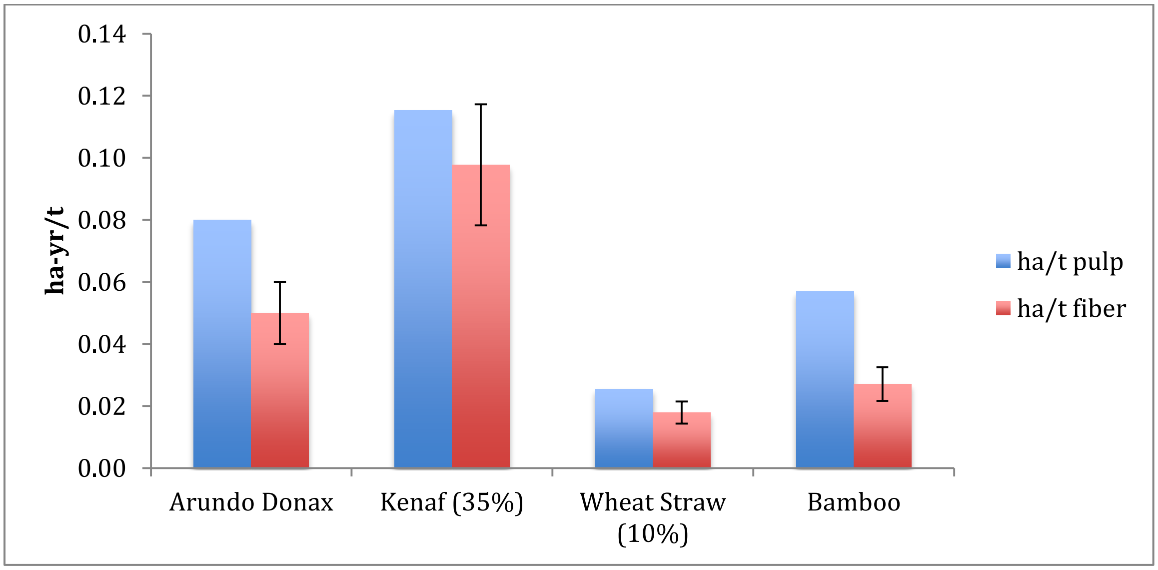

Figure 3.5.b Land occupation for production of one ton of pulp (blue) and fiber (red), excluding northern softwood.

Figures 3.5.a and 3.5.b show that production of pulp from northern softwood requires much more land than production of pulp from the other fibers. In this presentation the allocation between kenaf bast and kenaf core, and the allocation between wheat straw and wheat grain, is taken into account.

In addition to the land used directly for fiber production, land is also used for roads, the pulp mill, and other infrastructure. These values are included in the ecoinvent background data used in this study; they comprise much less than 1% of the land used and are therefore not considered further.

Land use is associated with a number of environmental impacts, including changes in soil carbon that are part of the lifecycle climate change impacts, effects on biodiversity, and effects on soil quality. These are addressed in the following sections. Also, yields of each fiber, and the allocation choices, affect the evaluation of land use and the environmental impacts that are associated with land use. These are discussed in more detail in the following sections, with uncertainty and variability emphasized where the effects are relatively large.

3.5 Climate Change

Greenhouse gas emissions attributable to fiber and paper production include the carbon dioxide emitted from use of fossil fuels throughout the product lifecycle, the emissions of nitrous oxide (N_2O) from soils, and any emissions of methane (CH_4) and other greenhouse gases. In addition, the harvesting of feedstocks can increase or decrease the amount of carbon stored in biomass above ground, below ground and in soil.

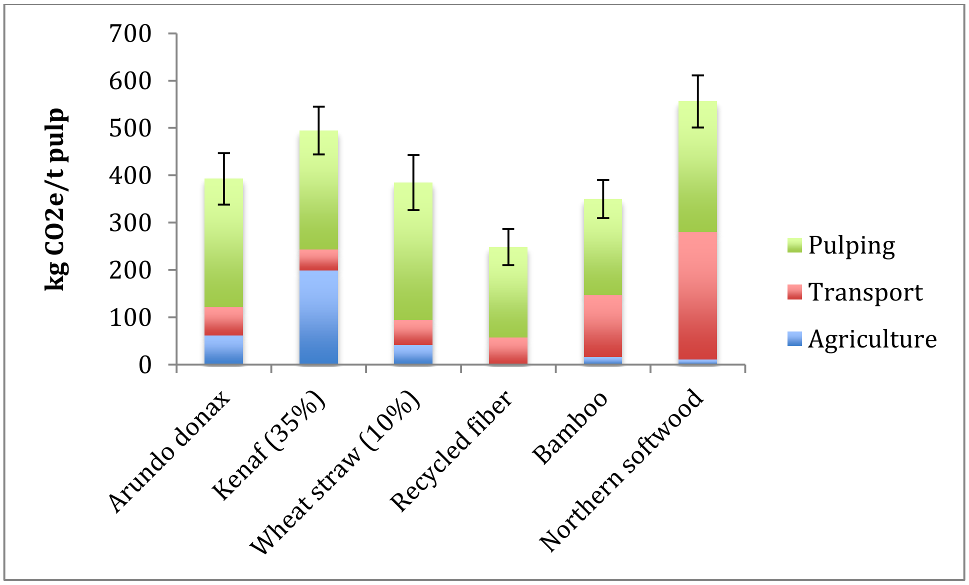

Figure 3.6 Greenhouse gas emissions from fossil fuel and chemical inputs in the production of pulp.

Figure 3.6, showing only the emissions from fossil fuel combustion and from use of nitrogen fertilizers, shows that pulping operations are responsible for most of the greenhouse gas emissions in pulp production. Northern softwood pulp is shown as having larger emissions than bamboo. There are two reasons for this: first, the northern pulp mill modeled here uses petroleum fuel oil as the main fossil fuel input, while the bamboo pulp process is projected to use natural gas, which has a lower greenhouse gas emission. Second, the northern pulp is modeled as being transported from Canada to the southeast of the U.S., whereas the bamboo is assumed to be grown and pulped closer to the paper mill. If the Kraft pulp mills used for northern softwood had the same energy sources and the same energy efficiency, the greenhouse gas emissions from each would be basically the same. Further, as can be seen in the figure, Kraft pulping of bamboo can have lower greenhouse gas emissions than the mechanical pulping of the other alternative fibers.

Figure 3.6 is not a complete evaluation of the climate change impacts of the fibers, because it does not include the release of biogenic carbon – carbon stored in trees, crops, and soils – due to the harvesting of any of the fibers. Calculation of greenhouse gas emissions from carbon stored in trees and soils involves consideration of carbon sources and sinks (EPN 2012). These emissions are calculated below.

Biogenic carbon emissions from northern softwood pulp

Northern softwood pulp comes from across Canada, and includes some areas in which forests have been repeatedly logged, as in Nova Scotia, and other areas in which forests may not have been previously logged. The details of biogenic carbon emissions can vary with location and forest management practices. Here the goal is to characterize a typical magnitude for biogenic carbon loss from northern softwood pulp; future research could refine this estimate for particular locations, sources, and logging practices. As discussed in Chapter 2, the baseline assumption is harvesting of 70-year-old spruce trees, with an input of 2.6 dry tons of wood chips per ton of pulp produced, as well as 0.817 dry tons of biomass used as fuel, for a total of 3.4 tons of dry biomass per ton of pulp. With an average softwood carbon content of 0.53 tons of carbon per ton of wood (Ragland et al. 1991), the total removal of carbon in harvested material is 1.8 t C/t pulp.

Loss of carbon from soil is variable and uncertain. Emissions vary by soil type and other factors. Taylor et al. (2008), in their study of eastern Canadian red spruce stands, found that carbon in soil and ground-level dead organic matter remains largely constant through the harvesting and regrowth stages, with loss of soil carbon providing roughly a 10-20% addition to the removal of biomass carbon. Accordingly we estimate the total carbon lost from harvesting to be 2.1± 0.1 t C/t of pulp, equal to 7.7 ± 0.4 t CO_2 per ton of pulp. The variance noted here includes only the soil carbon range; the additional variation and uncertainty of harvesting trees with different regeneration times and different forest management practices is also addressed in the sensitivity analysis.

Over time, the forest regrows and carbon is absorbed into the trees and the soil. The rate of regrowth can vary by location and over time; but after 70 years, there would be no net loss of carbon from the forest to the atmosphere.

Data presented in Taylor et al. (2008) on forest carbon regeneration after logging show quite a bit of scatter. Taylor et al. also show that techniques for partial cutting result in much less carbon loss than clear-cutting, as shown in Figure 3.7.

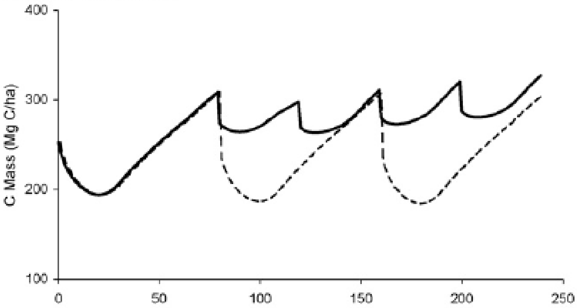

Figure 3.7 Total ecosystem carbon in eastern Canadian red spruce forests, for partial cutting (solid line) and clear-cutting (dashed line). The x-axis is in years. From Taylor et al. (2008).

Biogenic Carbon Emissions for Wheat Straw, Kenaf, Bamboo, and *Arundo donax*.

In principle, the biogenic carbon calculations for wheat straw, kenaf, *Arundo donax* and bamboo are exactly parallel to the calculation for the northern softwood. However, the time scale of regeneration of these fibers is shorter. Wheat straw and kenaf are annual plants; they have a growing cycle of one year or less. *Arundo donax* is a perennial that would be harvested annually. [CONFIDENTIAL K-C DATA]

Assuming that dry pulp and paper can be approximated as cellulose, $C_6H_{10}O_5$, each kg of pulp or paper will contain 0.44 kg of carbon, corresponding to 1.6 t CO_2.

Some plants can increase the storage of soil carbon over time. Examples include mixed prairie grasses, miscanthus, and switchgrass, all candidate bioenergy feedstocks. There is one report that bamboo grown in China has increased sequestration of carbon in soil, particularly in the first five years of growth (Yipping et al. 2010). However, there is no indication that growing *Arundo donax* or kenaf would add to soil carbon, and no quantification of the potential for bamboo to increase soil carbon. It is possible that a transition from timberland to bamboo could either reduce or increase soil carbon storage.

The excess removal of wheat straw from wheat fields can reduce long-term soil fertility and soil carbon. Here it is assumed that wheat straw will only be sourced in a manner that does not reduce soil fertility or soil carbon; this may mean that wheat straw is only sourced from wheat fields managed with no-till or reduced till cultivation, in areas with soil well suited to straw removal (US DOE 2011).

In our baseline model, we assume no soil carbon benefit or loss from these fibers; the issue is further explored through sensitivity analysis.

Timing of the release of the biogenic carbon

Some of the carbon removed in the harvesting of wood or alternative fibers is released within a short time after harvesting. In particular, when the fiber is processed at the pulp mill, the biomass that is used for process heat and electricity generation results in immediate release of carbon to the atmosphere. The forest carbon that is lost from soil and from the forest floor can be released over a period of several years after harvesting, as illustrated in Figure 3.7; here we estimate that time period to be five years for northern softwood. The carbon that is in the pulp is, obviously, not released immediately, and in consideration of a lifecycle assessment with a system boundary limited by delivery of the pulp to the paper mill gate, the carbon in the pulp has not yet been released.
However, since the timing of the release of biogenic carbon to the atmosphere has a substantial effect on the relative climate change impacts of the fibers, we extend the calculation through the disposal phase.

Of the 7.7 t CO_2 associated with the harvesting of northern softwood for pulp, 1.6 t CO_2e is in the pulp itself, 1.1 t CO_2e is released over a period of years from the soil, and 4.9 t CO_2e is released quickly through biomass combustion.

The pulp considered here could be made into a variety of products, particularly toilet tissue and commercial bathroom towels. Toilet tissue would mostly be disposed in wastewater; commercial bathroom towels would mostly be disposed to landfills although some would be disposed in municipal waste incinerators. For the purpose of exploring the potential effect of end-of-life management on the biogenic carbon, we consider here a scenario in which the paper is disposed to landfills. We expect that biogenic carbon would be released more slowly from landfills than from wastewater treatment or from incineration processes, so this scenario is expected to result in a small biogenic carbon impact than other disposal scenarios. In the landfills, some portion of the paper will decompose over time into carbon dioxide and methane, some of which may be captured and flared or used for energy production, and some fraction of which may be stored for long periods in the landfill. Different types of paper can have different degradation behavior in landfills (Barlaz 1998), which has been attributed to differing proportions of cellulose and lignin; here we assume that all fiber types have the same degradation behavior in landfills. Assuming that dry pulp and paper can be approximated as cellulose, $C_6H_{10}O_5$, each kg of pulp or paper will contain 0.44 kg of carbon, corresponding to 1.6 t CO_2; this is within ±10% of the measured carbon fraction for other types of paper in Barlaz (1998). For landfilled carbon, we follow US EPA guidance by assuming release of 7.5% of the carbon as methane, 7.5% as CO_2, and long-term storage of 85% of the carbon (ICF 2005). The methane is counted with its full standard global warming potential, without discounting for its biogenic origin.

Global warming potential of biogenic carbon emissions.

The cycling of biogenic carbon can be considered to be shorter than the cycling of carbon emitted from fossil fuel combustion, because as the trees and other fiber plants grow to replace the harvested fiber, they will absorb carbon dioxide from the atmosphere. A number of approaches to quantifying the global warming potential of biogenic carbon have been developed (Manomet 2010, Offsetters 2012). Here we use a global warming potential for biogenic carbon, as discussed below.

There is a well-established methodology for accounting for greenhouse gases with different atmospheric lifetimes; global warming potentials have been calculated for different greenhouse gases, such as N_2O and CH_4, taking into account that their atmospheric lifetimes and radiative forcing characteristics are different from CO_2. The global warming potential of biogenic carbon can be calculated in the same way, by taking into account the shorter residence time of biogenic carbon in the atmosphere (Cherubini et al. 2011). Guest et al. (2012) provide a useful reference in which the biogenic global warming potential for biomass is calculated for biomass with rotational times ranging from 0 to 100 years; relevant values are shown in Table 3.2. The table shows that the global warming potentials for biogenic carbon are less than for standard CO_2. The largest value in the table is the global warming potential for northern softwood in the 100-year time horizon; the value of 0.29 means that biogenic carbon dioxide from northern softwood can be counted as having 29% of the global warming impact of a similar quantity of carbon dioxide released from fossil fuel combustion. Bamboo, with a regeneration time of three years, has a much smaller global warming potential in the 100-year time horizon; the value of 0.01 means that carbon dioxide released from harvest of bamboo can be considered as having 1% of the global warming impact of release of the same amount of carbon dioxide from fossil fuel combustion.

Table 3.2 Global warming potentials of biogenic carbon for time horizons of 100 and 500 years. Values shown are for biomass with regeneration times of 70 years, 3 years and 1 year, corresponding to northern softwood, bamboo and kenaf, wheat straw and *Arundo donax*. Data from Guest et al. (2012).

	time horizon	CO_2	northern softwood	bamboo	kenaf, wheat straw, arundo donax
lifetime (regeneration years)			70	3	1
global warming potential	100 500	1 1	0.29 0.054	0.01 0.005	0.00 0.003

Of the carbon that is released from or harvested from the forests, some will be released nearly immediately during the process of pulp production which includes combustion of biomass for process heat and electricity, some will be released from the harvested forest soil over a period of several years, some of the carbon becomes the main ingredient of the pulp which is processed into paper. At end of life, some of the paper – particularly toilet tissue – will be disposed in wastewater, and some – particularly bathroom towels – will be disposed in landfills or in waste combustion facilities. At the waste disposal facility, some of the carbon will be emitted over time as carbon dioxide, some may be emitted over time as methane (CH_4) and some may be sequestered essentially permanently in landfills. The amounts of methane released and carbon sequestered will depend on landfill gas management and the full range of product use and waste management practices, we use the US EPA LMOP (Landfill Methane Outreach Program) model for these estimates (US EPA 2012). Even though there is substantial uncertainty in the timing of the degradation of the pulp, the uncertainty introduced due to the variation of end-of-life management is relatively moderate because most of the biogenic carbon is released within a year or so, and the biogenic carbon global warming potential varies only slowly with time, so that while sequestering carbon for decades can have a significant effect, a difference of a year or two in release time has little impact.

End-of-life impact of landfilling paper made from *Arundo donax*, kenaf, wheat straw, recycled fiber, and bamboo pulp:

Although northern softwood is the only fiber considered here that has a non-negligible biogenic global warming factor (Table 3.2), when paper made from any of the pulps considered in this study is disposed in landfills, the resulting carbon storage and methane emission are assumed to be identical. As for paper made from northern softwood pulp, for each ton of paper made from other types of pulp that is disposed to landfills at end-of-life, 85% of the carbon will remain there in long-term storage, 7.5% of the carbon will be emitted as CO_2, and 7.5% of the carbon will be emitted as CH_4. In the baseline 100-year time horizon, methane has a global warming potential of 25, meaning that each ton of methane released has the same global warming impact as 25 tons of carbon dioxide. For each ton of pulp, with an assumed carbon content of 44%, complete release of all the carbon as carbon dioxide would result in 1.6 tons of CO_2; this value takes into account the mass of the carbon as well as the oxygen and is a standard way to report carbon emissions. Of this, 85% – 1.37 tons – is assumed to be sequestered in long-term storage, 7.5% is released as carbon dioxide, and 7.5% is released as methane – 44 kg of CH_4 taking into account the mass of the four hydrogen atoms as well as the carbon, which has a global warming potential of 1.1 tons CO_2-equivalent. Thus the net carbon sequestration is -0.27 tons CO_2e per ton of pulp in the 100-year time horizon.

To provide insight into the sensitivity of this result to the time horizon of the analysis, we also consider a 500-year time horizon, for which the global warming potential of methane is 7.6; this is because methane has a relatively short lifetime in the atmosphere, so its global warming potential relative to carbon dioxide is smaller over this longer time horizon. In this time horizon, the effect of the carbon remaining in the landfill is larger than the effect of the methane released, so the net global warming impact of landfilling of the pulp products is sequestration of 1.04 tons CO_2e per ton of pulp in the 500-year time horizon. We note, however, that there are no data on the behavior of landfilled paper over a 500-year period; to the extent that carbon is released from the landfill this calculation may underestimate carbon releases.

Figures 3.8.a and 3.8.b show the estimated total greenhouse gas emissions from all of the pulp alternatives, including fossil fuel combustion, use of fertilizers, and biogenic carbon emissions, using (a) the 100-year global warming potentials and (b) the 500-year global warming potentials. The figures show that in both the 100-year and 500-year time horizons, biogenic carbon emissions from northern softwood are significant. In the 100-year time frame, biogenic carbon is the largest contributor to greenhouse gas emissions; in the 500-year time frame biogenic carbon is considerably reduced, comparable to the carbon emissions from pulping or transportation.

The uncertainty in this calculation is largely due to the uncertainty in the total amount of carbon removed from the forest, and the amount of carbon sequestered.

The calculation does not include any foregone growth that would have occurred in the forest if the trees had not been harvested. The topic of foregone growth is briefly addressed in section 4.3 on the consequential assessment of use of alternative fibers for pulp production. An example scenario presented there suggests that there is substantial potential for additional carbon storage in forests with adjusted harvesting and management practices.

