Life cycle and market review of the major alternative fibers for paper production

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Contents

1. Executive Summary

Non-wood fibers proposed for paper include hemp, flax (linen), reed (arundo donax), bamboo, kenaf, and elephant grass (miscanthus). These may substitute for wood pulps including southern and northern softwood, eucalyptus, and acacia, among others, and may substitute for recycled fibers. Some of these alternative fibers are used in specialty markets. All are currently produced in larger quantities outside of the United States than domestically.

In the U.S. a number of major manufacturers are now selling products with non-wood fibers. Bamboo is used in paper towels sold by Kimberly-Clark. Flax is used in industry wipes sold by Georgia Pacific. Sugarcane bagasse copy paper is sold by Staples and Office Depot. Bamboo and bagasse paper plates and other products are widely available. Use of elephant grass (miscanthus) is being discussed in Europe.

The environmental hot-spots for alternative fibers are agricultural inputs and activities – planting, fertilizers, pesticides, water, and harvesting – as well as invasiveness or other special ecosystem effects. Miscanthus and bamboo are high yield perennials with low agricultural inputs that may have low overall environmental impacts. Arundo donax (reed) also is a fast growing low input fiber, although questions remain about invasiveness in some regions and its water resources impacts. Hemp is a low input annual plant, although low impact harvesting processes need further demonstration. Kenaf and flax are high quality fibers whose environmental impacts are not particularly low, yet these might be mitigated by low-impact agriculture and development of co-products.

The alternative fibers can be compared with tree fibers and recycled fibers. There can be substantial environmental and ecosystem impacts from harvesting of trees, and not only for operations that do not meet best-practice forest certification standards. There may be substantial climate impacts from harvesting of trees, particularly the slow-growing northern softwoods or trees grown in peatlands. Recycled fibers generally have low environmental impact, although efficient collection, processing, and manufacturing is essential to create lowest impact paper.

A substantial portion of the environmental impacts of paper products is associated with the pulping and paper making processes, across all fiber types. Alternative fibers may have somewhat different pulping impacts from each other and from traditional fibers, although there is no evidence that any of these differences are large contributors to the overall life cycle impacts.

There is also growing interest in the pulping of agricultural residues globally. Agricultural wastes, such as sugar-cane bagasse and wheat straw, have low environmental impacts because their production impacts are shared with their main application (e.g. sugar and wheat production).

The U.S. pulp market is in the range of 40 million tons per year, with southern softwood selling at about $30 per dry ton delivered. Roughly 6 to 7 million tons of U.S. wheat straw could be available at less than $40 per dry ton. The non-waste alternative fibers are more expensive, with U.S. miscanthus most readily available at $60 per dry ton delivered. Yet with development, as much as 65 million dry tons per year of U.S. miscanthus could be supplied at $40 per dry ton by 2040.

Bottom Line: Fiber type, fiber production and harvesting methods, transportation and pulping methods can also have significant impacts on the environmental impact of paper. Fibers that grow quickly with low input, or that are waste products, tend to have overall lower environmental impacts.

2. Introduction

Study goal: This study provides a life cycle review of the major alternative fibers for the production of paper. These include virgin fibers from rapidly renewable sources, including hemp, flax, *arundo donax*, bamboo, kenaf, elephant grass, and also agricultural residues, including wheat straw and bagasse. The study highlights the major environmental impacts of alternative fibers that have been identified in previous studies. Comparison is made with conventional wood fibers, including northern and southern softwood, eucalyptus and acacia, and with recycled fiber. The study includes a market review on the presence of alternative fibers in the U.S. domestic market and the trends and potential for their use.

3. Methodology

This literature review was undertaken as follows. First, an inventory of existing life cycle analyses of alternative fibers for paper was prepared and studies were either retained for further analysis, or dismissed if the background information and data quality were low. The retained studies were summarized according to the fibers studied and the LCA indicators included in the analysis. Then, the hot spots were identified and assessed.

4. Fibers

The alternative fibers considered are hemp, flax, *Arundo donax*, bamboo, kenaf, elephant grass, wheat straw and bagasse. The conventional fibers included for comparison are northern and southern softwood, eucalyptus, acacia, and recycled fibers. This section describes all the fibers and Table 1 summarizes the most important data.

4.1 Eucalyptus – a conventional wood fiber

Short description: Eucalyptus is one of the most common wood species used for paper production, and is included in this study for comparison purposes. The Brazilian planted forests (6.7 million ha) are dominated by eucalyptus (over 5.1 million ha) (Gomes et al 2014). Eucalyptus is used due to its high productivity, low rotation periods, and long fibers that provide a high quality pulp and paper (Vieira et al. 2010).

Expected yield: The average productivity of eucalyptus ranges between 30 and 40t/ha/year (Lopes Silva et al. 2015; Gomes et al. 2013; 2014).

Production inputs: For soils low in organic matter (OM) and available P, which mainly occurs in SW Spain, application of 40–60 kg/ha N, 30–40 kg/ha P2O5 and 40–60 kg/ha K2O is recommended, considering planting plus maintenance fertilization. Where soils are richer in OM and water deficiency is lower, the application (planting + maintenance fertilization) of 15–30 kg/ha N, 30–40 kg/ha P2O5 and 60–80 kg/ha K2O is recommended (Vieira et al. 2016).

4.2 Acacia – a conventional wood fiber

Short description: Acacia is a fast growing species used in forest plantations, in both monsoon Asia and the Pacific. Due to its fast growth and good adaptability on degraded soils, its adoption has been considered a positive step for sustainable forestry practices. Pulping of Acacia species, particularly plantation-grown species, has gained significant attention in recent years because of its potential uses for producing high quality paper products and potential for high-yield pulping (Rosli et al. 2009).