Figures 3.8.a and 3.8.b include the sequestration of carbon in the landfills. In general, when biogenic carbon remains in landfills, the carbon is sequestered. For biomass that grows much faster than the time horizon, the sequestration is effectively immediate. However, for biomass that grows at a rate that is not small compared to the time horizon, the sequestration effect is reduced, delayed until the corresponding amount of biomass is regenerated. For this reason, the sequestration benefit for long-lived biomass is less than that for short-lived biomass, particularly for the 100-year time horizon (Figure 3.8.a). For the 500-year time horizon the difference between the long-lived and short-lived biomass is small.

Northern softwood is assumed to regenerate in 70 years, so by 100 years all of the carbon released from harvesting northern softwood has been reabsorbed into to the forest. Nevertheless, the biogenic greenhouse gas emissions in the 100-year time horizon are large. This is because the global warming potential takes into account the time during which the biogenic carbon was in the atmosphere. Although some fossil-fuel carbon dioxide can remain in the atmosphere for centuries (Archer et al. 2009), a substantial portion of carbon dioxide is absorbed by the ocean within 100 years. Thus the 70-year time frame for northern softwood regeneration is not very short compared to the rate at which carbon dioxide is absorbed into the oceans as part of the broader carbon cycle. For this reason, the biogenic carbon dioxide emitted in the utilization of northern softwood does have a substantial effect on the overall greenhouse gas emissions total.

It is currently most common to report greenhouse gas emissions in the 100-year time frame. This choice is by convention, and is not required by the science; perhaps in the future the 500-year time horizon will be used more often. However, currently the results for the 100-year time horizon will be most appropriate for explaining the lifecycle greenhouse gas emissions of alternative fibers; this is the time-horizon generally emphasized in greenhouse gas emissions studies. In the 100-year time frame, as already noted, the biogenic greenhouse gas emissions dominate the greenhouse gas emissions for northern softwood.

The overall implication is that all of the alternative fibers have a considerably smaller global warming impact than that of northern softwood. Although there is variation among the alternative fibers in terms of energy use in pulping and use of agricultural chemicals, all of which have greenhouse gas implications, these effects are small compared to the dominant effect of use of slow-growing trees for fiber.

The exact results shown here will vary depending on the efficiency of pulp production and the regeneration time of the trees, as well as details of soil carbon fluxes which can be affected by forest management practices. Trees with a shorter regeneration time, of 30 years, for example, having a biogenic global warming potential of 0.12, would also make substantial contributions to the greenhouse gas emissions of pulp.

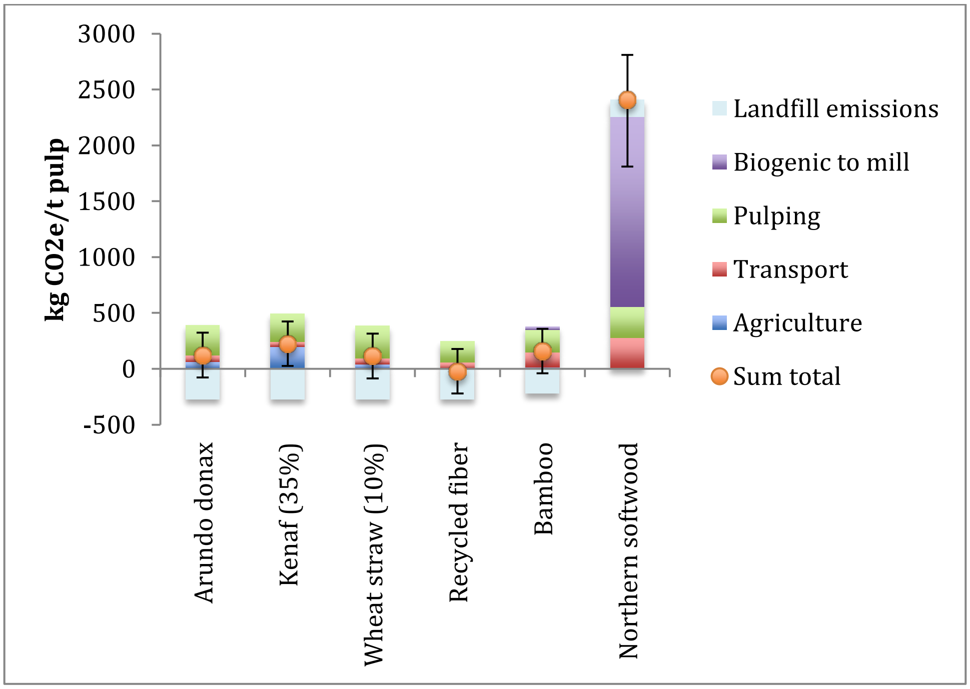

Figure 3.8.a Net greenhouse gas emissions from each fiber option under a 100-year time horizon and (b) under a 500-year time horizon.

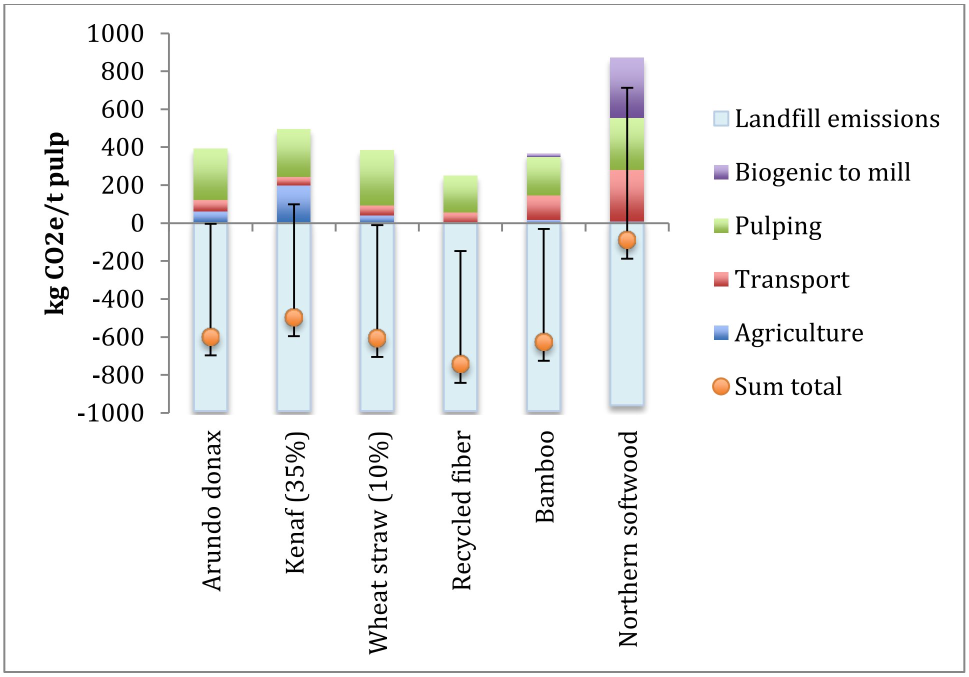

Figure 3.8.b Net greenhouse gas emissions from each fiber option under a 500-year time horizon.

3.6 Human Toxicity

Figure 3.9 shows the human toxicity potential in terms of equivalence to 1,4 dichlorobenzene (1,4-DB), which has a range of human health effects and is classified as a probable human carcinogen (US EPA 2000). These values shown result primarily from the air and water emissions from agricultural production. As discussed in chapter 2, data on emissions to air and water from the pulping process are not complete, consequently the results shown here may not fully reflect the impacts from pulping.

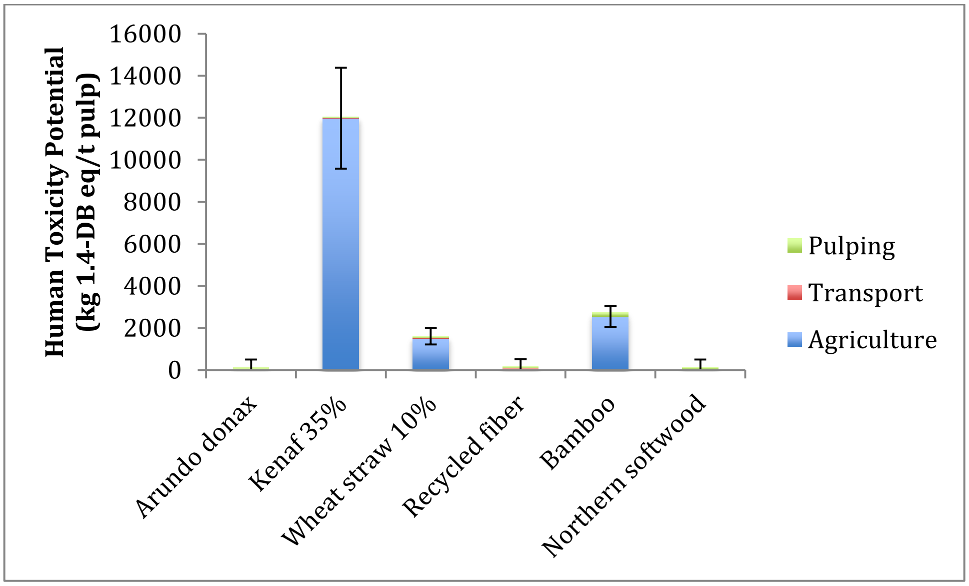

Figure 3.9 Human toxicity potential in terms of amount of 1,4 dichlorobenzene. Error bars indicate expected variation and error due to data quality characteristics.

3.7 Particulate Matter

Figure 3.10 shows particulate matter emissions per ton of pulp. The measure used here is particulate matter of diameter 10 microns or less. These emissions result from the pulping process, from electricity production, from transportation, and from agricultural processes. The relatively high value for northern softwood pulp production may reflect the relative age of the pulp mill studied, and also reflects the relative long transportation distance from the pulp mill to the paper mill. The error bars indicate variation and uncertainty due to data quality characteristics.

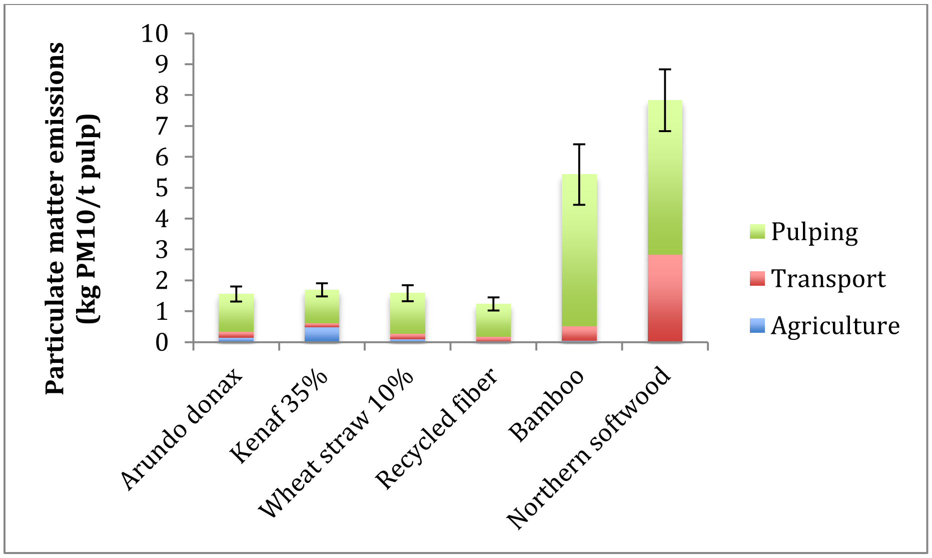

Figure 3.10 Particulate matter emissions (PM 10) per ton of pulp. Error bars indicate data quality.

3.8 Freshwater and Marine Eutrophication

Figure 3.11 shows freshwater eutrophication potential in terms of kilograms of phosphate (kg P) per ton of pulp. Kenaf has the largest use of phosphate fertilizer per ton of pulp, and correspondingly the largest freshwater eutrophication impact. There is also some phosphorus release from the pulping processes.

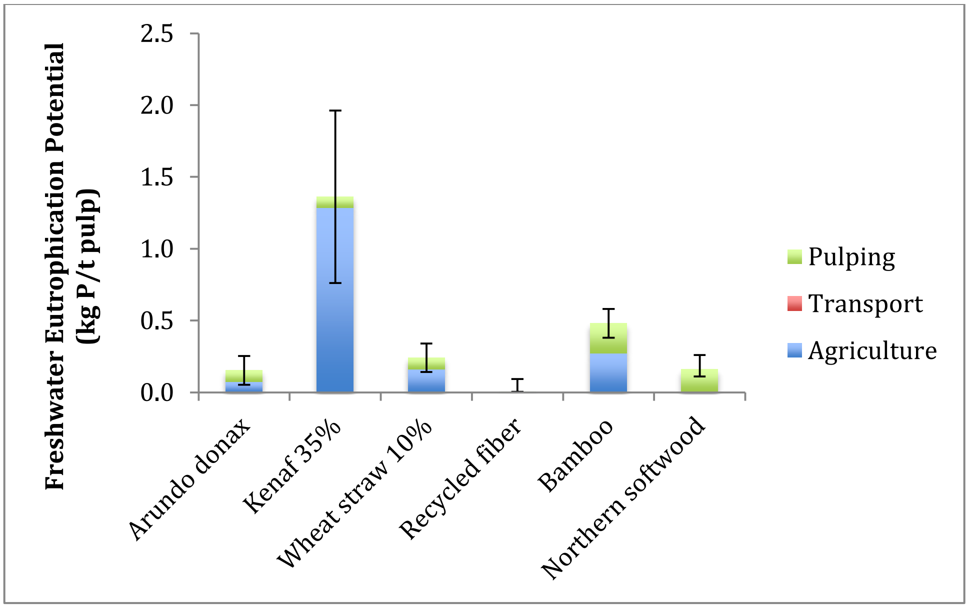

Figure 3.11 Freshwater eutrophication potential per ton of pulp (kg P/t pulp). Error bars indicate data quality uncertainty.

Figure 3.12 shows marine eutrophication potential. This potential is calculated from the amounts of nitrogen fertilizer used and leached into groundwater, as well as from the nitrogen oxides emitted from combustion processes during pulp production as well as transportation. Marine eutrophication from a combination of use of fertilizers and emission of nitrogen oxides is a significant problem in the Gulf of Mexico, the Chesapeake Bay, and other watershed outlets from agricultural regions worldwide.

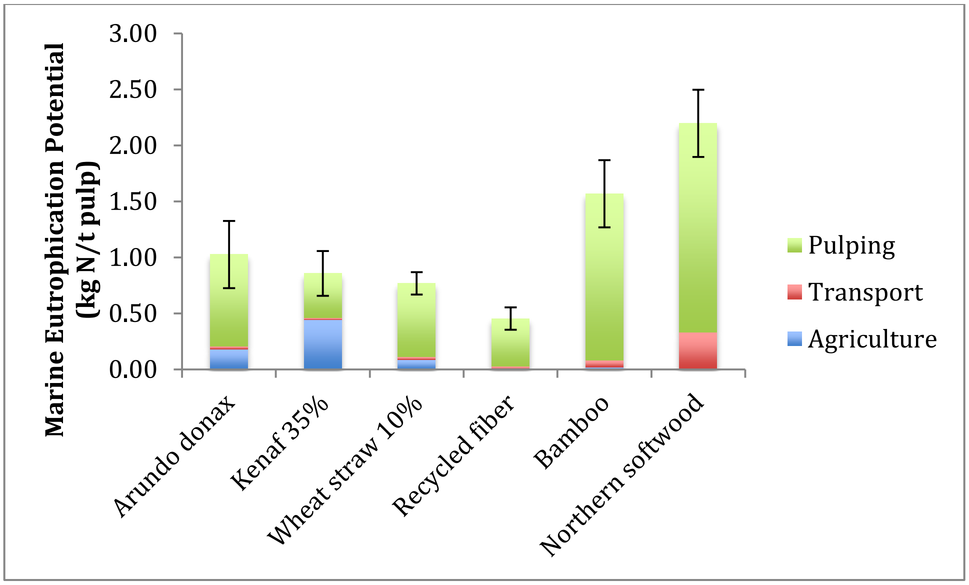

Figure 3.12 Marine eutrophication potential from nitrogen fertilizer use and nitrogen oxide emissions, as kilogram of nitrogen per ton of pulp.

The error bars in Figure 3.12 indicate the data quality characteristics.

3.9 Terrestrial, Freshwater, and Marine Toxicity

We evaluated marine, freshwater, and terrestrial ecotoxicity potentials. Figure 3.13 indicates that agriculture is responsible for most of the terrestrial ecotoxicity potential of the fibers.

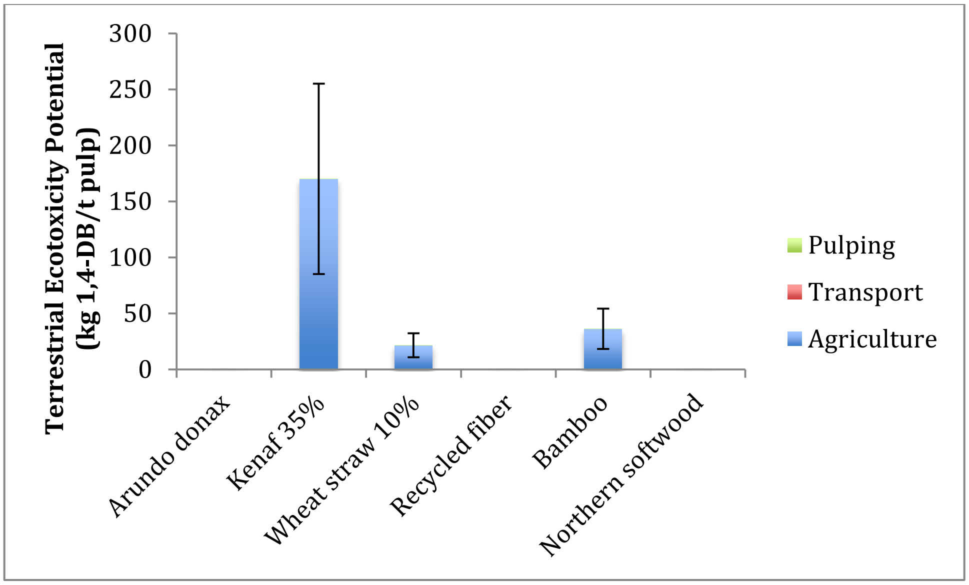

Figure 3.13 Terrestrial ecotoxicity potential for pulp production from alternative fibers (kg 1,4-dichlorobenzene per ton pulp).

Figure 3.14 shows that freshwater ecotoxicity potential stems primarily from pulping, although there are some agricultural and transportation impacts as well.

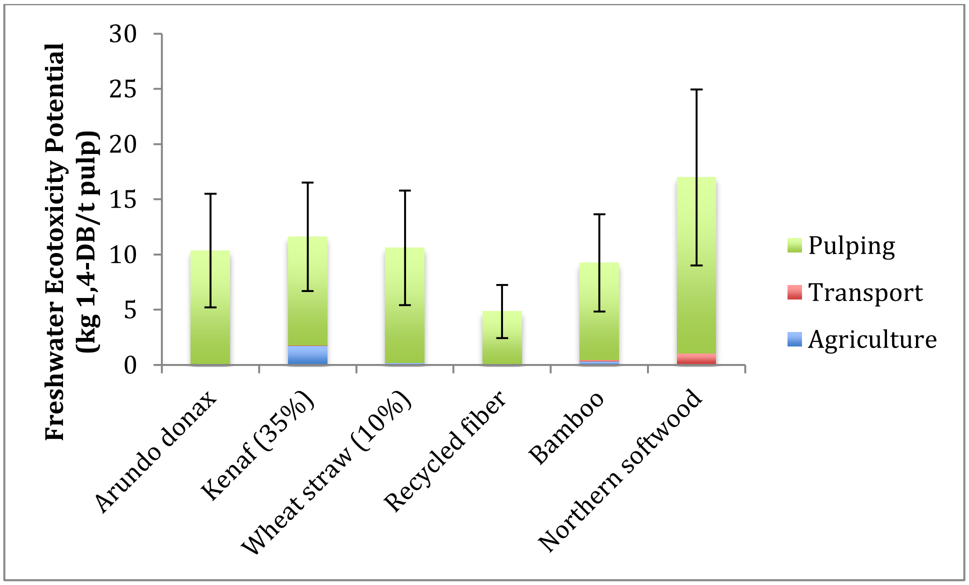

Figure 3.14 Freshwater ecotoxicity potential for pulp production from alternative fibers (kg 1,4-dichlorobenzene per ton pulp).

Figure 3.15 shows marine ecotoxicity potential has contributions from agriculture, transportation and pulping.

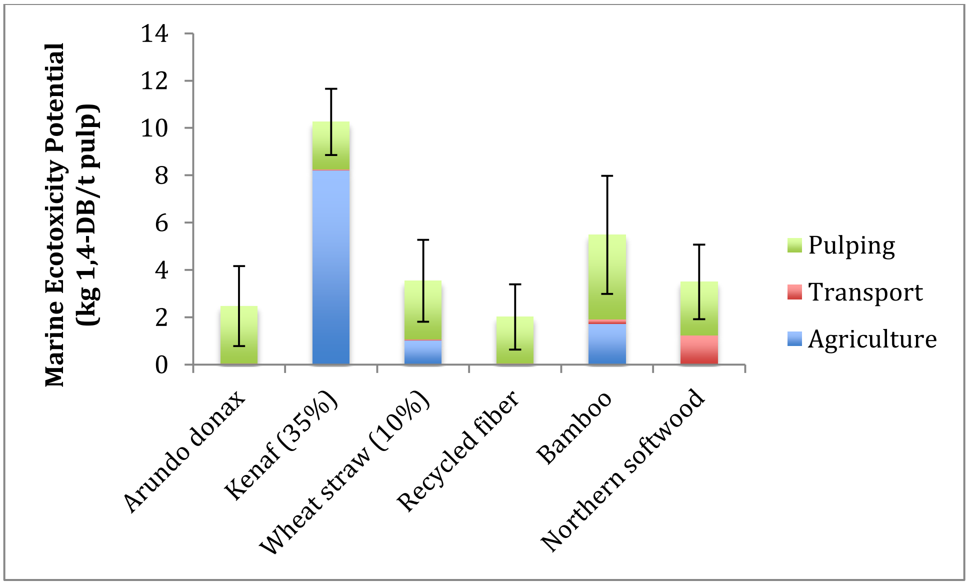

Figure 3.15 Marine ecotoxicity potential for pulp production from alternative fibers (kg 1,4-dichlorobenzene per ton pulp).

3.10 Ozone Depletion, Photochemical Oxidant Formation, Ionizing Radiation, and Mineral Resource Depletion

We also evaluated the potential impacts with respect to ozone depletion, photochemical oxidant formation, ionizing radiation, and mineral resource depletion. For each of these categories the primary inventory material flow is small to negligible and we do not show these results here. The results are provided in the appendix.

Chapter 4: Endpoint Assessment and Interpretation

4.1 Potential Endpoint Impacts on Human Health

An advantage of the endpoint indicators is the potential to compare different types of environmental impacts. However, endpoint indicators involve some uncertainty and subjectivity.[5] For this reason both midpoint and endpoint indicators are used: midpoint indicators have greater quantitative certainty in some cases and provide measures that are somewhat familiar to many stakeholders, while endpoint indicators provide one way to gauge the relative magnitude of different types of impacts.

Figure 4.1 summarizes the potential human endpoint impacts of the fibers considered. The metric of human health impact is the disability adjusted life year (DALY), a widely used measure of health impacts that can encompass both acute and chronic health conditions. The figure shows that there is a large potential climate change impact from northern softwood due to release of forest carbon. The main potential human health impacts are toxicity and climate change, with a small contribution also from release of particulate matter. The potential climate change impacts shown in Figure 4.1 include biogenic carbon release from the northern softwood. Note that the uncertainty in these values is large.

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[5] The ReCiPe impact assessment methodology is used. For impact evaluation, this method offers a choice of weightings; the default, which is termed the hierarchist perspective is used here. The explicit choice of perspective makes explicit some of the subjective choices, such as the time horizon for calculations of global warming potentials, that are often not made explicit in environmental assessments. The framework for the perspectives is discussed in Thompson et al. (1990).

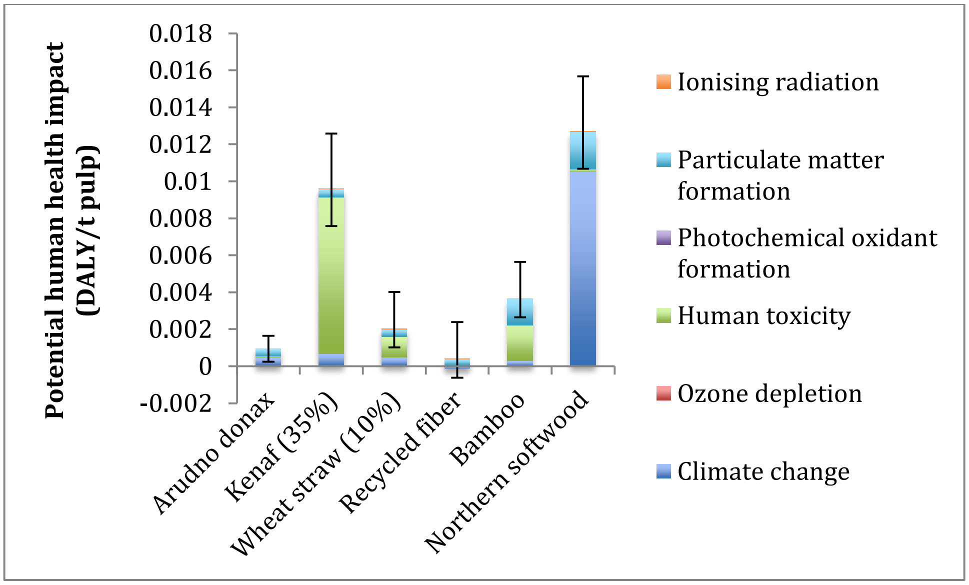


Figure 4.1 Overall potential human health impacts per ton of pulp, expressed in disability adjusted life years per ton of pulp (DALY/t pulp), for the baseline fiber parameters. The error bars indicate data quality uncertainty and variability. The perspective used here for health impact assessment is the hierarchist perspective, which uses a 100-year time horizon for climate change impact assessment.

4.2 Potential Endpoint Impacts on Species and Ecosystems

Ecosystems can be affected by land occupation, by the emission of toxic chemicals to air and water, by climate change, by water use, and by other stressors. Below we consider first the impact of land occupation on species, and the impact of climate change and terrestrial ecotoxicity on species, all within a lifecycle assessment framework. Then we broaden the discussion to consider ecosystem and biodiversity implications that may not be captured in the lifecycle assessment, to bring forward issues that could be considered and assessed as information on alternative fibers continues to develop

4.2.1 Land Occupation

The effect of human activities on the biodiversity of a landscape or region depends in complex ways on the nature and extent of the human activities and of the qualities of the biological systems. Although it is challenging to capture these effects in a lifecycle assessment, there are emerging lifecycle assessment methods to assess the potential for biodiversity impacts. Mila i Canals et al. (2010) provide a suggested framework, from the perspective of the UNEP-SETAC Life Cycle Initiative, to address land use impacts. Ongoing work to provide region-specific characterization factors could create a basis for more geographically specific analysis (Koellner 2012). Recent methodological approaches have used data on species richness in different regions and different types of land use (Schmidt 2008; DeSchryver et al. 2010; Alkemade et al. 2009). This approach is included in the ReCiPe methodology, and is illustrated here. It can be considered as a screening level assessment, which does not take into account the fine details of biodiversity and ecosystem conditions, or the details of harvesting and land management.

The end-point indicator for land occupation is the potentially disappeared fraction of species. The damage is calculated by multiplying by the area of land use, the occupation time, and by the species density.

Table 4.1 shows land use characterizations used (Goedkoop 2008, Table 10.7). The values characterizing the potentially disappeared fraction of species draw on data from Köllner (2001) and species count data (CS 2000), and take into account the scaling of biodiversity with area (Crawley and Harral 2001). Whereas the entire species count data include all known species, the quantitative species-area relationship factors are based on vascular plant survey data.

Table 4.1. Characterization for calculation of potential land occupation impact on species.
(Characterization factors from Goedkoop et al. 2008, Table 10.7)

Fiber	Land Type	Location	Land Use	Characterization factor 10^{-9} species m^{-2}
Arundo Donax	Perennial cropland	US SE	Extensive crops	17.8
Kenaf	Annual cropland	US SE	Intensive crops	18.4
Wheat Straw	Annual cropland	US SE	Intensive crops	18.4
Bamboo	Secondary forest	US SE	Mixed plantations	15.2
Northern Softwood	Secondary forest	Canada	Woodland	8.7

Figure 4.2 shows the endpoint evaluation for results for land occupation. Although the analysis takes into account the types of land use impacts involved in each fiber production scenario, the large difference in land use is what drives the results; that is, the large amount of land affected by northern softwood production dominates the potential ecosystem impact from land use. The figure indicates that, with the baseline land occupation values, the potential biodiversity impact of northern softwood pulp is about eight times larger than the other fibers.

Figure 4.2 also shows results for alternative land occupation values. These include a 25% increase in northern softwood yield, which could be achieved in some areas of Canada, a 20% decrease in bamboo yield, which is the bamboo yield reported in some other studies, a higher allocation for kenaf, which would be appropriate if there were no market for kenaf core co-product, and a higher allocation for wheat straw, which would be appropriate in situations with weak markets for wheat grain and relatively high prices for wheat straw. Even with the alternative yields, all in the direction of bringing potential northern softwood impacts down and alternative fiber impacts up, the potential impact of northern softwood still is several times larger than the other fibers. The error bars show the variation implied by the data quality characterization; even though the data do imply variation and uncertainty, the implied errors are small compared to the gap between northern softwood and the other fibers.

Although the land occupation of each type of fiber is fairly well characterized here, the quantitative evaluation of the potential impact on species should be interpreted with caution. The characterization factors were largely developed from European data; moreover the actual impact on species will depend on the details landscape-scale scope of disruption. The characterization of species impacts based on the area of land used may be interpreted as an indicator of potential impact; the actual impact depends on location-specific activities and circumstances.

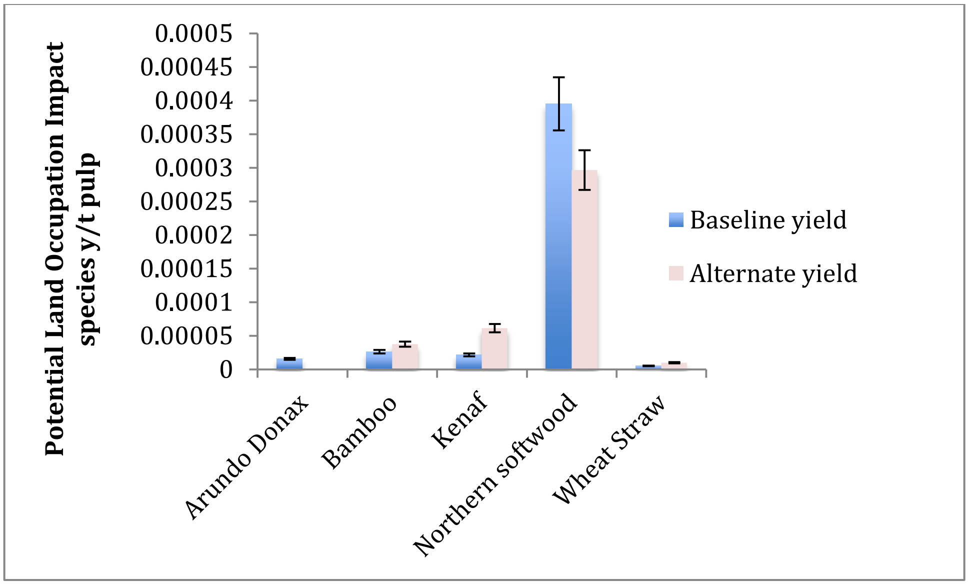


Figure 4.2. Potential land occupation endpoint impact on species. The alternate yields show the result with a 25% higher yield for northern softwood, and 50% lower yield for bamboo, alternative allocations for kenaf (100% versus 35%) and wheat straw (20% versus 10%).

4.2.2 Potential Impact on Species from Climate Change and Ecotoxicity

Figure 4.3 and 4.4 summarize ecosystem impact potentials for climate change, ecotoxicity, and land occupation. The figures show that the impact potentials of land occupation and climate change are generally larger than those of terrestrial ecosystem toxicity. We also calculated the impact potentials due to water consumption, marine ecotoxicity, and freshwater toxicity; all were much smaller than the potential impacts shown in the figures. Figure 4.3 shows the results with the baseline yield assumptions of this study. That figure shows northern softwood potential impacts to be larger than those from the other fibers. Figure 4.4, with the same alternate yield assumptions used previously, shows that even with the alternate yield assumptions, northern softwood still has higher ecosystem impact potential, although the difference is less pronounced than in Figure 4.3. Land occupation is the dominant contributor for northern softwood; for the other fibers, the climate change impacts of fossil fuel are also important. And for fibers with substantial herbicide use, notably kenaf as modeled here, the potential ecotoxicity impacts are of a similar magnitude as the climate and land occupation impact potentials.

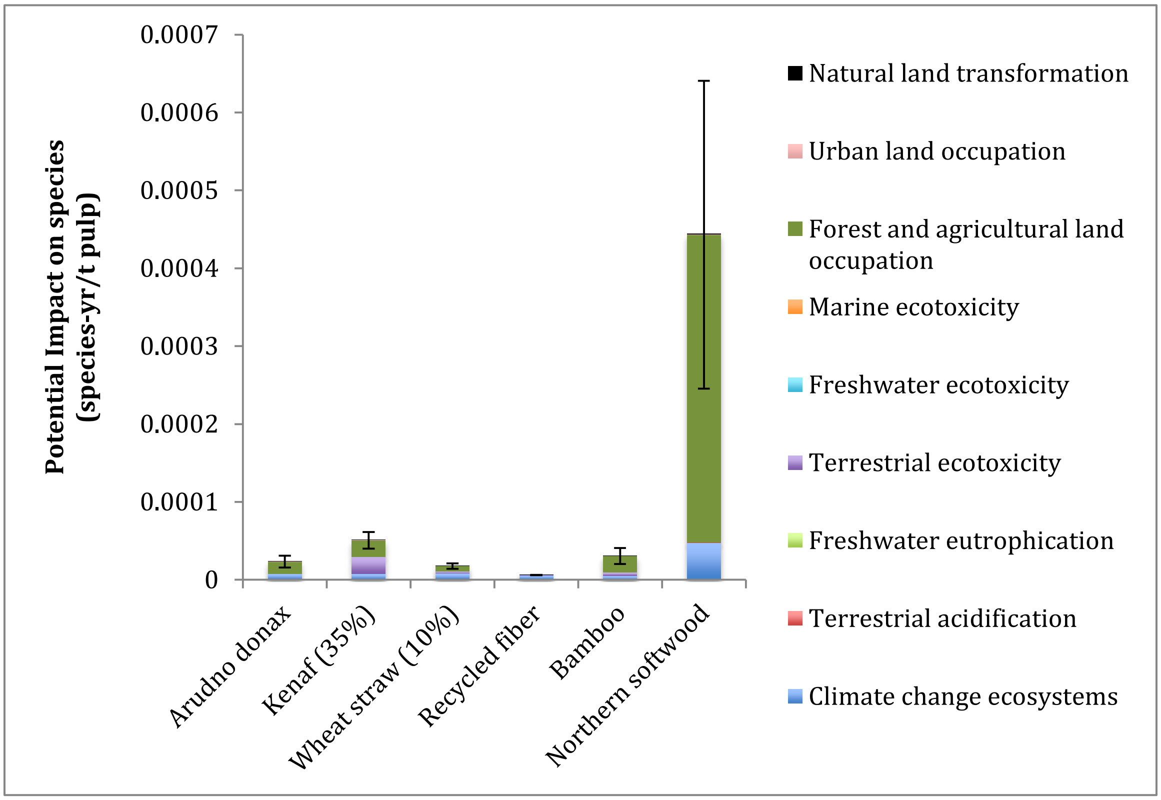


Figure 4.3 Potential impacts on species, for the baseline yield and allocation value of this study.

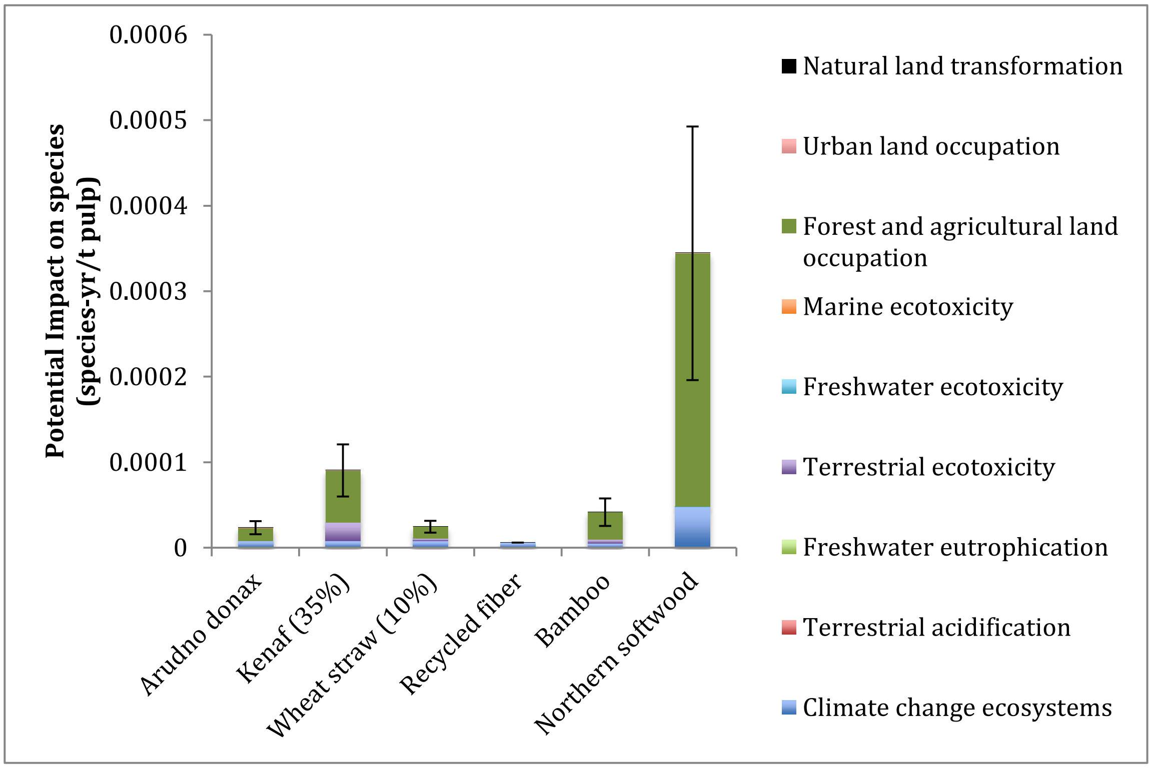


Figure 4.4 Potential impacts on species, for the alternate yield and allocation values considered: 25% higher yield for northern softwood, 50% lower yield for bamboo, alternative allocations for kenaf (100% versus 35%) and wheat straw (20% versus 10%).