Due to the faster growth cycle of acacia species in tropical climates, the volume of wood that can be harvested per hectare is high compared to northern latitude fibers. In Indonesia, acacia rotation times are five to six years, a considerably shorter time than for northern latitude plantation species (April 2015).

Production inputs: A report from the Rainforest Action Network (RAN) and Japan Tropical Forest Action Network (JATAN) estimates greenhouse gas emission footprint from acacia plantations in Indonesia to be 16-21 tons CO_2e per ton of paper, due to the clearing of peat lands for plantation establishment (RAN and JATAN 2010). That report was in response to a carbon footprint study for Asia Pulp and Paper Group (APP) by Environmental Resource Management (ERM); that study is reported to have found much lower emissions although it was never released publicly and we were unable to locate the executive summary. In August of 2015, recognizing the substantial greenhouse gas emissions from peatland, APP retired some plantation lands in order to protect peatlands (APP 2015), and in May 2016 APP established a monitoring dashboard (APP 2016) to allow tracking of its forest conservation policy.

4.3 Southern Softwood – a conventional wood fiber

Short Description: Loblolly pine is the dominant wood species used commercially in the southeastern United States. We did not identify life cycle assessment studies that contained detailed information on southern softwood pulp. However, in comparison with northern softwood, discussed below, southern softwood is faster growing with therefore larger yield per hectare. This fast growth implies a lower biogenic carbon footprint for southern softwood than for northern softwood, because the carbon released from use of southern softwood can be more rapidly recaptured in new growth. And unlike northern softwood it is essentially entirely harvested from plantations.

4.4 Northern Softwood – a conventional wood fiber

Short Description: Northern softwood is produced throughout Canada, in the Nordic countries, and in the northern United States. Bamboo has been considered as a potential substitute for northern softwood pulp in tissue papers (Thomas and Liu 2013).

Expected yield: Kissinger et al. (2007) report spruce yields of 1.3, 2.0 and 1.6 m3/ha-y in Manitoba, Saskatchewan and Alberta, respectively, whereas aspen in those same regions has a reported yield of 2.5, 2.4 and 2.9 m3/ha-y, respectively. Sendak et al. (2003) report harvest yields of northern softwoods in the range of 27-32 ft3/acre-year, corresponding to 1.4 t/ha-y. 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 m3/ha-y, corresponding to 5.4 t/hay, has been achieved in British Columbia with intensive management (Binkley, C. S. 1999).

Production inputs: 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 (Thomas and Liu, 2013).

4.5 Recycled fiber – a conventional wood fiber

Short Description: Recycled fiber is widely used in tissue products, copy paper, and other paper products. De-inked recycled fiber is a lower strength fiber that is extensively used as a component in tissue paper production. Arundo donax, kenaf, and wheat straw have been considered as potential substitutes for deinked recycled pulp in tissue papers (Thomas and Liu 2013). Recycled fiber for tissue paper is typically sources from mixed office paper collected from office locations and transported to a materials recovery facility (MRF) and from there it is transported by a combination of truck and rail to a de-inking pulp mill.

Collection Inputs: 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; 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.

Reprocessing of waste paper into new paper products uses less energy and causes fewer emissions than manufacturing of the same quantity of paper from virgin resources. Separate collection and recycling of waste paper may thus constitute an environmental benefit. The actual savings will depend on the technology used for the reprocessing of paper and its emissions, source and amount of energy used, etc., as well as on the technology used for manufacturing of virgin paper which is assumed to be avoided because of the waste paper reprocessing (Merrild et al. 2008).

4.6 Hemp

Short description: Industrial hemp (Cannabis sativa) is native to Central Asia. Hemp is a slender and annual herbaceous crop which depending on its handling and agro-chemical aspects can supply up to 20 tonnes of dry matter per hectare. Hemp is a multi-use annual crop cultivated for fiber, animal feed and seed. There is current interest in hemp as a renewable source for industrial products including paper making, horse bedding, house building and insulation materials or biodiesel (Gonzales-Garcia et al. 2010). Hemp is a cool season crop that is high yielding compared to other crops (Van DerWerf et al., 1996) and can be grown over a wide range of agro-ecological conditions. It is a low-input crop as its rapid growth ensures quick canopy closure, providing good natural weed control and also has low fertilizer requirements (Bennett et al. 2006).

Expected yield: Hemp can be cultivated in crop rotation (Gonzales-Garcia et al. 2010). The average yield ranges from 7-15 (t/ha) per year (Pande 1995, da Silva Vieira et al. 2010). Due to the low yield of hemp stems in terms of fibers, where only 34.3% is usable for the pulp industry, hemp pulping produces high amounts of black liquor, which can be used as a source of renewable energy (da Silva Viera et al. 2010).

Production inputs: Hemp is an annual plant, which needs to be sown and fertilized every year (da Silva Viera et al. 2010). Fertilizer inputs are reported as 85 (N), 65(P_2O_5), 125 (K_2O), in kg/ton of fiber (Gonzales-Garcia et al. 2010).

Energy requirements for hemp are reported as 15,000MJ for traditionally processed organic hemp to 33,000 MJ for conventionally grown hemp processed through a green decortication system. The greatest energy requirements for hemp are in the fiber production stage, as the cultivation of the crop requires fewer inputs (Cherrett et al. 2005).

Pesticide and herbicide: Hemp is reported to be grown without pesticides or herbicides (Gonzales-Garcia et al. 2010)

Irrigation: Hemp is reported to be grown without irrigation, with rainfall sufficient to support the crop (Gonzales-Garcia et al. 2010).