4.2.3 Broader Consideration of Ecosystem Impacts

An alternative to the LCA land use impacts approach is to use a site-specific method. For example, at the local and regional scale, a spatially explicit modeling tool, Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) has been used to evaluate the ecosystem services consequences of alternate land use decisions. Through a site-specific approach, carbon balance, water quality, water purification, biodiversity, flood control, sediment retention, soil nutrient cycling and habitat risk can be assessed (Tallis and Polasky 2009). Goldstein et al. (2012) used InVEST to evaluate ecosystem service tradeoffs of land use decisions in Hawaii. This approach has not been implemented here; in our assessment the fibers could be produced in any number of specific locations, with different impacts on ecosystem services. For example, northern softwood is sourced from a number of pulp mills across Canada, using both boreal and non-boreal softwood, with each harvesting from a number of locations. In future studies, a site-specific ecosystem services assessment might be applied to sites for a range of fibers; this could provide insight into the consequences of alternative sourcing options.

In addition to direct land use impacts there are other biodiversity and ecosystem issues that might be relevant. In particular, both bamboo and *Arundo donax* have been identified as potentially invasive (Buckingham et al. 2001; Hendrickson and McGaugh 2005); invasive species can crowd out native species. The potential impact of invasiveness has not been quantified or characterized in this analysis, although the herbicides included in agricultural production provide one approach to management of invasiveness.

The activities of forest products companies and environmental organizations indicate that biodiversity is a significant concern in the northern forests; in the absence of more analytical data, their activities also provide some indication of actions that could reduce ecosystem impacts. The member companies of the Forest Products Association of Canada have entered into an agreement with environmental organizations, the Canadian Boreal Forest Agreement, for protection and management of the Boreal forest of Canada. An early component of the Agreement is suspension of logging on nearly 29 million hectares of Boreal Forest, representing virtually all the boreal caribou habitat within company tenures. Another component is the suspension, by participating environmental organizations, of divestment and “do not buy” campaigns targeting the Boreal operations and products of companies participating in the Canadian Boreal Forest Agreement (CBFA 2012). Figure 4.5 shows the Canadian boreal forest agreement areas, and Figure 4.6 shows caribou ranges and soil carbon values. However, it should be noted that the caribou action plans and protected area plans for the CBFA have not yet been completed, and there are proposals to continue harvesting in the CBFA areas; the effect of the CBFA would need to be evaluated after there is a record of implementation.

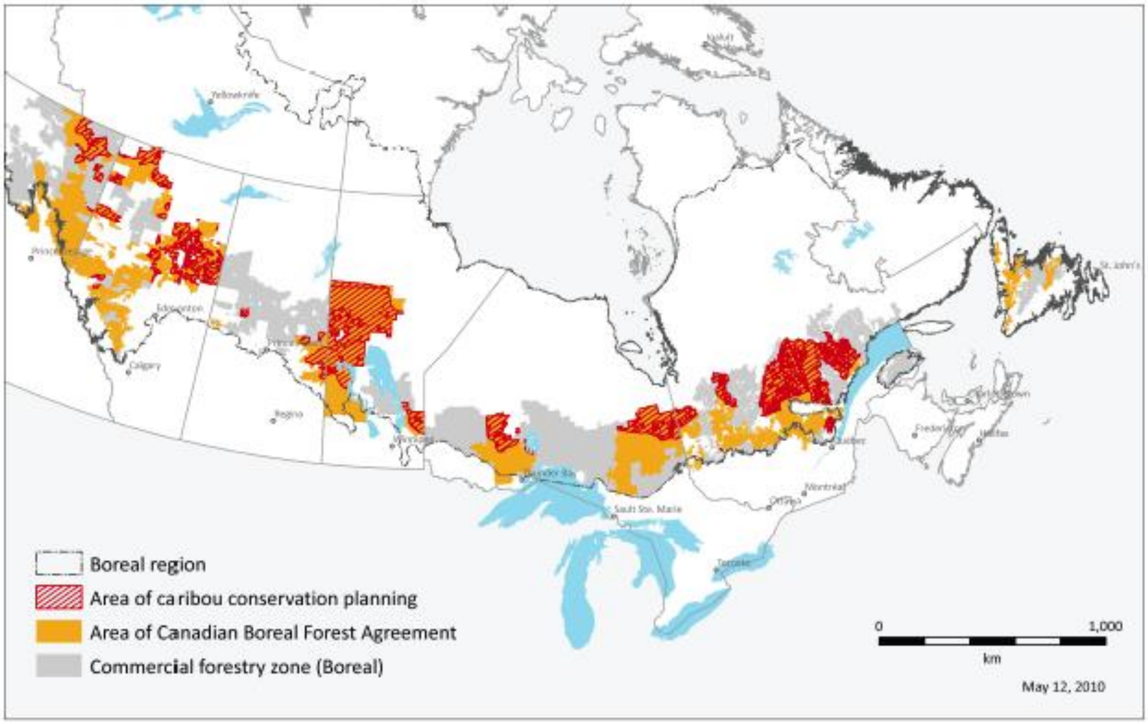
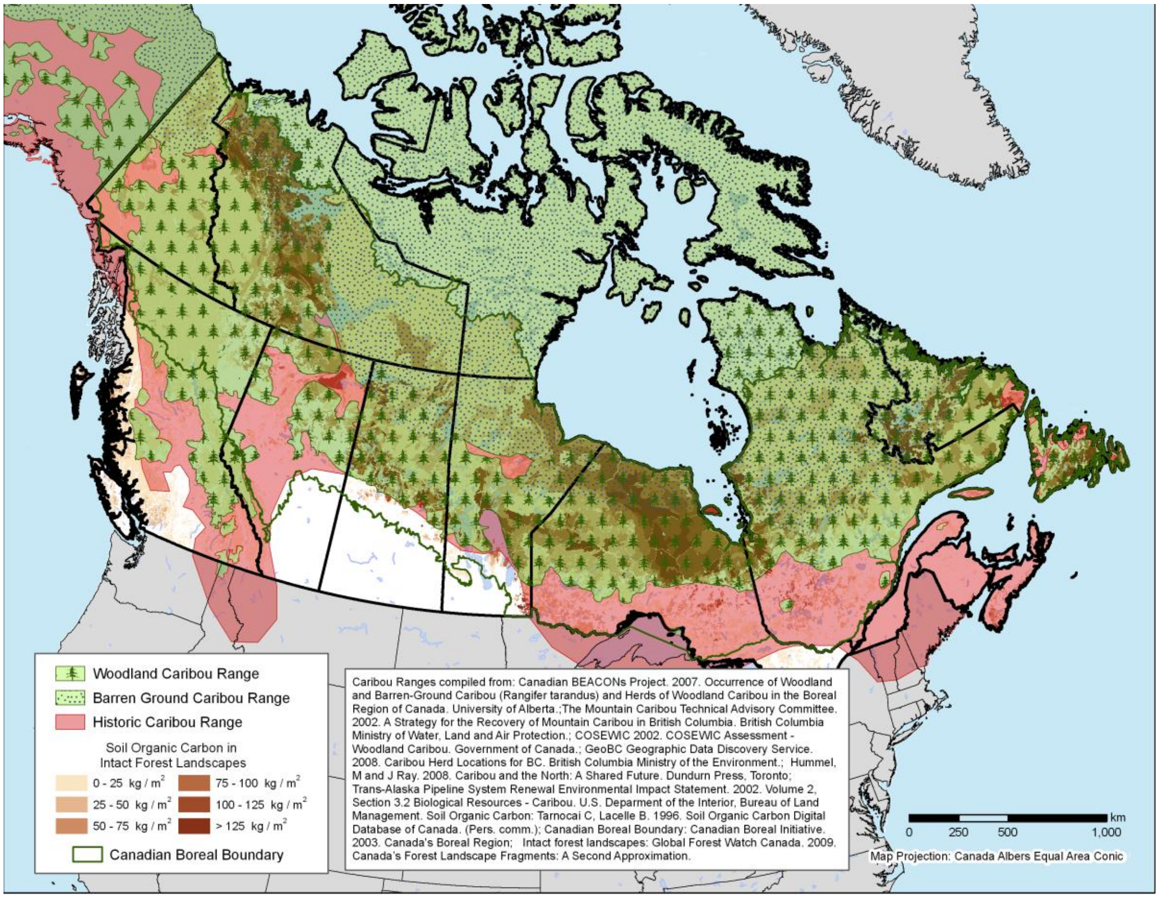


Figure 4.5 Map showing the boreal region of Canada, the boreal commercial forestry zone, the area of the Canadian Boreal Forest Agreement, and the area of caribou conservation planning under the Canadian Boreal Forest Agreement (Canadian Boreal Forest Agreement 2010).



Caribou Ranges compiled from: Canadian BEACONs Project. 2007. Occurrence of Woodland and Barren-Ground Caribou (Rangifer tarandus) and Herds of Woodland Caribou in the Boreal Region of Canada. University of Alberta.;The Mountain Caribou Technical Advisory Committee. 2002. A Strategy for the Recovery of Mountain Caribou in British Columbia. British Columbia Ministry of Water, Land and Air Protection.; COSEWIC 2002. COSEWIC Assessment - Woodland Caribou. Government of Canada.; GeoBC Geographic Data Discovery Service. 2008. Caribou Herd Locations for BC. British Columbia Ministry of the Environment.; Hummel, M and J Ray. 2008. Caribou and the North: A Shared Future. Dundurn Press, Toronto; Trans-Alaska Pipeline System Renewal Environmental Impact Statement. 2002. Volume 2, Section 3.2 Biological Resources - Caribou. U.S. Deparment of the Interior, Bureau of Land Management. Soil Organic Carbon: Tarnocai C, Lacelle B. 1996. Soil Organic Carbon Digital Database of Canada. (Pers. comm.); Canadian Boreal Boundary: Canadian Boreal Initiative. 2003. Canada's Boreal Region; Intact forest landscapes: Global Forest Watch Canada. 2009. Canada's Forest Landscape Fragments: A Second Approximation.

Map Projection: Canada Albers Equal Area Conic

Figure 4.6 Map showing current and historic caribou ranges and soil carbon.

The Canadian Boreal Forest Agreement, and the geographic distinctions shown in these maps, indicates that there are measures that can be taken to reduce the biodiversity impact of northern softwood harvesting, as well as of fiber production elsewhere.

One approach to reducing biodiversity impacts is forest certification. A number of systems for certifying forest products have been developed, including those of the Forest Stewardship Council (FSC), the Sustainable Forestry Initiative (SFI) and the Canadian Standards Association Sustainable Forest Management Standard (CSA). These standards have some broad similarities (Howe et al. 2004), although not all require the maintenance or improvement of biodiversity within the forest management unit or broader landscape. Masters et al. (2010) have found that in Canada, the FSC audits require more changes in environmental, social, and economic aspects, whereas the SFI and CSA require more changes in management systems and aquatic ecosystems management. The FSC standard includes a high conservation value forest designation, which can provide an additional protection for designated areas. Use of the high conservation value forest assessment framework can provide a mechanism for evaluation of forest sites and forest management activities (FSC 2010).

Adherence to these standards does not indicate that there is no biodiversity or other environmental impact, but certification can be expected to provide some level of sustainable management.

Forest certification provides a set of standards for forest management, and provides some protection for wildlife. In addition, however, agreements such as the Canadian Boreal Forest Agreement indicate that stronger protection in specific locations may also be needed. Under that agreement, logging has been suspended on some land, and further agreements are under discussion for other locations. In this and other regions, the Forest Stewardship Council has prioritized areas termed High Conservation Value (HCV) forests for special protection.[6]

Forests in the southeastern portion of the United States also have biodiversity significance, and there has been substantial activity among both forest products companies and environmental organizations to address the risks to biodiversity. At the landscape and regional scale, intensive forest management in the southeast has contributed to the decline of rare ecosystems and natural communities (EDF 1995). Most of the forest land in the southeast is privately owned, and this presents special challenges for forest protection.

High conservation value forests in the US southeast include areas of longleaf pine forest, which is one of the most diverse North American ecosystems north of the tropics (Hanson et al. 2010). Data from state Natural Heritage Programs and other databases have been used to identify endangered forests and special areas in the US southeast; one large timber buyer has made a commitment not to purchase timber from these areas or

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[6] HCV forests are those that contain concentrations of biodiversity values, that contain rare, threatened or endangered ecosystems, that provide critical natural services such as watershed protection or erosion control, or that are fundamental to meeting basic needs of local communities.

from new plantations established at the expense of natural hardwood forests (NRDC 2010; Georgia-Pacific 2011). Following a similar process for screening of southeast timberland to be used for bamboo production could provide assurance of protection of high conservation value areas.

Invasive plants can have a significant impact on biodiversity and ecosystem function. As discussed previously, *Arundo donax* has been identified to have some invasive properties in some areas. Although the bamboo species under consideration is identified by the supplier as a non-invasive type of bamboo, concerns about invasiveness may persist until the characteristics of the species can be evaluated in the proposed production environment. Moreover, evaluation of how local fauna will adapt to bamboo forests, and how they would use it for shelter and food, could provide additional information on potential ecosystem impacts. Monitoring of environmental and ecological characteristics through field tests could provide data on and assurance of the non-invasive character of fibers selected for production.

4.2.4 Endpoint Impacts of Water Consumption

Here we develop a more in-depth and partially site-specific assessment of water consumption. This example may serve as a guide to the ways in which lifecycle assessment approaches can develop a stronger linkage to specific locations and circumstances.

The method of Pfister et al. (2009) is used to assess the environmental impacts of freshwater consumption within a lifecycle assessment framework. This method includes three endpoint indicators, in the areas of human health, ecosystem quality and damage to resources. The advantage of an endpoint approach is that the results can be compared directly with the endpoint scores of other environmental impacts. In particular, examination of the endpoint impacts provides a way to evaluate the impact of water use – irrigation in particular – in comparison with the other environmental impacts of pulp production.

Endpoint 1: Human Health: Water shortages can have a significant effect on irrigation needed for food production; this can be severe in developing countries. For the US and Canada, however, Pfister et al. (2009 fig. 2d) calculated that these values are low, less than 4×10^{-9} DALY per m^3 of water consumed.[7] Figure 4.7 shows the resulting upper limit values of human health impact per ton of pulp.

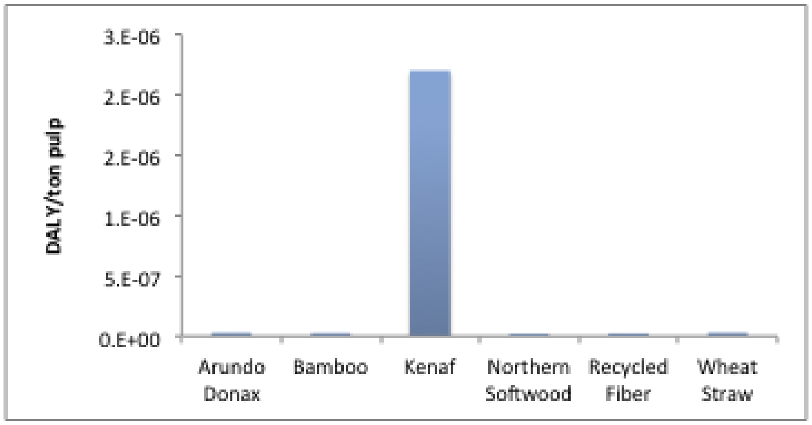

Figure 4.7 Upper limit estimate of human health impact of water consumption for pulp production, in disability adjusted life years per ton of pulp.

Endpoint 2: Ecosystem Quality: In places where plant growth is water-limited, water consumption can diminish vegetation and plant diversity. Characterizations of the impact of water deprivation of terrestrial ecosystem quality have been developed by Pfister et al. (2009), these values are converted here to the ReCiPe impact assessment method, as shown in Figure 4.8.[8]

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[7] Disability Adjusted Life Year (DALY) is a standard metric for human health impact.

[8] The ReCiPe method uses a terrestrial species density, SD, of $1.48 \times 10^{-8}/m^2$ (Goedkoop et al. 2012, section 2.3.5,). The endpoint indicators developed by Pfister et al. (2008) for ecosystem impacts include only terrestrial ecosystems impacts, so the analysis is restricted to terrestrial ecosystem impacts. Ecosystem Impact $= CF_{EQ}$ (m^2-yr/m^3) x SD (species/m^2) x WU (m^3)

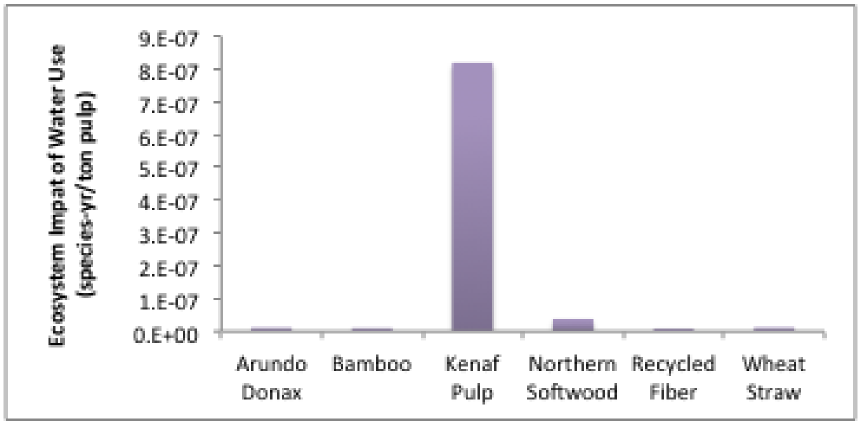

Figure 4.8 Ecosystem impact of water use per ton of pulp.

Endpoint 3: Damage to Resources: In some locations there may be water stock exhaustion at some point in the year, potentially requiring desalination for replacement water. This is not a concern in the regions in which fibers would be grown or pulps would be produced, so damage to resources is not further considered for water use.

Comparison of Water with Other Impacts: Comparison of the magnitude of the water impacts on human health (Figures 4.7) and ecosystems (Figure 4.8) with the total human health and ecosystem impact of pulping, in Figures 4.1 and 4.3 respectively, shows that the human health and ecosystem impacts per ton of kenaf pulp – the fiber with the largest water consumption – is small compared to the other human health and ecosystem impact of fibers production. This suggests that water use, even for irrigated fiber crops, is not one of the major environmental impacts of fiber production. However, the issue of water use impacts should be regularly revisited from a range of perspectives. Water availability and scarcity can be expected to change over time, and even recent changes in water availability – evidenced by the US drought in the summer of 2012 - may not be reflected in the data used here. Moreover, other effects warrant investigation: for example, the thermal impacts of power plant cooling water (Verones et al. 2010) have not been evaluated.

In summary, water consumption impacts are dominated by irrigation, yet these impacts are small compared to other environmental impacts of pulp production. Impacts not directly assessed here, such as the high evapotranspiration of *Arundo donax*, should continue to be assessed.

4.3 Consequential Assessment of Use of Alternative Fibers for Pulp Production

The previous analysis considered the impacts of each fiber pulp separately. Here any additional impacts from changing from one pulp to another are considered. The assessment is developed qualitatively, in terms of the supply and demand features of each affected market. The Canadian pulp market, the southeast timber market, the recycled fiber market and the southeast agricultural market are considered. [DATA REMOVED]

General supply and demand arguments are applied. For example, if demand for a product is reduced and supply is very elastic, then supply can fall nearly as much as demand, and prices may be relatively constant. In this case, the induced production activity would be small, with corresponding small environmental impacts. In contrast, if production of a product in one location is stopped or displaced, and if the demand is very inelastic, then market demand can be expected to induce production at another location to nearly replace the displaced production. In this case, the induced replacement production could be significant, with environmental impacts also potentially significant.

Consequences of changing pulp consumption from Canada

A first consideration is the magnitude of KC purchases to the overall scale of Canadian pulp production and to the scale of forest protection efforts. As of 2011, K-C purchased approximately 0.34 million tons per year of northern softwood pulp for its North American production. With the yield estimate of 2.36 hectares per ton of pulp for northern softwood, this comes to about 0.8 million hectares of land in Canada providing pulp for K-C. Canada produces about 19 million tons of pulp annually, as of 2010 (FAO 2012), making these pulp purchases about 4% of those from Canada.

To consider the scale of forest protection efforts, a point of reference is the Canadian Boreal Forest Agreement, which covers a large portion of Canadian forests. 28.5 million hectares were deferred from harvesting on signing of the 2010 agreement; overall some 75 million hectares fall under the agreement (Canopy, Forest Ethics, and Greenpeace 2012). Thus, taking into account that only a portion of K-C's Canadian fiber is from boreal forests, the amount of forest area potentially affected by K-C's sourcing is less than 2% of the land area encompassed by the Canadian Boreal Forest Agreement.

The relatively small role of K-C in the market for Canadian pulp (4%) and in the overall forest protection efforts in Canada (2%) suggests that K-C's decisions on pulp procurement will not in themselves transform the Canadian pulp market or forest activities; the effects of its procurement choices should be considered in the context of the existing market.

The relatively small magnitude of K-C's purchases should not be taken as the scale of its potential strategic influence. German pulp and paper companies had a similar market share in the Canadian coastal forest market and yet were a driving force in the protection of the Great Bear Rainforest (Armstrong 2009). K-C may have a substantial influence on the overall pulp and paper market and on the broader forest products industry; this influence, however, is a function of its vision, innovation, and persuasiveness, rather than the size of its purchases *per se*.

The consequence of reduced purchase of Canadian pulp would be reduced total demand for Canadian pulp and, consequentially, some reduction in logging activity. Press reports indicate that the market for Canadian forest products has been in decline, that some saw mills and pulp mills are expected to close, and that efforts are being made to increase the markets for wood pellets and other bioenergy products (SIFI 2012). Accordingly, Canadian pulp production is taken to be elastic, meaning that pulp production would fall nearly as much as pulp demand. Of course, in the limit of very large decreases in softwood demand, softwood supply could become less elastic: programs to develop alternative markets for Canadian products are already underway and a substantial decrease in current product markets could advance the efforts to develop new markets.

If there were changes in logging activity or changes in forestry practices in Canada, the amount of carbon stored in trees and forests could change. The dynamics of carbon storage in forests is affected not only by the processes of undisturbed growth and harvesting practices, but also by disturbances such as fire and insect infestations, and by management practices (Stinson et al. 2011). The carbon storage in Canadian forests increases with stand age, although this can be influenced by fire, insects and other disturbances (Kurz and Apps 1999). Observations of total ecosystem carbon in Canadian spruce forests indicate that carbon storage would increase if harvesting were delayed (Taylor et al. 2008). Accounting for the carbon and greenhouse gas implications of forest harvesting could be considered to include not only the carbon harvested from the forest, but also the foregone growth of the forest: the carbon that would have been sequestered in the forest had it not been harvested. Quantifying this effect is beyond the scope of this study, but we do provide an example scenario, as follows: Taylor et al. (2008) show that a transition from clear-cutting to partial cutting in Canadian spruce forests can increase the time-average total carbon storage by approximately 25 t C/ha, while decreasing the harvest by 13%. With our baseline pulp yield estimate of 2.36 hectares per ton of pulp for northern softwood, the scenario investigated in the Taylor et al. study indicate that this type of change in forest harvesting procedures would increase forest carbon storage by the equivalent of 60 tons of carbon per ton of pulp per year. Such a change in forest carbon storage would be larger than the other carbon emissions and greenhouse gas impacts considered in the lifecycle analysis calculations developed in the earlier portions of this report. While there could be other scenarios in which a transition from northern softwood to other fibers would not increase forest carbon storage, the potential magnitude of this effect suggests that further consideration of carbon storage could provide improved understanding of the net greenhouse gas impacts of northern softwood pulp.

Consequences of Growing Bamboo on Southeast Timberland.

In the scenario considered here, bamboo would be grown on softwood timberland in the southeast. The land would be logged, the wood sold, and the land planted with bamboo.

As with northern softwood, demand for southern softwood has been weak. Overall US wood pulp production peaked in the mid-1990s at around 65 million tons per year and as of 2011 had fallen to about 53 million tons per year. Pulp mill capacity in the southeast US has fallen from about 50 million tons per year in the 1990s to about 45 million tons per year as of 2011. Pine plantings in the US south have fallen from a peak of about 2.5 million acres in the late 1980s to about 1 million acres in 2008 (Harris et al. 2012). This is an annual rate of reduction of about 150 thousand acres per year.

Production of enough bamboo to replace all of K-C's 0.34 million tons of northern softwood pulp would require [CONFIDENTIAL K-C DATA]. The timber that could have been produced on this land is about a third of one year's reduction in southern timber production. Pulping of the bamboo fiber would require additional pulping activity in the southeast, potentially at an existing Kraft mill with excess capacity.

Our assumption is that, at this scale, the conversion of timberland to bamboo in the southeast would have little impact on timber prices, although it could marginally offset reductions in timberland areas.

The conclusion that reduced purchase of northern softwood pulp could result in a nearly equal softwood pulp production decrease is, from an environmental perspective, a positive conclusion; it indicates that the environmental impacts of northern softwood pulp production could, on a per ton basis, be nearly eliminated by transition to a different type of fiber. However, this same argument provides a negative conclusion in terms of socio-economic impact: jobs could be lost and Canadian pulp mills could close. On a more or less one to one basis, a transition from northern softwood pulp produced in Canada to bamboo pulp produced in the United States can be expected to result in job loss in Canada and job gain in the US southeast.

Consequences of reduced use of recycled fiber

The consequences of a shift from use of recycled fiber to use of wheat straw, kenaf, or *Arundo donax* are considered here. The baseline scenario is the continued use of recycled fiber as de-inked pulp (DIP), with consumption of 1 million tons of de-inked pulp, sourced from 1.6 million tons of recycled paper; results could be scaled up or down accordingly.

Availability of recycled fiber in North America is declining and projected to continue to decline. This is due both to decreasing consumption of printing and writing papers in North America, and to increasing demand for recycled paper in Asia. A reduction in use of recycled fiber for tissue production could be viewed as a consequence of declining recycled fiber availability and growing demand for recycled paper. For this reason, it is assumed that waste paper would not be landfilled and that paper collection would not decrease as a result of reduced use of recycled fiber by K-C.

The assumption of continued high recycled paper collection and use can only hold if the overall global demand for recycled paper remains strong. The supply of waste paper is inelastic, if global demand were to fall, waste paper would be landfilled instead. In a situation with a weak market for recycled fiber, a transition away from recycled fiber would involve environmental impacts of the unused paper. Clearly, if every purchaser of recycled fiber transitioned to alternative fibers, the market for recycled fiber would collapse and waste paper would be landfilled or burned. In the scenario considered here, however, the demand for recycled paper is strong and growing; a transition away from recycled fiber by one purchaser could affect prices but the market will continue to clear.

Consequences of increased use of wheat straw, *Arundo donax*, or kenaf.

For wheat straw, it is assumed that there is no land use change, and no change in the amount of wheat produced, so the only change is the management of the wheat straw. Wheat straw is assumed to be procured only from fields with no-till or reduced till management on soils appropriate for wheat straw removal, so that there is no reduction in soil carbon or soil fertility.

For *Arundo donax* and kenaf, their production is assumed to displace crops in the US southeast. The US EPA has evaluated the effect of crop displacement on greenhouse gas emissions. The context of EPA's evaluation is at a much larger scale than considered here. The production of biofuel in the United States is projected to result in the shift of up to 22 million acres of cropland and 41 million acres of pastureland shift into energy crops by 2030 at a simulated farmgate price of $60 per dry ton (US DOE 2011). [CONFIDENTIAL K-C DATA] Since the indirect effects are expected to increase with the scale of change, the EPA results could overestimate the magnitude of the effects if total production is at a smaller scale.

Here the results for switchgrass are considered as a proxy for the type of impact that might result from introduction of *Arundo donax* or kenaf into the US agricultural landscape. Like *Arundo donax* and kenaf, switchgrass has high biomass yield on low inputs and is not itself a food crop. An exact comparison is difficult, since the EPA did not model direct and indirect effects separately; the results are roughly apportioned here. The EPA modeling effort concluded that for each hectare of land used for switchgrass, there would be a net US decrease of 0.35 hectares of soybeans, 0.22 hectares of other crops, and 0.11 hectares of wheat, as well as in increase of 0.01 hectares of corn and silage. In addition, there would be changes in international agricultural production, with increased production of soybeans on current pastureland in Brazil making up for much of the US reduction. For each ton of switchgrass produced, an indirect emission of 93 kg CO_2e was estimated through use of global trade models coupled with global models of soil and land use dynamics, with a 95% confidence range from 30 to 160 kg CO_2e per ton of switchgrass (US EPA 2010). The average yield of switchgrass is an estimated 4.75 t/ha-y, so the 93 kg CO_2e per ton of switchgrass corresponds to 809 kg CO_2e/ha-y. [CONFIDENTIAL K-C DATA] Compared to the direct greenhouse gas impacts of *Arundo donax* and kenaf pulp production, shown in Figure 3.6 to be in the range of 400 kg CO_2e per ton of pulp, these potential indirect land use change impacts are not negligible.

Table 4.2 summarizes this assessment of the consequences of alternative fiber choices. Overall, our initial conclusion is that the indirect environmental impacts of a transition from northern softwood and recycled fiber to bamboo, *Arundo donax*, kenaf, or wheat straw would be small, and that the environmental impacts are well represented by the attributional assessment presented in this study.

Table 4.2 Consequences of a transition to alternative fibers. Shaded area indicates transition from recycled fiber to fibers grown on southeast cropland; unshaded area indicates transition from northern softwood to bamboo grown on southern timberland

Market	**Scenario**	**Market Characteristics**	**Market Consequences**	**Local Economic Impact**
Northern softwood	Demand falls	Supply elastic	Supply falls	Negative
Southern timber	Supply falls [CONFIDENTIAL K-C DATA]	Demand elastic and decreasing	Increased income for land owners, kraft pulp mills	Positive
Recycled paper	Demand falls (1.6 M t/yr)	Overall demand high, supply inelastic although continuing to decrease	Little effect on recycled fiber market, in context of overall high demand and continuing supply decline	Neutral
Southeast Cropland	Supply falls [CONFIDENTIAL K-C DATA]	Medium elasticity	Agricultural market adjustments	Higher farmer profit

Chapter 5: Interpretation and Conclusions

5.1 Data Quality, Sensitivity Analysis, and Uncertainty

Data quality indicators developed in Chapter 2 have been used to characterize uncertainty in the midpoint and endpoint results shown in Chapters 3 and 4. Data quality scores of 1, 2, or 3 are considered to fully meet the data quality requirements. This does include some data based partly on qualified estimates, without full coverage of all sites, and with some extrapolation across fiber types and technologies. These data limitations are expected for a study such as this, which is considering the environmental impacts of processes before they have been implemented at commercial scale. Data quality scores of 4 or 5 are considered to indicate substantial data limitations.

For the fiber production stage (Table 2.2), data on the production inputs and yields generally do meet the data quality requirements. The exception is the estimated yield for bamboo, which could be better characterized after field trials in the US southeast. This yield uncertainty is reflected in the error bars on the results. In addition, the effect of a potentially lower yield was explored in a sensitivity analysis. However, even with a lower yield that is representative of data from commercial bamboo activities in other regions, the conclusion that bamboo is a high-yield fiber remains robust.

Also at the fiber production stage (Table 2.2), data on the emissions of agricultural chemicals to air, water and soil do not meet the data quality requirements for any fiber; none of the emissions data are based on on-site measurements. Improved information about chemical use, including measurements of the fate of the chemicals would reduce the uncertainty regarding air, water, and soil emissions from fiber production.

For fiber transport (Table 2.3), all data meet the data quality criteria, with the exception of data on the transportation of recycled fiber. This data gap does not substantially affect the conclusions of this study. Nevertheless, data on recycled fiber transport and management may be readily available; inclusion of improved data in future studies could reduce this uncertainty.

For fiber pulping (Table 2.9), the data for energy use, chemical inputs, and efficiency meet the data quality requirements for *Arundo donax*, kenaf and wheat straw, although it should be kept in mind that the data are based on pulping trials and not full-scale commercial production. The energy use, chemical inputs, and efficiency data for northern softwood and bamboo do not meet the data quality criteria, because the northern softwood data are from one site only, and the bamboo data are based on the estimates and extrapolations of pulping engineers as well as on data from research partners, but are not based on measurements of pulping trials in a kraft mill. Accordingly, direct quantitative comparisons between bamboo pulping and northern softwood pulping are premature; it is possible that at other northern softwood pulping sites the efficiency may be higher and the chemical use somewhat different. And when bamboo pulping trials have been completed these data would provide more confidence in the overall energy and material inventory for this process. For emissions to water, air, and solid waste, the data do not meet data quality requirements for any of the fibers. Improved emissions data, including measurements, and with greater specificity regarding the chemical compounds released, beyond the generic BOD, COD, and AOX indicator values, would allow for more detailed assessment of the impacts of the pulping processes. These data may well be available, so future analyses could reduce these uncertainties and limitations.

A key result of the baseline analysis of this study is that the high yield of the alternative fibers reduces land occupation and the environmental impacts associated with land occupation, in comparison with northern softwood. To examine the robustness of the implications of high yield fibers, we have explored the sensitivity of the results to changes in yield assumptions, specifically examining the effects of higher yields of northern softwood, lower yields of bamboo, and greater allocation of agricultural inputs to wheat straw and to kenaf. All of these changes, taken separately or together, have the effect of reducing the magnitude of the difference in the land occupation impacts of northern softwood and the other fibers. However, even with the changes, which were chosen to represent the plausible range of current practice, the alternative fibers still have substantially smaller land occupation impacts than northern softwood. This finding, however, is limited not so much by the assumptions about yield, but rather by the limitations of current LCA analysis in evaluating environmental impacts of land use. Although better data on actual fiber yields will be useful, a fuller understanding of land use impact will require more site-specific or landscape level analysis beyond environmental lifecycle assessment.

To examine the climate change impacts of biogenic carbon, our baseline assessment is within the confines of the main system boundary, which considers pulp production to the paper mill gate. Although we expect all the fibers to have similar behavior at the paper mill and in use, and to follow the same pathways at end-of-life, there are emissions of biogenic carbon at end-of-life. The biogenic carbon in the quickly-regenerating fibers – *Arundo donax*, kenaf, wheat straw, and bamboo, have very small biogenic carbon global warming factors: because these plants grow quickly, the biogenic carbon is reabsorbed through the annual growth of the fiber plants. In contrast, the northern softwood has a relatively large biogenic global warming factor: because northern softwood grows slowly, the carbon released from this fiber has an impact on the atmosphere that is somewhat more like fossil fuel carbon than the faster growing fibers. At end of life, pulp products disposed in landfills will result in both long term sequestration of biogenic carbon in the landfill, and emissions of methane, which has a large global warming impact, from degradation of some of the paper. In order to examine this effect, in a supplementary analysis we evaluated these emissions for the case of landfilled products. The result is that the landfilling of paper made from any of the pulps results in significant greenhouse gas emissions. Even though most of the carbon in the landfilled paper remains in long-term storage, the methane emissions have a greater impact over the 100-year time frame.

To further analyze the effect of the model choice on the climate change impacts of biogenic carbon, we evaluated the impacts both within the “hierarchist” perspective, using the standard 100-year time horizon for climate change impact analysis, and also in using the 500-year time horizon for climate change impact assessment. The 500-year time horizon is currently not commonly used; however the longer-term perspective does result in a lower relative impact from biogenic carbon. This effect is seen both within the baseline system boundary of pulp production to the paper mill gate, and when end-of-life is considered. Moreover, end-of-life methane emissions have a smaller effect in the 500-year time horizon, because methane has its main effect in the first few years after it is emitted. Thus over this long time-horizon, the relative impact of the northern softwood biogenic carbon is smaller, although still significant, and the landfilling of the shorter-rotation fibers – *Arundo donax*, kenaf, wheat straw, and bamboo – results in a net reduction of greenhouse gas reductions for the end-of-life phase, due to the long-term sequestration of carbon in the landfill. Since, however, there are few data on the behavior of carbon in landfills over a 500 year period, these results should be interpreted broadly in terms of the direction of the results, but not with quantitative certainty.

5.2 Completeness of the Life Cycle Inventory Analysis

Although the completeness and cut-off criteria were discussed in Chapters 1 and 2, consideration of the full results of the study provides a perspective from which to consider elements that may be incomplete. This study has been developed as a cradle-to-gate study, from the production of fiber in the forest or on the farm to the delivery of finished pulp to the paper mill gate. The goal has been to compare different types of fiber, with the assumption that the pulps will all undergo similar processes after pulp production. However, consideration of the impacts of biogenic carbon required opening the system boundary to allow consideration of the fate of the carbon in the paper when it is disposed to landfills, wastewater or other disposition. The result is a lifecycle inventory in which the additional impact of fiber at end-of-life is also included.

The data on emissions to air, water, soil, and solid waste generally do not meet the data quality requirements, and are spotty enough to be considered incomplete aspects of the inventory. These data are incomplete for the existing, established process data sets for northern softwood pulping, recycled fiber de-inking and for the other data sets from which the mechanical pulping data have been estimated. Completing and improving these data sets may be a matter of gathering existing data sets from suppliers and existing operations.

5.3 Limitations and Significance

Life cycle inventory results are relative expressions and do not predict impacts on category endpoints, nor address the exceeding of thresholds or safety margins.

As discussed in Chapter 1, on the goal and scope of the study, the system boundaries encompass the production of fiber, its transformation into pulp and its delivery to the paper mill gate. The environmental impacts considered here are consistent with the state-of-the-art of environmental lifecycle assessment. As discussed above, the full impact of human activities on ecosystems is an area in which environmental lifecycle assessment, and environmental assessment overall, is not yet fully developed. Accordingly, this assessment does not provide a full or completely definitive assessment of ecosystem impacts of fiber production. The discussion above seeks to highlight those areas of ecosystems and biodiversity that might be affected, to provide appreciation of impacts that cannot yet be adequately quantified.