4.7 Flax

Short description: Flax is an annual plant with slender stems. It is native from the eastern Mediterranean to India. It is a bast fiber plant, i.e. its fibers are derived from the outer part of the stem. This crop is sown for both its seeds (linseed or seed flax) and fibers (fiber flax), which are alternative types of the same species, Linum usitatissimum (Gonzales-Garcia 2010).

Herbicide: Herbicides are used in flax fiber production as the plant does not defend well from weeds. Different types and rates of herbicide application have been reported (Easson and Molloy, 2000; Lloveras et al., 2006; Schmidt et al., 2004; van der Werf and Turunen). In Gonzales-Garcia et al. (2010) authors assume a dosage of 0.468 kg of active ingredient, (4-chloro-2-methylphenoxy) acetic acid, per ton of fiber.

4.8 Arundo donax

Short description: Arundo donax L. (giant reed) is a widely distributed naturally growing perennial rhizomatous grass with a segmented tubular structure like bamboo. It has been considered as a promising non-wood plant for the pulp and paper industry (Shatalov and Pereira, 2002). The easy adaptability to different ecological conditions, the annual harvesting period and the high biomass productivity reached by intensive cultivation, combined with appropriate chemical composition have drawn attention to Arundo donax as an alternative source of fibers (Shatalov and Pereira, 2005).

Expected yield: Arundo donax produces a high amount of biomass per unit area compared to traditional energy crops; yield depends on several factors such as the age of the plants, pedo-climatic conditions, plant density and agronomics, so that high variability is reported in the literature (Corno et al. 2014). The expected yields are between 7 and 39 t/ha/yr (Bruner et al. 2015). Other studies report a range of Arundo donax yields of 20 t/ha/yr and 37.7 t/ha/yr (Forte et al. 2015 and Angelini et al. 2009a).

Production inputs: After the first year of plantation, Arundo donax does not need organic or inorganic fertilization to complete its life cycle and to achieve high yields, but the application of fertilizers enhances biomass production. The addition of nutrients (Angelini et al., 2005; Christou et al., 2003; Gilbert et al., 2010), especially nitrogen (Borin et al., 2013; Quinn et al., 2007) promotes a better development of rhizomes and consequently of new sprouts, allowing yield increases. Nutrient availability defines, also, qualitative improvement of the biomass, above all if it is related to a specific use, e.g. for combustion (Corno et al. 2014). Reported annual fertilizer application rates for nitrogen (N), phosphor (P) and potassium (K) are 111, 60 and 385 kg per hectare, respectively (Schmidt et al. 2015). Total energy input for the production of Arundo donax biomass was 17,000 MJ/ha for year 1 and 4000 MJ/ha in years 2 through 12 (Angelini et al. 2009a).

Irrigation: Water availability is not a limiting factor for plant growth: it was reported that Arundo donax could resist both soil characterized by lack of water and soil that is water-saturated (Lewandowski et al., 2003;Corno et al. 2014). However, in Schmidt et al. (2015), they assumed irrigation m3/ha/year of 6000.

Invasiveness: Invasiveness may be a concern for Arundo donax (Breed 2012) in some regions. Because of its rapid growth rate (Dudley 2000; Perdue 1958) and ready ability to resprout (Else 1996), Arundo donax is capable of forming dense, monotypic stands within a relatively short time (Bell 1997; Coffman 2007; Perdue 1958; Rieger and Kreager 1989), thus reducing the biodiversity of the riparian zone. (Moore et al. 2010). For instance, losses in the abundance and richness of the aerial invertebrate communities have been positively correlated with Arundo donax coverage in California) (Herrera and Dudley 2003). Although it is not a federally-listed invasive species, it is considered a noxious weed in California, Colorado, and Texas. Oregon recognizes its invasiveness but may allow small-scale biomass production in regulated areas (Burner et al. 2015).

Effects on soil: The long-term cultivation of Arundo donax could present technical problems for soil restoration at the end of the crop cycle, as it requires all plants to be removed and rhizomes to be destroyed by both herbicides and soil plowing. Because of high biomass production, attention must be paid to the impact of Arundo donax cultivation on soil properties. Literature speculates that prolonged nutrient uptake could reduce the availability of the main elements in the soil, especially N (Angelini et al., 2009a; Borin et al., 2013). Other authors reported positive effects on soil, i.e. the increase of both organic matter and microbial biomass content (Riffaldi et al., 2012). In particular, because Arundo donax is a no tillage crop, soil can accumulate organic matter more than that obtainable with other cultures such as, for example cropping sequences: legumes and cereal conventionally cultivated, and natural grassland (with forage removal) (Riffaldi et al., 2012). Other positive effects are reported by Christou et al. (2003) that highlighted the importance of Arundo donax on preserving soil erosion in soil slopes and in limiting nitrate leaching (Corno et al. 2014).

Pulp production: Thanks to the strength of its structure and to the huge amount of cellulose contained, Arundo donax can be used in the paper industry. The plant internodes were found to be the more suitable parts for pulping and paper making thanks to the lower lignin content after treatment and to the viscosity, strength and brightness properties of the pulp (Shatalov and Pereira, 2002).

4.9 Bamboo

Short description: Bamboo is a giant woody grass that grows in tropical and subtropical regions of the world. Bamboo stalks can be cut leaving the roots intact to grow. Each plant can stay up to 75 years and bamboo reaches harvesting maturity in three to six years (Egbewole et al. 2015). Globally, bamboo forests grow on at least 37 Mha (Sohel et al. 2015) and make up 3.2 % of the forest areas of their host countries, and about 1% of the global forest area. India, China, Indonesia, Ecuador, Myanmar, and Vietnam have the largest bamboo resources of 25 countries recently surveyed (Lobovikov et al. 2009).