The alternative fiber production systems are not yet in operation. Although this assessment has sought to include and anticipate the impacts of the prospective fiber production systems, there may be some impacts that are not fully characterized. These include the energy system for bamboo pulping, including the source of biomass fuel for bamboo pulping, the energy and chemical inputs required for *Arundo donax* pulping, and emissions to air water, and solid waste from all pulping processes. Revisiting these issues as alternative fiber production scales up could fill in this assessment with improved data drawn from commercial scale activities. Also, it should be emphasized that the process for pulping of *Arundo donax*, kenaf, and wheat straw are specific to K-C's integrated mill in [LOCATION REMOVED]; at that mill the pulp does not have to be completely dried because it can be sent directly to the co-located tissue production equipment. At a different mill, similar pulping of these fibers could require more energy for drying the pulp in order to transport it to a tissue mill. These energy requirements for drying could be readily estimated with process engineering estimates.

This study has considered all fibers in terms of a functional unit of one metric ton of pulp delivered to the paper mill gate, measured as air-dried tons. As discussed previously, in this study both the northern softwood pulp and the bamboo pulp are processed using the kraft chemical process; the resulting fibers are long and strong and these two fibers can be considered as alternatives to each other. In contrast, the de-inked pulp made from recycled paper has shorter, weaker fibers that are similar to the pulps made from the mechanical process, which in this study are *Arundo donax*, kenaf, and wheat straw. Even so, the plant fibers are not identical, so the resulting pulps are not completely identical. As a result, although recycled de-inked pulp and mechanical pulps made from *Arundo donax*, kenaf, and wheat straw are considered to be comparable, they may nevertheless have differences in mechanical strength, softness, or other features that may affect the extent to which these fibers might substituted one for another. Also, bamboo, *Arundo donax*, kenaf, and wheat straw could potentially be pulped using other processes; this would result in different material and energy consumption and different resulting fiber properties.

The large biogenic climate change impact of northern softwood pulp is significant, even though there are substantial uncertainties in the carbon flows both in the forest and in the pulp product at end-of-life. Both sensitivity analysis of yields and analysis of data quality limitations indicates that the overall climate change impact of northern softwood is larger than for other fibers.

The differences in the overall human health impacts among the fibers may not meet the test of significance, when considering both the limitations due to data quality, and the potential for yields in practice to be different than yields assumed in this study. However, the dominance of toxicity and climate change as the main contributors to human health impacts in these systems does seem to be robust to changes in data and yield assumptions.

This indicates that focus on reducing greenhouse gas emissions and reducing toxic emissions would reduce human health impacts.

5.4 Conclusions and Recommendations

This study has considered the relative environmental impacts of six fiber types over a wide range of impacts, subject to numerous conditions and considerations of special circumstances and data limitations. Kraft pulp made from bamboo is considered as an alternative to kraft pulp made from northern softwood; and mechanical pulp made from *Arundo donax*, kenaf, or wheat straw are considered as alternatives to deinked pulp made from recycled paper. These comparisons are considered in turn below. Overall, the endpoint impact analysis indicated that land occupation, climate change, and human toxicity are the three categories with the largest impacts on either human health or ecosystems.

Northern Softwood v. Bamboo

In comparing northern softwood and bamboo, bamboo appears to be better on all scores except possibly for human toxicity. However, part of this result is due to the specific circumstances assumed for bamboo and northern softwood pulp production, and may not be true for these fibers in all circumstances. Bamboo pulp has lower fossil fuel consumption than northern softwood pulp mainly because its production is assumed to be much closer to the tissue mill. In a different situation, with bamboo and northern softwood pulp production facilities located at the same distance from the tissue mill, bamboo could potentially have equal or greater requirements for fossil fuels than northern softwood. On the other hand, some of the toxicity attributed to bamboo is due to assumptions about herbicide use to control invasiveness; this is a conservative assumption since the proposed bamboo species has not been characterized as invasive and alternative management practices could potentially reduce this impact.

The greenhouse gas emissions from fossil fuels and chemicals basically track the fossil fuel use of bamboo and northern softwood, and thus in a situation of co-location, the bamboo and northern softwood could have fossil greenhouse gas emissions that were roughly equal. However, the biogenic greenhouse gas emissions from northern softwood are much larger than those from bamboo, because bamboo regenerates in 3 years while northern softwood regenerates in about 70 years. Biogenic carbon emissions, both during the production process and from emissions after disposal of the produce, are the largest component of greenhouse gas emissions for any of the pulps considered. Due to the long time required to grow northern softwood trees, the greenhouse gas impact of pulp made from northern softwood is significantly larger than for bamboo (see figure 3.8).

For land use impacts and biodiversity, bamboo is indicated as having lower impact because of its high yield and relatively low land use, but quantification of these impacts is not yet fully established in the lifecycle assessment methodology. As a result of these limitations, (1) care should be taken in making claims about biodiversity based on lifecycle assessment results, (2) further study and analysis of ecosystem impacts using other methods should be considered, and (3) for both bamboo and northern softwood, effort should be made to select sites and management practices that would have low ecosystem impacts.

Arundo donax, Kenaf, and Wheat Straw v. Recycled Fiber

Recycled fiber, particularly as produced in the integrated mill modeled here, has a relatively low environmental impact. The alternative fibers have, in comparison, somewhat larger environmental impacts under current assumptions, due both to greater energy required in pulp production, as well as all the agricultural activities required to grow the alternative fibers. From the available data and current assumptions, kenaf has higher impacts than the other fibers, due primarily to the greater use of agricultural chemicals. To the extent that a market can be found for kenaf core, which is a co-product of kenaf fibers, the environmental impact of the kenaf fiber can be somewhat offset by the additional productive use of kenaf material.

The production of these alternative pulps is currently in the pilot study stage. Because these fibers – *Arundo donax*, kenaf, and wheat straw - are somewhat different from each other, the extent to which they can be completely substituted for one another has not yet been tested at commercial scale.

Recommendations

This study explored a limited set of fiber types and used comparison sets that may or may not represent the actual fiber substitution opportunities the company pursues. As Kimberly-Clark continues to explore fiber substitution alternatives, environmental impacts can be better understood as experience is gained. This could include but would not be limited to: availability of more data, better understanding and development of fiber substitution and mix choices, and expanded analysis. Continued reporting of environmental data, and open discussion among stakeholders can provide additional insight.

Fuller understanding of the ecosystem implications of alternative fiber production would be enhanced with site-specific field studies of the fibers under the proposed production conditions.

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Appendix

There are several impact categories for which the endpoint analysis indicated an endpoint contribution much smaller than those of other impact categories; these are ozone depletion (<0.003% of the human health impact), ionizing radiation (<0.03% of the human health impact), mineral resource depletion (<0.2% of the resource depletion), urban land occupation (<0.6% of the ecosystem impacts), terrestrial acidification (0.3% of ecosystem impacts), and photochemical oxidant formation (<0.003% of the human health impacts).

Figure A.1 shows the impact of emissions of ozone depleting substances. There are no ozone depleting substances in the primary inventory of this study; accordingly all the emissions indicates in Figure A.1 are due to background processes of the production of chemicals, fuels and infrastructure.

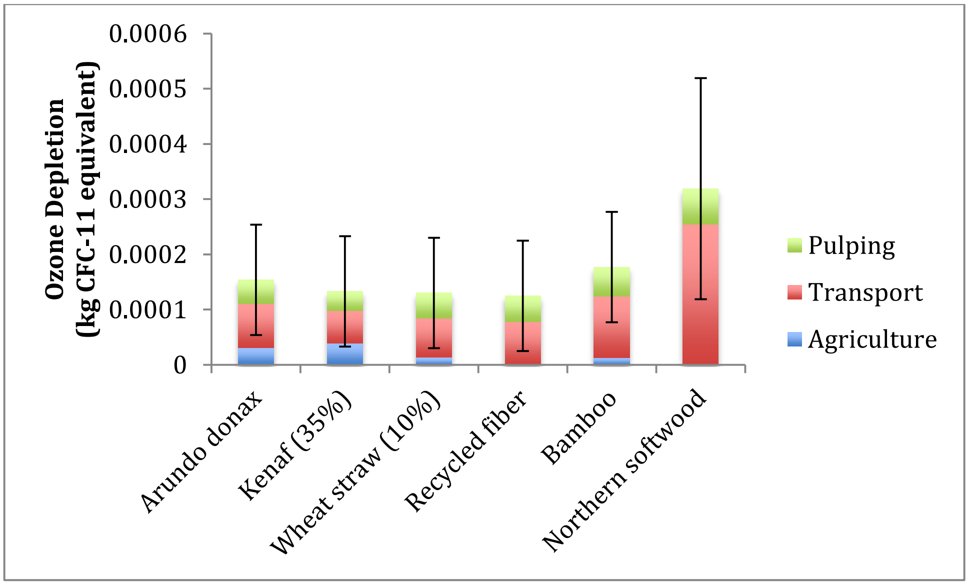


Figure A.1. Ozone depletion potential (kg CHC-11 equivalent)

Figure A.2 shows photochemical oxidant formation, in kg of non-methane volatile organic compounds.

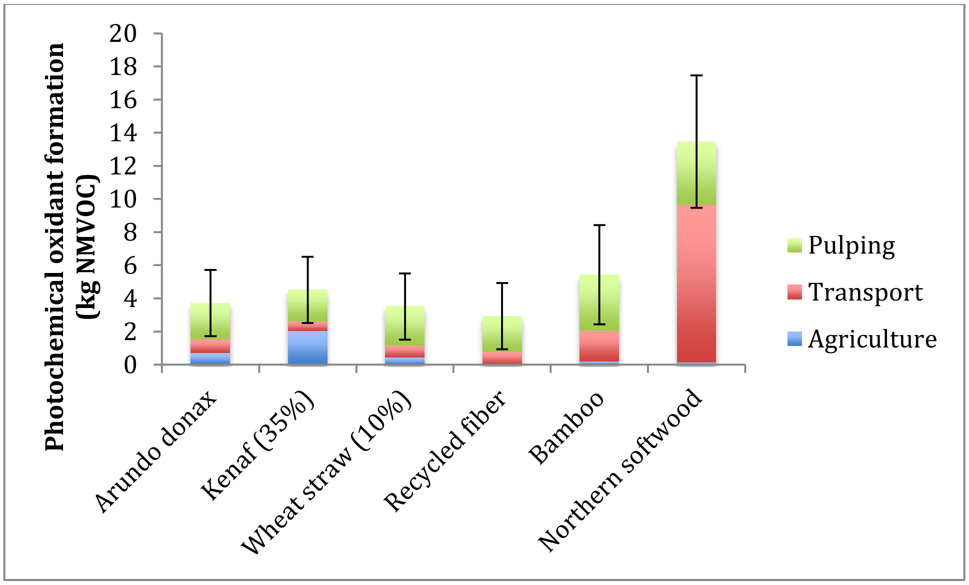


Figure A.2. Photochemical oxidant formation (kg non-methane volatile organic compounds)

Figure A. 3 shows metal depletion, in kg iron (Fe) equivalent.

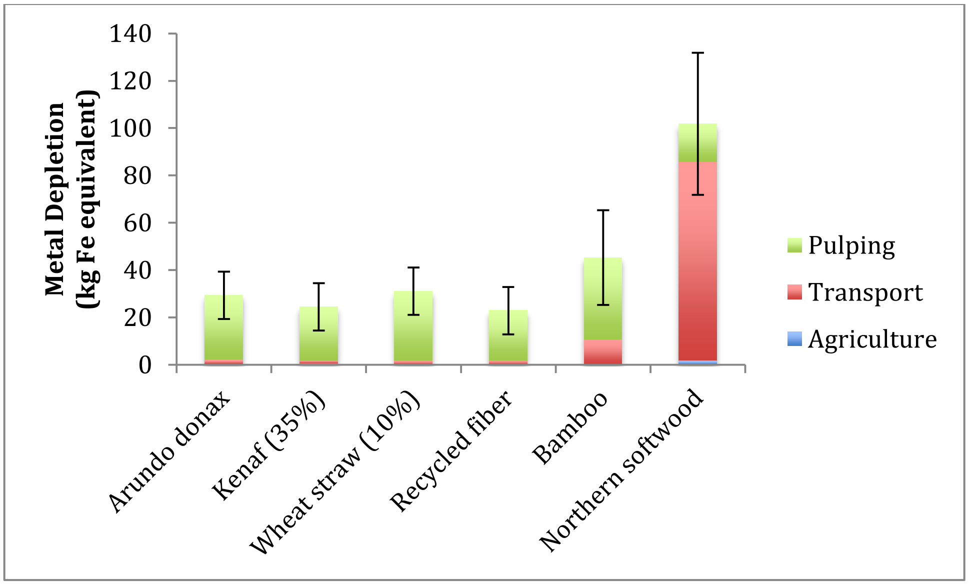


Figure A.3. Metal depletion, in kg iron (Fe) equivalent.

Figure A.4 shows emissions of ionizing radiation, in units of U235 equivalent.

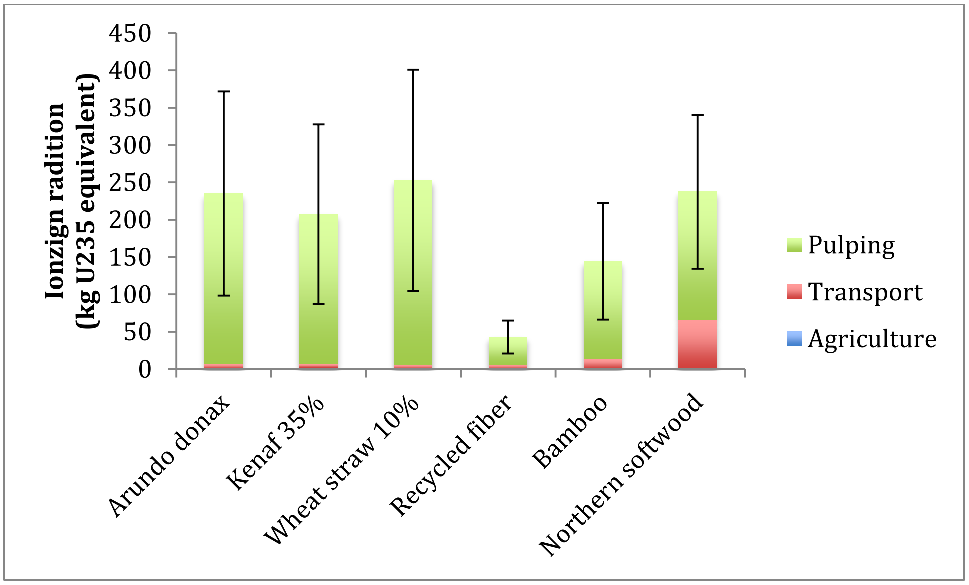


Figure A.4 Ionizing radiation (kg U235 equivalent)

Figures A. 5 shows urban land occupation, due to the land occupied by infrastructure.

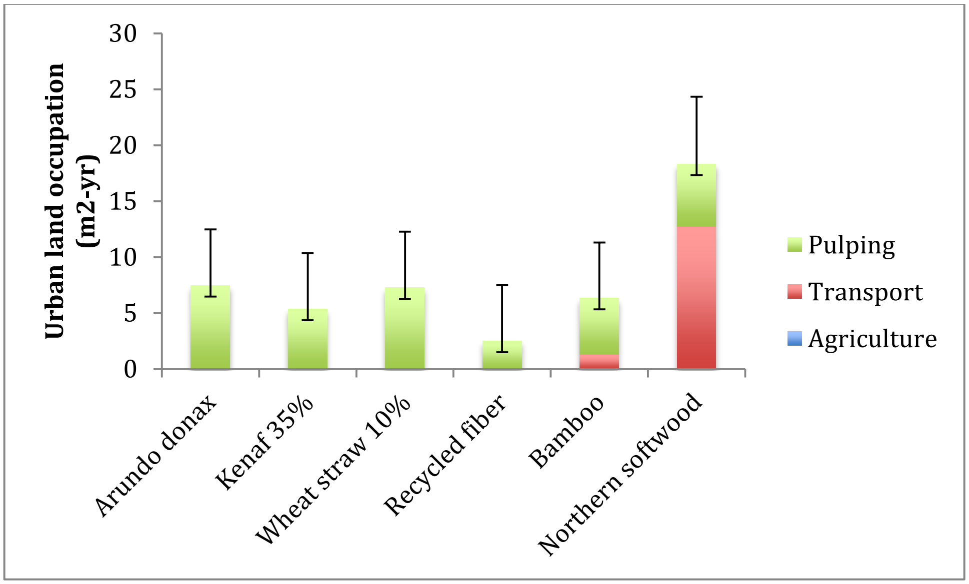


Figure A.5. Urban land occupation (m^2-y)

Figure A.6 shows results for terrestrial acidification, expressed in kg SO_2 equivalent.

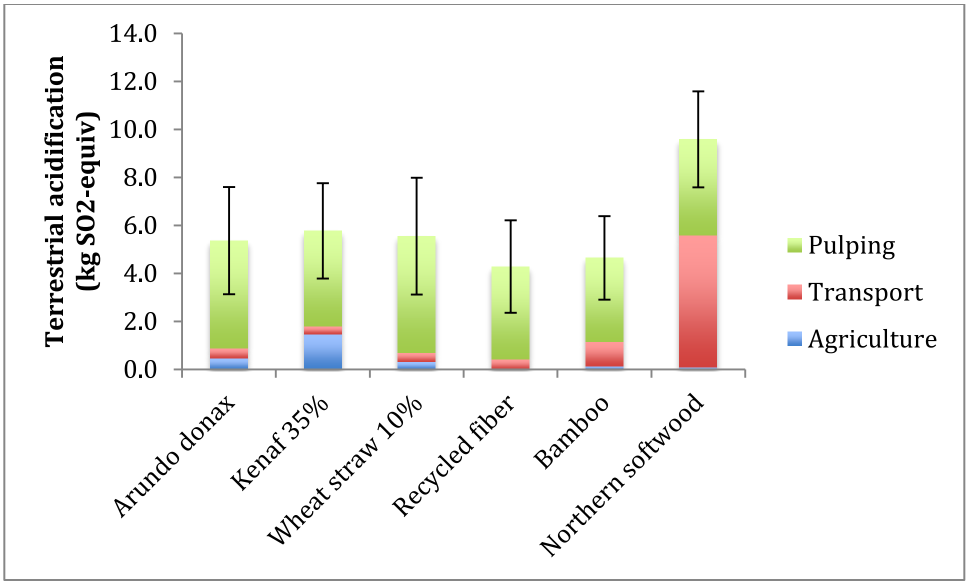


Figure A.6. Terrestrial acidification (kg SO_2-equivalent).

Critical review of Assessment of Alternative Fibers for Pulp Production

Critical Review Report

Prepared for: **Kimberly-Clark Corporation**

Prepared by: **Quantis**
François Charron-Doucet
February 19, 2013

Quantis is a leading life cycle assessment (LCA) consulting firm specialized in supporting companies to measure, understand and manage the environmental impacts of their products, services and operations. Quantis is a global company with offices in the United States, Canada, Switzerland and France and employs close to 70 people, amongst which several are internationally renowned experts in the LCA field.

Quantis offers cutting-edge services in environmental footprinting (multiple indicators including carbon and water), eco design, sustainable supply chains and environmental communication. Quantis also provides innovative LCA software, Quantis SUITE 2.0, which enables organizations to evaluate, analyze and manage their environmental footprint with ease. Fuelled by its close ties with the scientific community and its strategic research collaborations, Quantis has a strong track record in applying its knowledge and expertise to accompany clients in transforming LCA results into decisions and action plans. More information can be found at www.quantis-intl.com.

This report has been prepared by the Canadian office of Quantis. Please direct all questions regarding this report to Quantis Canada.

Quantis Canada
395 Laurier St. West
Montreal, Quebec
Canada, H2V 2K3
+1 (514) 439-9724
info.canada@quantis-intl.com
www.quantis-intl.com

CRITICAL REVIEW PROCESS INFORMATION	
Project title	Assessment of Alternative Fibers for Pulp Production
Authors	Pr. Valerie M. Thomas Georgia Tech ISyE Wenman Liu Georgia Tech ISyE
Contracting organization	Kimberly-Clark Corporation
Report	Critical review report
Panels	François Charron-Doucet, Eng., MScA, Scientific Coordinator –Quantis Canada (francois.charron@quantis-intl.com) -Chairperson Neva Murtha, Second Harvest, Printer and Magazine Campaigner, Canopy (neva@canopyplanet.org) Martha Stevenson, Senior Program Officer - Research & Development, WWF (Martha.Stevenson@wwfus.org) Rosie Saad, Analyst –Land Use expert, Quantis (rosie.saad@quantis-intl.com) Samuel Vionnet, Water Sustainability expert, Quantis (samuel.vionnet@quantis-intl.com)
Client contacts	Howard Connell Global Sustainability Leader Kimberly-Clark Corporation (Howard.Connell@kcc.com)

1 Introduction

The present document is the critical review report of the *Assessment of Alternative Fibers for Pulp Production* report. This study has been conducted by Prof. Valerie Thomas from Georgia Tech and commissioned by Kimberly-Clark Corporation. Final conclusions of this critical review report apply on the February 11th version of the report.

2 Scope of the Critical Review

The goal of this critical review is to ensure that the LCA report complies with the requirements listed in the ISO 14044 standard. According to this standard, the critical review process shall ensure that:

- the methods used to carry out the LCA are consistent with this International Standard;
- the methods used to carry out the LCA are scientifically and technically valid;
- the data used are appropriate and reasonable in relation to the goal of the study;
- the interpretations reflect the limitations identified and the goal of the study, and;
- the study report is transparent and consistent.

In addition to the ISO 14044 requirements, panelists from NGO's were asked to comment the appropriateness of the study for broader societal discussions including the possible implications of the study in the marketplace/society. This request was addressed through the position statement provided by Canopy Planet and WWF (see section 5)

3 Description of the Critical Review Process

The critical review panel was chaired by François Charron-Doucet, scientific coordinator at Quantis. The panel was composed of two NGO environmental experts and two LCIA experts from Quantis.

Neva Murtha, Second Harvest, Printer and Magazine Campaigner, Canopy
Martha Stevenson, Senior Program Officer - Research & Development, WWF
Rosie Saad, Analyst –Land Use expert, Quantis
Samuel Vionnet, Water Sustainability expert, Quantis

The critical review process started in April 2012 and was concluded in February 2013.

Two types of meeting were held during this critical review: review panel meetings and topics meetings. The goal of review panel meetings was to provide an opportunity to the reviewers to comment the report and ask questions on the model and the results to the research team from Georgia Tech. The four following meetings were held:

- Kick-off and Goal and scope meeting: April 17th, 2012;
- Early results meeting: July 13th, 2012;
- Preliminary results meeting: September 6th, 2012;
- Final draft report meeting, December 26th, 2012.

Prior to each meeting, an updated version of the report was sent to the reviewers. In addition to the discussion during the meeting, the reviewers had the opportunity to provide written comments to the research team, who in return answered comments or/and modified in the report. The lists of comments and answers for each meeting or version of the report are presented in section 7.

Topic meetings were also held to facilitate methodological discussions between LCA practitioners and reviewers. Four meetings were held on the following topics:

- Land use/biodiversity/ecosystem service and consequential thinking: May 18th, 2012;
- Water and carbon assessment: May 24th, 2012;
- Additional meeting on biodiversity: July 23th, 2012;
- Additional meeting on water assessment: August 13th, 2012.

The topic meetings were an opportunity for the reviewers to share their expertise and knowledge with the practitioners about the different topics. However, final decision on how to model these aspects was left to the research team.

4 Critical Review Conclusion

The main conclusion of the review panel is this LCA study meets ISO 14 044 requirements. In particular:

- The report is consistent with ISO standard and LCA best-practices;
- Methods used are scientifically sound and in some case are at the state-of-the-art in the LCA field;
- Although data quality requirements are not met for several key data, sensitivity and uncertainty assessment demonstrate a good level of robustness for the conclusions;
- Interpretation largely takes into account the limitations of the study and is consistent with the Goal & Scope.

It should be noted that this report is not intended to support comparative assertions disclosed to the public. However, the comparison between fibers can be used to better understand the advantage and challenge associated with the production of different fibers used in tissues products. The reader can also refer to the table in section 6 for a detailed list of the ISO requirements assessed during this review.

The following paragraphs aim at underlining the main conclusions and observations for each element of the scope of a critical review as defined by ISO 14 044 (see section 2). Note that two of the panelists (from Canopy and WWF) each have also provided a final statement which addresses both ISO requirements and a broader discussion on the implication of this study (see section 5).

1. The methods used to carry out the LCA are consistent with this International Standard,

The study has been conducted as prescribed in the ISO 14 044 standards including the four phases of an LCA through an iterative and transparent manner. The conclusion of the panel is that the LCA report is consistent with ISO 14 044 and follows the best practices in LCA.

2. The methods used to carry out the LCA are scientifically and technically valid,

The initial goal set for this study can be described as ambitious. The scope includes five different fiber production systems which require large uses of land. Many aspects of how the alternative fiber systems are represented is prospective (including fiber farming practices and pulp production technologies) and the study aims at covering a large array of environmental issues. Among these issues, impact characterization for biodiversity, water use and climate change were identified as the most challenging problems.

Regarding **biodiversity**, the main concern from the reviewers was that existing Life Cycle Impact Assessment (LCIA) methods (including the ReCiPe method used in this study) provide rough and incomplete characterization of the impact on biodiversity. However, the panel recognizes that the interpretation of the results takes into account these important limitations. Furthermore, the assessment gaps were openly discussed and a potential solution for future analysis was identified.
For practical reason, the practitioners used ReCiPe (V1.07) ecosystem quality assessment approach. Although the use of a more recent methodology such as the one developed by the UNEP/SETAC working group was discussed during the project, it was not readily available at the moment of the study.

Water assessment goes beyond a simple quantity indicator of water consumption and tries to capture some regional parameters of where this water is consumed. However, as mentioned for the biodiversity assessment, the used approach (Pfister method) does not take into account all the complexity of the water issue and relies on generic and somewhat rough assumptions. However, this approach can be considered as in line with current LCA best practices and certainly a step forward regarding a better characterization of impacts related to water consumption. The panel acknowledges that limitations of this method were also considered in the interpretation.

The panel recognizes the use of novel methodology for **biogenic carbon accounting** which takes into account the most recent scientific publications in this field. We note however that there are some aspects of this approach that may be subject to discussion, in particular, the impact of permanent biogenic carbon sequestration in landfill. The actual quantity of carbon that would be definitely sequestered as well as the methodology to interpret this quantity in terms of impacts on a 100 and 500 year time horizon are still uncertain. The study may need to be updated once a consensus is agreed in the scientific community.

It is also important to underline the issues that are partially or not integrated in the main LCA results. These include:

- Invasiveness
- Evapotranspiration of different land uses
- Indirect impacts of fiber production systems through market mechanism
- Biodiversity significance of land use potentially affected by the fiber production systems, especially the risk for High Conservation Value (HCV) areas.

The panel recognizes the effort made for including these issues in the interpretation of the results in the appropriate sections of the report. This gives the opportunity to put in perspective the main results and act as a reminder of what needs to be considered in further assessments of these systems.

3. The data used are appropriate and reasonable in relation to the goal of the study,

As mentioned above, although data quality requirements are not met for several key data, sensitivity and uncertainty assessment demonstrate a good level of robustness for the conclusions. The practitioners have also identified the main weaknesses in terms of data quality. In particular, several datasets for pulp production processes were based on small scale experiment or extrapolation of similar existing processes. There is also a significant uncertainty on large scale agricultural practices on most of the alternative fibers studied. The panel strongly encourages the commissioner to make a careful follow-up of this study and update the results when more precise data become available.

4. The interpretations reflect the limitations identified and the goal of the study,

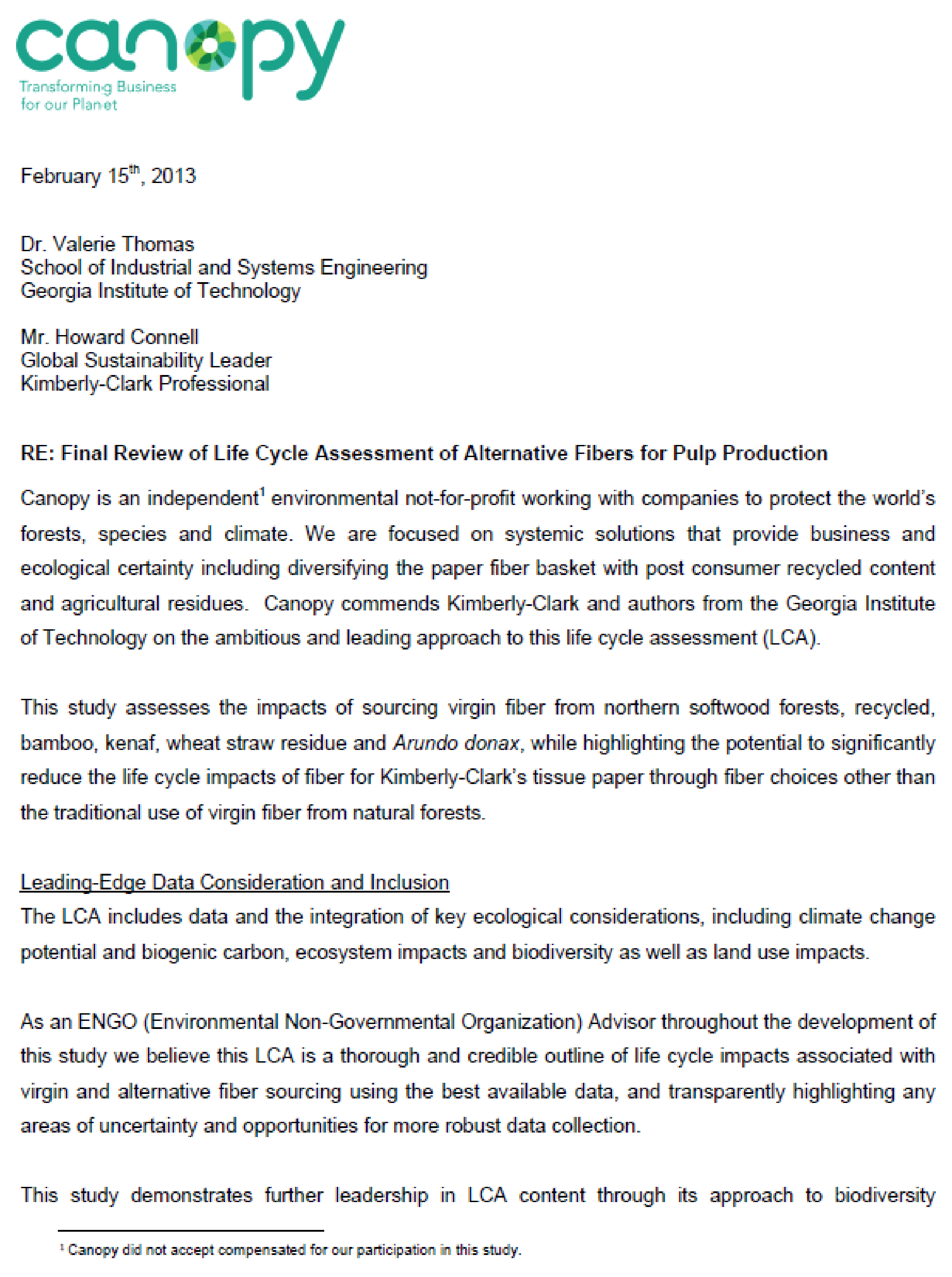
The panel agrees that interpretation of the results is made with respect of the limitations and the goal of the study. The study provides a better understanding of the advantage and challenge associated with each type of fiber. Hence, this study can be presented as a first step towards a demonstration of the environmental relevance (or not) of alternative fibers. However, the support of strong comparative assertion is not possible and would require:

- Use of site-specific assessment: for addressing limit of the biodiversity and water assessment.
- Improvement of fiber and pulp production data: several data are based on fiber production processes that have not been brought to scale.
- Demonstration of equivalence between fibers: need to develop a better understanding of the use of this fiber and how they can substitute each other for the production of tissue products.

5. **The study report is transparent and consistent.**

The report presents a good level of transparency and meets the ISO requirements for third party report. Although it cannot be used for supporting comparative assertions disclosed to the public, it can be used as a basis for communicating the advantage and challenge associated with the production of the different fibers used in tissue products.

5 NGO Statements



canopy
Transforming Business
for our Planet

February 15th, 2013

Dr. Valerie Thomas
School of Industrial and Systems Engineering
Georgia Institute of Technology

Mr. Howard Connell
Global Sustainability Leader
Kimberly-Clark Professional

RE: Final Review of Life Cycle Assessment of Alternative Fibers for Pulp Production

Canopy is an independent[1] environmental not-for-profit working with companies to protect the world's forests, species and climate. We are focused on systemic solutions that provide business and ecological certainty including diversifying the paper fiber basket with post consumer recycled content and agricultural residues. Canopy commends Kimberly-Clark and authors from the Georgia Institute of Technology on the ambitious and leading approach to this life cycle assessment (LCA).

This study assesses the impacts of sourcing virgin fiber from northern softwood forests, recycled, bamboo, kenaf, wheat straw residue and *Arundo donax*, while highlighting the potential to significantly reduce the life cycle impacts of fiber for Kimberly-Clark's tissue paper through fiber choices other than the traditional use of virgin fiber from natural forests.

Leading-Edge Data Consideration and Inclusion

The LCA includes data and the integration of key ecological considerations, including climate change potential and biogenic carbon, ecosystem impacts and biodiversity as well as land use impacts.

As an ENGO (Environmental Non-Governmental Organization) Advisor throughout the development of this study we believe this LCA is a thorough and credible outline of life cycle impacts associated with virgin and alternative fiber sourcing using the best available data, and transparently highlighting any areas of uncertainty and opportunities for more robust data collection.

This study demonstrates further leadership in LCA content through its approach to biodiversity

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[1] Canopy did not accept compensated for our participation in this study.

(Section 4.2.1), biogenic carbon (Section 3.5) and foregone growth impacts (Section 4.3). The authors include not only biogenic carbon but also ecosystem and biodiversity implications ("the potential biodiversity impact of northern softwood pulp is about eight times larger than the other fibers" (pg.76)). In fact, "this full [biogenic] carbon accounting has often not been included in previous environmental assessments of pulp and paper products." (pg.3). The critical nature of including biogenic carbon is highlighted through the LCA conclusion that "biogenic carbon emissions, both during the production process and from emissions after disposal of the product, are the largest component of greenhouse gas emissions for any of the pulps considered." (pg.101).

We agree with the report statement that "further study and analysis of ecosystem impacts using other methods should be considered, and for both bamboo and northern softwood, and effort should be made to select sites and management practices that would have low ecosystem impacts." (pg.101). Canopy also recommends a high conservation value (HCV) assessment be undertaken for any northern softwood procurement areas as well as on lands that may be converted to bamboo plantations before the bamboo is planted. The assessment would extend beyond vascular plants to encompass a full high conservation value (HCV) assessment.

Collaborative and Robust Process

The collaboration and consultation process of this LCA with representatives of the ENGO community also distinguishes the process undertaken in the development of the study. Canopy was involved in providing input to the scope of some impacts assessed in the study, was provided with numerous drafts and iterations, was involved in 8 meetings to offer problem-solving input, proactively supported the collection of data to inform indicators such as biogenic carbon and biodiversity impacts, and most importantly was engaged in meaningful consultation that resulted in changes to the approach being taken and quality of the data used to assess some of the results. The process allowed for the meeting of scientific methodology and data that responds to the issue depth held by environmental organizations focused on the protection of the environment as their core business.

Recycled Fiber and Leftover Straw

Canopy is the leading organization working globally on using agricultural residue (left over wheat straw) fibers to diversify the fiber basket away from the use of ancient and endangered forests and to build lasting system solutions. These agricultural residues are leftover after the food harvest, after enough straw has been used for traditional agricultural uses like soil regeneration and animal bedding and currently in North America are often burned or landfilled.

However, it is clear that diversity of the fiber baskets and lasting ecological solutions requires recycled fibers and, *not or*, agricultural residue. We support a robust paper-recycling infrastructure in North America designed to increase current paper recovery rates. At the same time, opportunities to replace high conservation and high carbon value virgin forest fibers with agricultural residues fibers are strongly encouraged. Consistent with the LCA findings both the use of left-over wheat straw and recycled offer the opportunity to reduce environmental impacts and combined as a solution set allow for greater fiber diversification.

We appreciate the careful work done in this study to highlight the life cycle impacts associated with the chemical load of growing wheat and the emphasis that the wheat is being grown for food regardless of co-product potential associated with utilizing leftover wheat straw in paper production. Currently wheat straw agricultural residue is being burned in areas that may be potential supply sources and the pollution associated with this has not been accounted for in the study.

Solutions to Address Invasiveness and Land Conversion

Canopy does not endorse the use of all fiber types in the study, particularly invasive species such as *Arundo donax* and invasive bamboo species. Proliferation of on purpose crops in the absence of full location specific LCAs showing benefits and including assessment of impacts to food security must be avoided. It is also critical to avoid the conversion of natural forest to plantations. This study does suggest Kimberly-Clark is looking at the conversion of plantations, not natural forests, to bamboo in the US Southeast. We agree with the report findings that more research needs to be undertaken with regards to the possible invasiveness of bamboo species as well as the watershed demands (site specific water depletion potential) of bamboo and the potential impact on biodiversity. If it is ultimately determined there are significant environmental benefits to bamboo plantations in the US Southeast, we recommend only using non invasive bamboo species and making sure that all bamboo is planted only in long standing FSC certified plantations, as FSC provides third-party certification to verify that no 'natural forests' were recently (since 1994) converted to plantations or other land uses. This guarantees that if bamboo is planted on FSC certified forestlands the pine plantation supplanted by the bamboo will not have been the result of a recent conversion of any 'natural forest.'

Next Steps

Kimberly-Clark has made a commitment to transition 50 percent of wood fiber sourced from natural forest to alternate fiber by 2025. We are excited to have contributed towards this study and hope it helps inform the decisions that will be made moving forward.