The wide distribution of bamboo across the tropics and subtropics of Asia, Africa and Latin America, with an annual production estimated at between 15-20 million tonnes of fiber implies that it is highly significant as a livelihood material (Lou et al 2010). Several bamboo-producing countries, such as China and India, use bamboo in pulp, paper and more recently cloth. Bamboo paper has practically the same quality as paper made from wood. Its brightness and optical properties remain stable, while those of paper made from wood may deteriorate over time. The morphological characteristics of bamboo fibers yield paper with a high tear index, similar to that of hardwood paper. The tensile stiffness is somewhat lower compared with softwood paper. The strain strength is between that of hardwood and softwood papers (Lobovikov et al. 2007). Bamboos also grow in the dry tropics, even on shallow degraded soils. In fact, bamboo plantations are often attractive options for marginal or degraded land. They may actually improve such sites by accumulating high amounts of soil organic matter through their decomposing leaf and abundant fine root litter (Lobovikov et al. 2009).

Expected yield: Average global bamboo yields are 4-4.5 t/ha (Panda 1998; van der lugt 2009) although higher yields have been reported.

Production inputs: 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. 2003). According to Vogtlander et al. (2010) cultivation and harvesting from plantation: gasoline consumption 0.016 liter/7.65 kg.

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.

4.10 Kenaf

Short description: Kenaf is an annual herbaceous fiber plant in the combination of bast and core fibers is unique, as its bast takes about 35% of the stalk dry weight. The kenaf plant can grow very fast with a height of 1.5–4.5 m tall with a woody base within 4–5 months with annual fiber yields of 600–10,000 kg of dry fiber/acre (Akil et al. 2011) and requires less water to grow because it has a growing cycle of 150–180 days (Ramesh 2016). Kenaf is well known as a cellulosic source with both economic and ecological advantages. It is a hardy plant with a fibrous stalk which is resistant to insect damage and it is able to grow under a wide range of climatic conditions while requiring minimal fertilizers, water, and pesticides (Rashdi, et al. 2009). Kenaf is adaptable to various soils and requires only minimal chemical treatment, typically a single herbicide treatment, to grow effectively. Globally, kenaf has been widely considered for bioenergy and pulp uses, because of its extensive adaptation, strong resistance, large biomass and rich cellulose. Kenaf has been deemed environmentally friendly and high interest in kenaf cultivation in recent years have been achieved for two main reasons; (i) kenaf accumulates carbon dioxide at a significantly high rate and (ii) kenaf absorbs nitrogen and phosphorous from the soil (Ramesh 2016). Earlier studies, however, found relatively high use of fertilizers and irrigation water compared to other alternative pulp options (Thomas and Liu 2013).

Expected yield: Kenaf is comprised of about 35% bast (bark) and 65% core (wood) fibers. It has a reported yield of 15 t/ha-y (Finell 2003; Ogunwusi 2014).

Production Inputs and irrigation: Fertilizer application of 112 kg nitrogen, 22.4 kg phosphorus and 33.6 kg potash per hectare (100, 20, 30 pounds per acre) (Thomas and Liu, 2013). In Italy, Amaducci et al. (2000) report nitrogen fertilizer application at a rate of 100 kg/ha. 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) (Thomas and Liu, 2013). The greater water requirement of kenaf could be a problem in areas where irrigated water is limited (Banuelos et al. 2002).

4.11 Elephant grass (Miscanthus)

Short description: Miscanthus is a fast-growing plant with high biomass productivity. It has reported beneficial characteristics for pulp production such as high fiber production (similar to sugar cane) and appropriate chemical composition (Gomes et al. 2013). Miscanthus is also of substantial interest as a feedstock for biofuel production, and a great deal of study of the cost and environmental impacts of its production have been published in recent years.

The Swedish Paper company SCA is exploring the potential of elephant grass as a complement to wood fibers in the paper making process. The grass could be a complement to wood fibers in manufacturing a range of paper products, including toilet paper, paper towels and kitchen paper.[1]

Expected yield: Fiber yield ranges from 12 t/ha/yr in Finell (2003) to 30-45 dry t/ha/yr in Gomes et al. (2013).

Production inputs: Miscanthus is a low-impact perennial and has been reported to be grown with minimal inputs (Wang et al. 2012).

Irrigation: Miscanthus can be grown without irrigation.

4.12 Wheat Straw

Short description: Straw residue is a byproduct of existing agricultural practices and it would be produced regardless of whether it is used for pulp or other products. In virtually no cases is it likely that land would be converted from non-agricultural to agricultural use based solely on the need for pulp production; therefore, there is no estimate of the impact of land-use change for wheat straw residue demand (Fix et al. 2011). There has, however, been extensive analysis of the environmental and productivity implications of wheat straw removal as a function of the amount removed and as a function of geographic location, soil characteristics, etc. Wheat straw is of substantial interest as a feedstock for biofuel production, and a great deal of study of the cost and environmental impacts of its production have been published in recent years.

Expected yield: Wheat is widely grown globally. Average global wheat yields are 4 t/ha (Pande 1998; Jahan et al. 2009) while US yields are 3 t/ha[2].

Production inputs: According to Meisterling et al. (2009) the production of wheat in the US uses 66 kg N, 8.7 kg P, 41 kg diesel and 9.3 kg gasoline per hectare [check: other data in Fix et al. 2011].

Irrigation: Wheat production is assumed to be non-irrigated since only 5% of all wheat acres are irrigated (Meisterling et al. 2009).

Herbicides: 152-685 MJ/ha (Fix et al. 2011).

Invasiveness: Invasiveness is not a concern for wheat.

4.13 Bagasse

Short description: Bagasse is the residue after crushing and processing of sugar cane to remove the sugar juice. Bagasse fibers are of 1.0-1.5mm length and ca20 micron diameter, which is similar to hardwoods such as eucalyptus (0.7-1.3mm by 20-30 micron) (Covey et al. 2006). Storage can be a reason for concern

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[1] http://www.sca.com/Documents/en/Shape/2015/3/EN-SCA-Magazine-SHAPE-3-2015-Hand-hygiene.pdf?epslanguage=en

[2] http://www.ers.usda.gov/data-products/wheat-data.aspx#25171

since sugar cane is a seasonal crop and the crushing mills operate for only about half the year, so it is usually necessary to store large quantities of bagasse for long periods. Unfortunately, bagasse is prone to degradation and therefore special methods of storage are required (Covey et al. 2006). Currently it is used as a renewable resource in the manufacture of pulp and paper products and building materials (Poopak and Reza, 2012).

Expected yield: 9 t/ha/yr (Jahan et al. 2009).

Fiber	Expected yield (t/ha/yr)	Fertilizer (N, P, K) (kg/ha)	Energy (MJ/ha)	Other data
Eucalyptus	15-40[1,14,15,20]	15-60; 30-40; 40-80[2]		
Softwood	0.8-1.5[20,23]		Harvest: 40 [23]	
Acacia	12-22.3[24]			
Recycled Fiber				Collection and delivery energy: 500[25] -1500[26] MJ/t
Hemp	6.72-20[3,4,13]	68-85; 30-65; 114-125[4,19]	15,003-32,622[5]	
Flax	0.9*[10]	40; 30; 60[19]		Herbicide: I0.468 kg of active ingredient, (4-chloro-2-methylphenoxy) acetic acid per ton of fiber[4]
Arundo donax	7-39[6,7,8]	111, 60, 385 [9]	4,000-17,000 [8]	Invasiveness may be a concern for *Arundo donax*
Bamboo	4-4.5[3,11,20]	9, 11.5, 7.5[12]	Harvest 2700; Chipping 90 MJ/tc [23]	
Kenaf	15[13,20]	100, - , - [21]		
Elephant grass	12-45[1,13]	3.8;1.3;5.2 [22]		
Wheat straw	2-4[3,13,16,10,20]	66, 8.7, --[17]	41 kg diesel and 9.3 kg gasoline per hectare[17]	Herbicide: 152-685 MJ/ha[18]
Bagasse	9[13,19,20]			

[1] Gomes et al. 2013; [2] Vieira et al. 2016; [3] Pande, 1998; da Silva Viera et al. 2010; [4] Gonzales-Garcia et al. 2010; [5]Cherrett el al. 2005; [6] Bruner et al. 2015; [7] Forte et al. 2015; [8] Angelini et al. 2009a; [9] Schmidt et al. 2015; [10] Kissinger et al. 2007; [11] van der lugt 2009; [12] van de lugt 2003; [13] Finell 2003; [14] Lopes Silva et al. 2015; [15] Gomes et al. 2014; [16]Jahan et al. 2009; [17]Meisterling et al. 2009; [18] Fix et al. 2011; [18]Jahan et al. 2009; [19] VanderWerf and Tutune 2008; [20] Ogunwusi 2014; [21] Amaducci et al. 2000; [22] Wang et al. 2012; [23] Thomas and Liu 2013; [24] Velez et al. 2007; [25] EPA 2002; [26] Hischer 2007. * flax straw

Table 1: Fibers data

Pulp production: Bagasse pulps are generally of low strength. They are similar or slightly deficient to hardwood pulp and generally a long fiber component must be added where high tear strength or high machine speed are required (however, one small mill in Peru uses bagasse to make multi-wall bags for cement). Bagasse pulps are generally smooth, and soft. However, chemical pulps have poor opacity. It does not produce 'universally applicable pulps' under open market conditions. Therefore it is important to consider the final use very carefully when planning a mill (Covey et al. 2006).

Pith is the main problem for bagasse pulping as it creates problems during pulp washing, clogging in machine wire, etc. Adequate removal of pith is essential to produce a satisfactory pulp and to avoid wastage of chemicals. The strength of bagasse pulp is slightly lower than that of hardwood pulp. Bagasse pulps are generally smooth and soft (Jahan et al 2009).

5. Life cycle analysis: review

Life cycle assessment is a quantitative, science-based evaluation of the environmental impact of a product or service. There is limited number of LCA studies of alternative fiber papers. There are however numerous studies addressing some specific aspect of the process for one or more fibers, so a broader picture can be gained from the totality of the literature.

Among the analyzed fibers, eucalyptus has the most LCA analysis (Lopes et al. 2003; Dias et al. 2007; Jawjit et al. 2007; Gonzales Garcia et al. 2009; Vieira et al. 2010 and Lopes Silva et al. 2015).

Lopes et al. (2003) performed an LCA of Portugal's pulp and paper industry, and reported that printing and writing paper is the most important contributor to non-renewable carbon dioxide (CO2) emissions due to on-site fossil fuel energy production for paper making, and that methane (CH4) emissions are the main factor for global warming due to waste paper landfilling.

Dias et al. (2007) studied the offset paper made from *Eucalyptus globulus* in Portugal, and evaluated the effect of differences in the market where the product is consumed: German market vs. Portuguese market. The paper consumed in Portugal showed lower environmental impacts in the distribution phase, but higher impacts in the final disposal phase than in Germany. The increase in the impacts of the final disposal phase in the Portuguese market was significant in the categories of global warming and photochemical oxidant formation due to CH4 emissions from landfills.

Jawjit et al. (2006) highlighted several environmental impacts caused by the eucalyptus-based Kraft pulp industry in Thailand, such as impacts on global warming, acidification, eutrophication, smog, toxicity and the production of solid waste.