Although this study does not make comparative assertions it verifies a lower footprint associated with

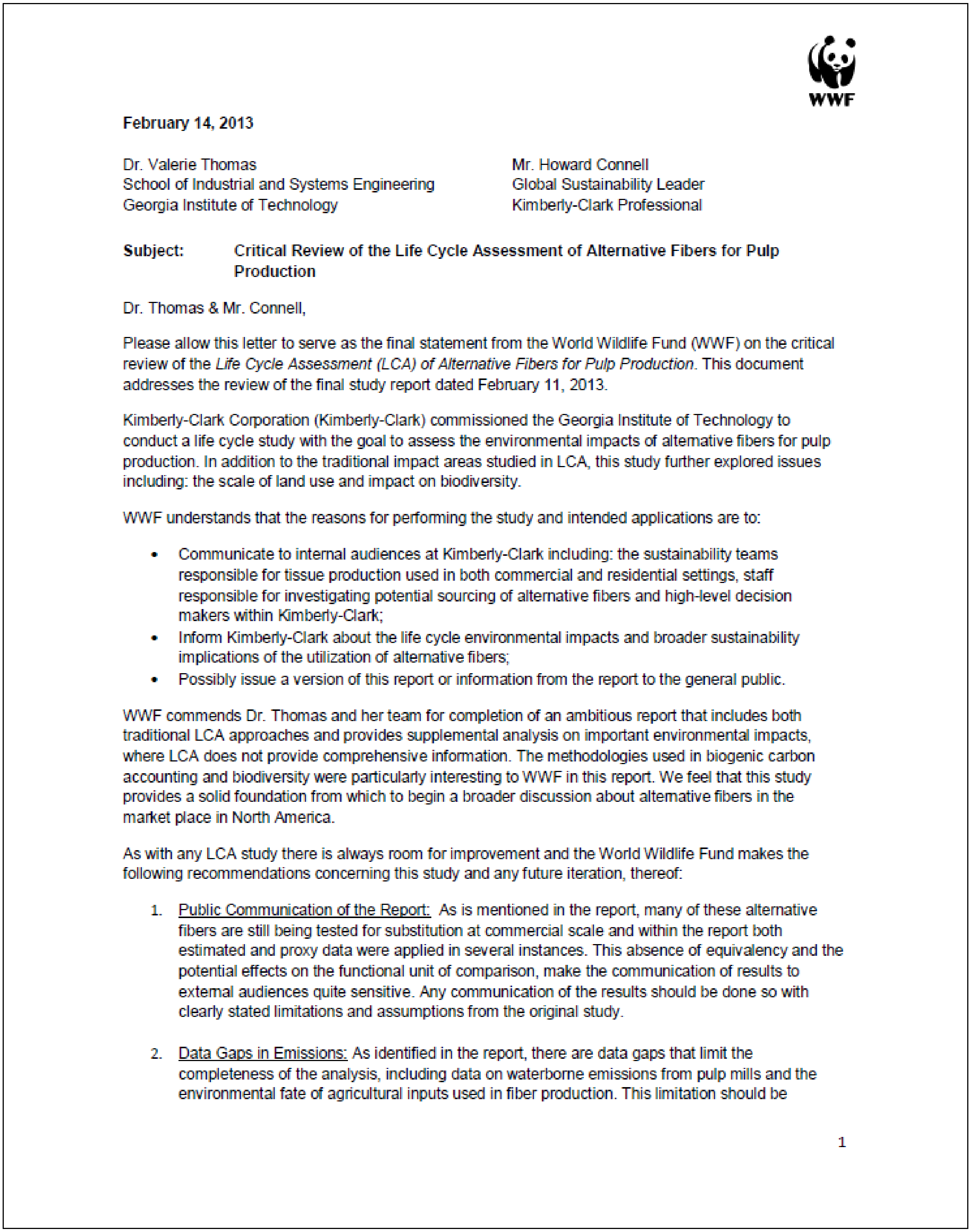
sourcing recycled fiber over virgin while also highlighting the value of some alternative fibers and their potential to significantly reduce the life cycle impacts. For example, as the study states in Section 3.5 "The overall implication is that all of the alternative fibers have a considerably smaller global warming impact than that of northern softwood. Although there is variation among the alternative fibers in terms of energy use in pulping and use of agricultural chemicals, all of which have greenhouse gas implications, these effects are small compared to the dominant effect of use of slow-growing trees for fiber." (Pg.66).

In addition, we encourage Kimberley-Clark to release a public version of this study as soon as possible, with all proprietary information removed, so that others may benefit from the scientific leadership if provides.

Sincerely,

Neva Murtha, Canopy

Canopy is a not-for-profit environmental organization dedicated to protecting forests, species and climate. We believe collaboration is the key and that businesses can be a powerful force for solutions, so we work with more than 700 companies to help ensure their supply chains are sustainable. Our partners include Sprint, The New York Times, Random House, Hearst, Scholastic, and Lonely Planet. For more information visit: www.canopyplanet.org.



WWF

February 14, 2013

Dr. Valerie Thomas
School of Industrial and Systems Engineering
Georgia Institute of Technology

Mr. Howard Connell
Global Sustainability Leader
Kimberly-Clark Professional

Subject: **Critical Review of the Life Cycle Assessment of Alternative Fibers for Pulp Production**

Dr. Thomas & Mr. Connell,

Please allow this letter to serve as the final statement from the World Wildlife Fund (WWF) on the critical review of the *Life Cycle Assessment (LCA) of Alternative Fibers for Pulp Production*. This document addresses the review of the final study report dated February 11, 2013.

Kimberly-Clark Corporation (Kimberly-Clark) commissioned the Georgia Institute of Technology to conduct a life cycle study with the goal to assess the environmental impacts of alternative fibers for pulp production. In addition to the traditional impact areas studied in LCA, this study further explored issues including: the scale of land use and impact on biodiversity.

WWF understands that the reasons for performing the study and intended applications are to:

- Communicate to internal audiences at Kimberly-Clark including: the sustainability teams responsible for tissue production used in both commercial and residential settings, staff responsible for investigating potential sourcing of alternative fibers and high-level decision makers within Kimberly-Clark;
- Inform Kimberly-Clark about the life cycle environmental impacts and broader sustainability implications of the utilization of alternative fibers;
- Possibly issue a version of this report or information from the report to the general public.

WWF commends Dr. Thomas and her team for completion of an ambitious report that includes both traditional LCA approaches and provides supplemental analysis on important environmental impacts, where LCA does not provide comprehensive information. The methodologies used in biogenic carbon accounting and biodiversity were particularly interesting to WWF in this report. We feel that this study provides a solid foundation from which to begin a broader discussion about alternative fibers in the market place in North America.

As with any LCA study there is always room for improvement and the World Wildlife Fund makes the following recommendations concerning this study and any future iteration, thereof:

1. Public Communication of the Report: As is mentioned in the report, many of these alternative fibers are still being tested for substitution at commercial scale and within the report both estimated and proxy data were applied in several instances. This absence of equivalency and the potential effects on the functional unit of comparison, make the communication of results to external audiences quite sensitive. Any communication of the results should be done so with clearly stated limitations and assumptions from the original study.

2. Data Gaps in Emissions: As identified in the report, there are data gaps that limit the completeness of the analysis, including data on waterborne emissions from pulp mills and the environmental fate of agricultural inputs used in fiber production. This limitation should be

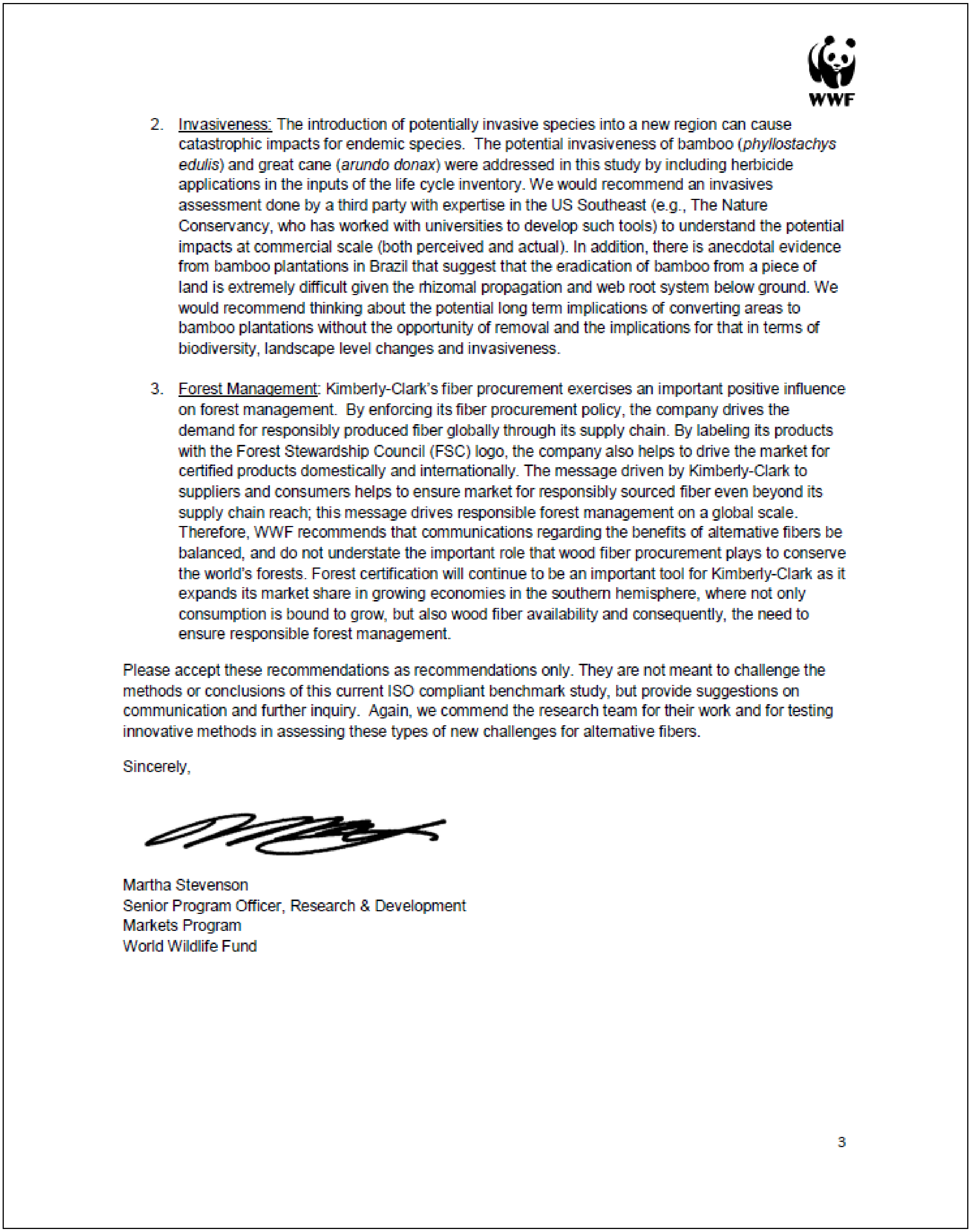
communicated clearly when discussing any results that may be affected especially ecosystem impacts.

3. Water: We applaud the addition of the evapotranspiration calculation and water withdrawal data in the water use portion of the assessment. We understand that the Pfister methodology is standard LCA practice, however, we find the method limited in that it only uses consumption in its water stress calculations, which does not provide a complete picture of the implications within the watershed. The Pfister methodology does not assess environmental flow (evapotranspiration of the natural (original) ecosystem and flow requirements of the rivers and streams) and also does not address freshwater biodiversity. The US Southeastern Rivers are some of the most biologically diverse watersheds according to World Wildlife Fund, Nature Conservancy, NatureServe and others. For these reasons, WWF would recommend site specific analysis of the water implications of large scale implementation of any alternative fiber production in the US Southeast.

4. Biodiversity: The ReCiPe method used in this report to assess land occupation and land transformation and the impact on ecosystems should be clearly described in any external communications. This method should not be short-handed to describe a "biodiversity assessment" as the model is based on vascular plant species from the United Kingdom and Central Europe, which have significantly different glaciation histories than North America (the academic literature has documented widely the low number of endemic species in the UK). Also, it does not account for freshwater biodiversity, for which the US Southeast is a key ecoregion globally. WWF would recommend a site specific analysis of the biodiversity implications of large scale implementation of any alternative fiber production in the US Southeast.

While Life Cycle Assessment is a useful tool for analyzing trade-offs between some environmental impact areas – it's not a perfect tool and in this specific application has some failings that could influence the current conclusions of this study. The research team has acknowledged the short comings of LCA in their study, including short comings in the assessment ecosystem services, biodiversity impacts (terrestrial and freshwater), and invasive species impacts. WWF understands this is the first step of KC's inquiry into alternative fibers and we would like to discuss some of these issues briefly to provide a conservation perspective and suggest some possible next steps for further assessment prior to entering full scale experimentation.

1. Ecosystem Services: Ecosystem Services are the benefits people obtain from ecosystems. They are typically divided into four categories including: provisioning services such as food and water; regulating services such as flood and disease control; cultural services such as spiritual, recreational, and cultural benefits; and supporting services such as nutrient cycling that maintain the conditions for life on earth. Ecosystem Services are typically assessed through a scenarios-based tool to understand how different human interventions/actions can impact the services of a given landscape and often these assessments are informed through a stakeholder process involving local experts, to be certain that the model reflects reality as closely as possible. Ecosystem Services have not been assessed as part of this study and WWF does not consider LCA a particularly adept method at analyzing these spatially explicit conditions. Prior to significant investment in alternative fiber production, especially those involving significant land use change or introduction of potentially invasive species, WWF would recommend a scenarios-based assessment to understand the potential impacts to a given area.



2. Invasiveness: The introduction of potentially invasive species into a new region can cause catastrophic impacts for endemic species. The potential invasiveness of bamboo (*phyllostachys edulis*) and great cane (*arundo donax*) were addressed in this study by including herbicide applications in the inputs of the life cycle inventory. We would recommend an invasives assessment done by a third party with expertise in the US Southeast (e.g., The Nature Conservancy, who has worked with universities to develop such tools) to understand the potential impacts at commercial scale (both perceived and actual). In addition, there is anecdotal evidence from bamboo plantations in Brazil that suggest that the eradication of bamboo from a piece of land is extremely difficult given the rhizomal propagation and web root system below ground. We would recommend thinking about the potential long term implications of converting areas to bamboo plantations without the opportunity of removal and the implications for that in terms of biodiversity, landscape level changes and invasiveness.

3. Forest Management: Kimberly-Clark's fiber procurement exercises an important positive influence on forest management. By enforcing its fiber procurement policy, the company drives the demand for responsibly produced fiber globally through its supply chain. By labeling its products with the Forest Stewardship Council (FSC) logo, the company also helps to drive the market for certified products domestically and internationally. The message driven by Kimberly-Clark to suppliers and consumers helps to ensure market for responsibly sourced fiber even beyond its supply chain reach; this message drives responsible forest management on a global scale. Therefore, WWF recommends that communications regarding the benefits of alternative fibers be balanced, and do not understate the important role that wood fiber procurement plays to conserve the world's forests. Forest certification will continue to be an important tool for Kimberly-Clark as it expands its market share in growing economies in the southern hemisphere, where not only consumption is bound to grow, but also wood fiber availability and consequently, the need to ensure responsible forest management.

Please accept these recommendations as recommendations only. They are not meant to challenge the methods or conclusions of this current ISO compliant benchmark study, but provide suggestions on communication and further inquiry. Again, we commend the research team for their work and for testing innovative methods in assessing these types of new challenges for alternative fibers.

Sincerely,

Martha Stevenson
Senior Program Officer, Research & Development
Markets Program
World Wildlife Fund

6 ISO 14044 Compliance Grid

Specification	Compliance
General reporting requirements and considerations	
Are the results and conclusions of the LCA completely and accurately reported without bias to the intended audience?	Requirement fulfilled
Are the results, data, methods, assumptions, and limitations transparent and presented in sufficient detail to allow the reader to comprehend the complexities and trade-offs inherent in the LCA?	Requirement fulfilled
Does the report allow the results and interpretation to be used in a manner consistent with the goals of the study?	Requirement fulfilled
LCA commissioner, LCA practitioner (internal or external)	Requirement fulfilled
Date of report	Requirement fulfilled
Statement that the study has been conducted according to the requirements of ISO 14040 and 14044	Requirement fulfilled
Goal of the study	
Reasons for carrying out the study	Requirement fulfilled
Intended applications	Requirement fulfilled
Target audiences	Requirement fulfilled
Statement whether the study intends to support comparative assertions intended to be disclosed to the public	N/A
Scope of the study	
→ ***Function***	
Definition	Requirement fulfilled
Statement of performance characteristics	Requirement fulfilled
Any omission of additional functions in comparisons	Requirement fulfilled
→ ***Functional unit***	
Definition	Requirement fulfilled
Consistency with goal and scope	Requirement fulfilled
Result of performance measurement	Requirement fulfilled
→ ***System boundary***	
Definition	Requirement fulfilled
Omissions of life cycle stages, processes or data needs. Quantification of energy and material inputs and outputs.	Requirement fulfilled
Assumptions about electricity production	Requirement fulfilled
→ ***Cut-off criteria for initial inclusion of inputs and***	

outputs	
Description of cut-off criteria and assumptions	Requirement fulfilled
Effect of selection on results	Requirement fulfilled
Inclusion of mass, energy and environmental cut-off criteria	Requirement fulfilled
Life cycle inventory analysis	
Data collection procedures	Requirement fulfilled
Qualitative and quantitative description of unit processes	Requirement fulfilled
Sources of published literature	Requirement fulfilled
Calculation procedures	Requirement fulfilled
Data quality analysis	Requirement fulfilled
Treatment of missing data	Requirement fulfilled
Sensitivity analysis for refining the system boundary	Requirement fulfilled
Documentation and justification of allocation procedures	Requirement fulfilled
Uniform application of allocation procedures	Requirement fulfilled
Life cycle impact assessment	
LCIA procedures, calculations and results of the study	Requirement fulfilled
Limitations of the LCIA results relative to the defined goal and scope of the LCA	Requirement fulfilled
Relationship of LCIA results to the defined goal and scope	Requirement fulfilled
Relationship of the LCIA results to the LCI results	Requirement fulfilled
Impact categories and category indicators considered, including a rationale for their selection and a reference to their source	Requirement fulfilled
Descriptions of or reference to all characterization models, characterization factors and methods used, including all assumptions and limitations	Requirement fulfilled
Descriptions of or reference to all value-choices used in relation to impact categories, characterization models & factors, normalization, grouping, weighting and, elsewhere in the LCIA, a justification for their use and their influence on the results, conclusions and recommendations	Requirement fulfilled
A statement that the LCIA results are relative expressions and do not predict impacts on category endpoints, the exceeding of thresholds, safety margins or risks	Requirement fulfilled
When applicable:	
Description and justification of the definition and description of any new impact categories, category indicators or characterization models used for the LCIA	Requirement fulfilled

Statement and justification of any grouping of the impact categories	Requirement fulfilled
Any further procedures that transform the indicator results and a justification of the selected references, weighting factors, etc.	Requirement fulfilled
Any analysis of the indicator results, for example, sensitivity and uncertainty analysis or the use of environmental data, including any implication for the results	Requirement fulfilled
Data and indicator results reached prior to any normalization, grouping or weighting shall be made available together with the normalized, grouped or weighted results	Requirement fulfilled
Life cycle interpretation	
Results	Requirement fulfilled
Assumptions and limitations associated with the interpretation of results, both methodology and data related	Requirement fulfilled
Data quality analysis	Requirement fulfilled
Full transparency in terms of value-choices, rationales and expert judgments	Requirement fulfilled
Additional requirements for comparative assertions intended for public disclosure	
Analysis of material and energy flows to justify their inclusion or exclusion	Requirement fulfilled
Assessment of the precision, completeness and representativeness of data used	Requirement fulfilled
Description of the equivalence of the systems being compared	Requirement fulfilled
Description of the critical review process	Requirement fulfilled
Evaluation of the completeness of the LCIA	Requirement fulfilled
Statement as to whether or not international acceptance exists for the selected category indicators and a justification for their use	Requirement fulfilled
Explanation for the scientific and technical validity and environmental relevance of the category indicators used in the study	Requirement fulfilled
Results of the uncertainty and sensitivity analyses	Requirement fulfilled
Evaluation of the significance of the differences found	Requirement fulfilled

Critical review	
Name and affiliation of reviewers	Requirement fulfilled
Critical review reports	To be added
Responses to recommendations	To be added

7 Critical Review Panels Comments [Removed]

This section has been removed to protect confidential Kimberly-Clark information that is discussed.