Gonzales-Garcia et al. (2009) performed an LCA of Spain's pulp production and demonstrated that activities related to wood paper pulp manufacture that take place inside the mill, such as cooking, bleaching and wastewater treatment, are not always the main contributors to the environmental impact of the process. In fact, a background process such as the upstream production of chemicals and fuels has been identified as the main contributor to impact categories related to toxicity (more than 50% of total contributions) and abiotic resources depletion (w100% of total). In addition, onsite energy production systems using fossil fuels can be to be an important concern in terms of acidification, global warming and ozone layer depletion, mainly due to the use of fossil fuel in the lime kiln.

Xu and Becker (2012) evaluated the environmental life cycle impacts associated with Bleached Eucalyptus Kraft Pulp supplied from a eucalyptus plantation in South China.

In a comparative LCA of paper produced from eucalyptus and hemp, da Silva Vieira et al. (2010) found that in Portugal, paper made from industrial hemp generates higher environmental burdens than eucalyptus. The main differences between the life cycles were in terms of global warming, acidification, eutrophication, photochemical oxidant formation, and land use impacts during the fiber and pulp production stages. This was mainly because the cultivation of hemp requires larger amounts of fertilizers and more mechanical operations in crop production, and also consumes larger amounts of chemical additives in pulp production.

In a more recent study, Lopes Silva et al. (2015) performed a complete LCA of offset paper production in Brazil.

Gonzales-Garcia (2010a; 2010b) aimed to identify and quantify the life cycle environmental impacts associated with the production of hemp and flax fibers for specialty paper pulp.

Poopak and Agamuth (2011; 2012) assessed the environmental impact caused by paper production with bagasse in Iran using a life cycle assessment approach. Results show that using bagasse and electricity contributed the lowest impact value because both of these inputs used renewable sources. Chlorine from the bleaching process contributes impact for photochemical oxidation and ozone layer depletion. From the results obtained, the use of bagasse instead of wood in paper and pulp production has potential to reduce global warming impact. Finally, hydroelectricity as the source of energy has less impact on the environment, while use of mazut (fuel oil) may result in acidification, global warming and ozone layer depletion. Poopak and Agamuth used consequential approach to evaluating greenhouse gas emissions, apparently subtracting emissions that would have been emitting from using trees as a pulp source rather than bagasse. Since the analysis in this review is on an attributional basis (that is, not taking into account how markets could change if the product were adopted) we have subtracted off the consequential portion and reported just the amount of emissions attributed to the bagasse pulp directly.

Forte et al. (2015) applied a LCA to the overall 15 years life cycle of Mediterranean giant reed cultivated in Southern Italy, including direct field emissions and non-productive phases of cultivation. Focusing on the overall life cycle, in this study yearly nitrogen fertilization for crop maintenance and harvest contributed the largest part of total impacts.

Gemechu et al. (2013), in an assessment of tissue papers, concluded that when the whole life cycle process is considered, the GHG emissions from the virgin pulp (VP) process are roughly 30 % higher than from the recycled waste paper (RWP) process, which implies a saving of 568 g CO2 eq per kilogram of tissue paper produced. The difference is due to the material and energy requirement for producing and transporting the main input materials. For example, the transportation of pulp from South America and Portugal contributes around 93 % of the total GHG emissions from transportation, whereas the GHG emissions caused by transportation during the RWP process are much lower because the paper waste is supplied by the local market.

Iosip et al. (2012) analyzed and quantified the life cycle environmental impacts associated with the production of testliner paper using 100 % recovered paper as fiber raw material in Romania.

Ghose and Carrasco (2013) assessed the environmental impacts of the Norwegian pulp and paper industry, considering the production of pulp fibers and printing paper from softwood and compared to the production based on Scandinavian and European energy mix.

ERM (2007) assessed the environmental trade-offs associated with the use of virgin fibers (Northern softwood and Brazilian eucalyptus) and recycled fibers for seven different uses (North American bathroom tissue; North American washroom towel; North American facial tissue; North American kitchen towel; European folded toilet tissue; European roll toilet tissue; and European commercial wipers).

RAN and JATAN (2010) assessed the greenhouse gas emissions associated with acacia grown in Indonesia. In this case the majority of the emissions were associated with land use change for establishment of the plantation, rather than with the production of the acacia or with the pulping process. Although this is a limited study and is not further assessed here, we mention it for the issues it highlights.

Thomas and Liu (2013) analyzed 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.

Elephant grass (miscanthus) does not have LCA analysis for the full paper production process. However LCAs of miscanthus have been developed for bioenergy applications (Dunn et al. 2013) and these are included in the review. Table 2 summarizes the fibers and locations discussed in each study.

Fiber	Location	Sources
Eucalyptus	China	Xu and Becker (2012)
	Portugal	Lopes et al. (2003); Dias et al. (2007); da Silva Viera et al. (2010)
	Spain	Gonzalez-Garcıa et al. 2009
	Thailand	Jawjit et al. (2006)
	Brazil	Lopes Silva et al. (2015)
Softwood	US	ERM (2007); Thomas and Liu (2013)
	Norway and EU	Ghose and Carrasco (2013)
Acacia	Indonesia	RAN and JATAN (2010)
Recycled paper	Romania (EU)	Iosip et al. (2012)
	US	ERM (2007); Thomas and Liu (2013)
	Europe	Gemechu et al. (2013)
Hemp	Portugal	da Silva Viera et al. (2010)
	Spain	Gonzalez-Garcıa et al. 2010a,b
Flax	Spain	Gonzalez-Garcıa et al. 2010a,b
Arundo donax	Italy, US	Forte et al. (2015); Thomas and Liu (2013)
	US	Thomas and Liu (2013)
Bamboo	US	Thomas and Liu (2013)
Kenaf	US	Thomas and Liu (2013)
Elephant Grass (Miscanthus)	US	Wang et al. (2012)
	Europe	Dunn et al. (2013)
Wheat Straw	US	Thomas and Liu (2013)
Bagasse	Iran	Poopak and Agamuth (2011, 2012)

Table 2: Location and fiber included in the analysis

5.1 Life cycle stages and Boundaries of LCA

In LCA, the system boundaries should be set so as to begin with all activities required for the acquisition of raw materials and end with the final disposal of manufacturing wastes and discarded product (NCASI, 2011). The system boundary of the life cycle of paper generally includes the following stages:

- production and harvesting of wood or other fibers, including production and use of fertilizers, pesticides, fuels and other inputs to fiber production;
- transportation among the life cycle stages, which may include fiber transport to the pulping site, transport of pulp to the paper manufacturing site, transport of paper to the printing or other finishing site, transport to the point of sale, transport to the point of use, and transport to end of life;
- pulp production,
- paper production,
- printing or other final production processes depending on the product,
- use of the product (not addressed in any studies reviewed here), and
- product end of life, which can include landfilling, recycling, composting, incineration or disposal in wastewater, depending on the product.

Table 3 shows which indicators are included in each of the main studies reviewed in this report.

5.2 Environmental impact indicators included in the analysis

In the life cycle assessments reviewed, the environmental impacts most commonly addressed are fossil energy use, greenhouse gas emissions, contributions to formation of ground level ozone, acidification, eutrophication, and emission of ozone-depleting chemicals. Some life cycle assessments include land use and water consumption. The greenhouse gas implications of land use change and biomass harvesting have been increasingly well studied in the past few years; older studies may not include these impacts. Soil erosion, soil nutrient depletion, impacts of chlorinated compounds, and impacts on biodiversity are often not included.

- <u>Global warming or climate change</u>: Greenhouse gases (GHGs), which are the main pollutants contributing to climate change, are expressed as carbon dioxide equivalents, with the weighting in terms of GWP (global warming potential). The GWP is an index of cumulative radiative forcing between the present and some chosen later time horizon caused by a unit mass of gas emitted, expressed relative to the reference gas CO2 (1 kg CO2) (Jawjit et al. 2006). The pulp and paper producing industry is the fourth largest GHG emitter among global manufacturing industries and is responsible for around 9 % of the total overall CO2 emissions from manufacturing industries (Environmental Paper Network 2007; International Energy Agency 2007). Increased paper consumption has been a driver of growth in the sector (Environmental Paper Summit 2002).

- <u>Photochemical oxidant formation</u>: Photo-oxidant formation is the formation of reactive chemical compounds that are damaging to human health, ecosystems and crops, by the action of sunlight on certain primary air pollutants. Photo-oxidants may be formed in the troposphere under the influence of ultraviolet light by means of VOCs and CO in the presence of NOx (Gonzales-Garcia et al., 2010a). When solvents and other volatile organic compounds (VOC) are released into the environment, they become oxidized in the atmosphere under the influence of sunlight and, in the presence of NOx, ozone can be formed photochemically (Wenzel et al., 1997). This ozone gas formed in the troposphere cannot rise to the stratosphere, so it attacks organic compounds in plants and animals or materials exposed to air (Lopes Silva et al. 2015).

- <u>Acidification:</u> Acidification, also known as acid rain, occurs when emissions of sulfur dioxide and nitrogen oxides react in the atmosphere with water, oxygen, and oxidants to form various acidic compounds. Acidification affects soil, groundwater, ecosystems and materials. Acidification mainly stems from combustion processes in electricity and heat production, and in transport systems (Gonzales-Garcia et al., 2010a).
- <u>Eutrophication:</u> Nutrient enrichment (NE) or eutrophication is an impact on ecosystems from substances containing nitrogen or phosphorus in a biologically available form. NE impacts can be caused by emissions into air (e.g., nitrogen oxides from combustion processes), water (e.g., nitrogen in the aquatic environment originating from the use of fertilizers in agriculture) and soil (e.g., emissions of phosphorus leaching into the soil from agricultural sources) (Wenzel et al. 1997; Gonzales-Garcia et al., 2010a).
- <u>Abiotic Depletion:</u> Abiotic depletion refers to the exhaustion of nonrenewable resources and the ensuing environmental impacts.
- <u>Ozone Depletion</u>: Stratsopheric ozone depletion potentials have been developed to assess the relative contribution of different organic compounds to stratospheric ozone depletion as a result of man-made emissions of halocarbons (chlorine or bromie), such as refrigerants, solvents and foaming agents (Wenzel et al., 1997). Ozone depleting refrigerants are still commonly used although they are being phased out.
- <u>Human and Eco-toxicity</u>: Chemicals emitted through anthropogenic activities contribute to ecotoxicity (EC) if they have toxic impacts on human health or the function of ecosystems (Wenzel et al., 1997).
- <u>Non-renewable resources depletion</u>: Non-renewable resources depletion refers to the depletion of energetic resources such as coal, crude oil, natural gas or uranium (Gonzales-Garcia et al., 2010a).

Table 4 shows which indicators are included in each study used in this report.

Thomas and Liu (2013) showed that for a range of pulps including softwood, recycled, and kenaf, key indicators included water consumption (with kenaf, an irrigated feedstock, the only feedstock showing significant impact) using the method of Pfister et al. (2009), forest and agricultural land occupation for its impacts on species (with northern softwood being the only feedstock showing significant impact), and both climate change and human toxicity and particulate matter emissions for their impacts on human health. Although this study is not a full life cycle assessment, we use the results of the Thomas and Liu (2013) to flag the potential impacts of different emissions.

Stages	Da Silva Viera et al. (2010)	Gonzále z-García et al. (2009)	Forte et al. (2015)	Dias et al. (2007)	Poopak and Agamuth (2011; 2012)	Jawjit et al. (2006)	Gonzale z-Garcıa et al. (2010a)	Gonzale z-Garcıa et al. (2010b)	Lopes Silva et al. (2015)	Lopes et al. (2003)	Geme chu et al. (2013)	Iosip et al. (2012)	Ghose and Carrasco (2013)	Thomas and Liu (2013)	ERM (2007)	Xu and Becker (2012)
Fiber cultivation	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Transportation to the pulp mill	■	■			■	■	■	■	■	■	■	■	■	■	■	■
Pulp production	■	■		■	■	■		■	■	■	■	■	■	■	■	■
Transportation to the paper mill					■				■	■	■	■	■	■	■	■
Paper production				■	■				■	■	■	■	■	■	■	■
Paper distribution				■						■	■		■	■	■	■
Paper final disposal				■						■	■					

■	LCA stage is included in the study

Table 3: Life cycle stages and boundaries of LCA discussed in each study

Indicators	Da Silva Viera et al. (2010)	González-García et al. (2009)	Forte et al. (2015)	Dias et al. (2007)	Poopak and Agamuth (2011;2012)	Lopes et al. (2003)	Jawjit et al. (2006)	Gonzalez-Garcıa et al. (2010a)	Gonzalez-Garcıa et al. (2010b)	Lopes Silva et al. (2015)	Gemechu et al. (2013)	Iosip et al. (2012)	Ghose and Carrasco (2013)	Thomas and Liu (2013	ERM (2007)	Xu and Becker (2012)
Global warming (GWP) or climate change	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Photochemical oxidant formation (POF or POP)	■	■	■	■	■	■		■	■	■		■	■	■	■	
Acidification (AP or A)	■	■	■	■	■	■	■	■	■	■		■	■	■	■	■
Eutrophication (EP or E) or Nutrient enrichment	■	■	■	■	■	■	■	■	■	■		■	■	■	■	■
Abiotic Depletion/ Non renewable recourses depletion		■			■				■			■			■	
Ozone depletion (OD)		■	■		■				■	■		■	■	■	■	
Human and Eco-toxicity		■	■		■		■		■	■		■	■	■		■
Particulate matter or smog			■				■						■	■		
Land use	■															

■	Indicator included in the study

Table 4: indicators are included in each study

5.3 Assessment results for each fiber

In the Appendix we provide a detailed summary of the LCA assessment results for each fiber according to the literature review. There are several LCA indicator results that we do not consider to be significant or reliable; we include those in the appendix.

5.3.1 LCA Indicators

Global Warming Potential

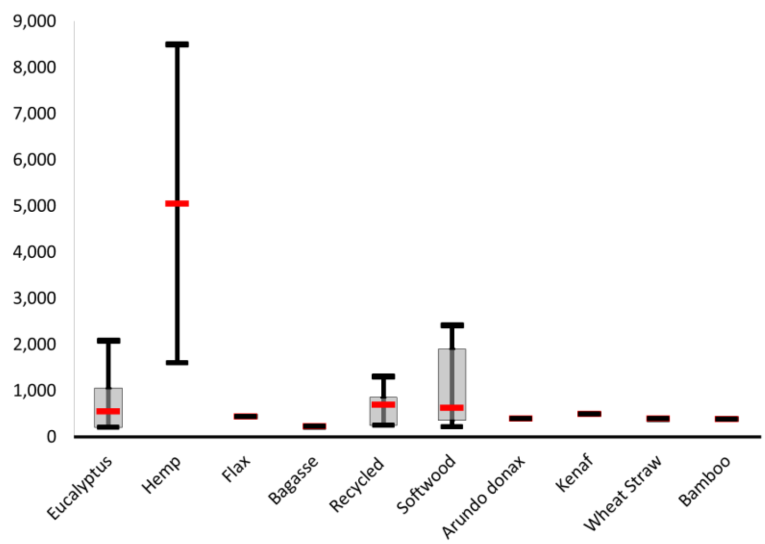

Figure 1: Global Warming Potential (kg CO2e/ton pulp)

Figure 1 shows the estimated global warming potential from all of the pulp alternatives.

Most studies, across all fibers, report greenhouse gas emissions of less than 1 ton of CO_2e per ton of pulp. All the studies identified fiber and pulp production as contributors, including N_2O emissions from the fertilizer applied to the soil, and CO_2 emissions from electricity generation (Gonzales-Garcia et al. 2009; 2010; da Silva Viera et al. 2010). For each study we endeavored to report just the emissions through pulp production, excluding paper production and excluding end-of-life impacts.

The two hemp studies show higher emissions due to the substantial agricultural activity required to produce hemp. Both of the hemp studies also included comparison with eucalyptus for which the results were comparable to other studies (da Silva Vieira et al. 2013; Gonzalez-Garcia et al. 2010a); this suggests that the high results for hemp are not due to an obvious error.

The softwood study with the highest reported emissions (Thomas and Liu 2013) is for northern softwood and includes biogenic carbon in the accounting; because northern softwood grows slowly, the replacement time for trees is long and the impact on atmospheric carbon dioxide is therefore higher.

Our interpretation of these results is that, with the exception of hemp, there are few clear differences between most of the fiber types, in terms of greenhouse gas emissions. Eucalyptus, softwood, and recycled fiber show a larger range of results because there are more studies of these fibers; their median values are very similar to those of all fibers. Moreover, although the hemp studies reported here show high emissions, better production techniques that could bring down the emissions from hemp pulp production may be possible.

There are no estimates on miscanthus GWP potential for pulp production. However, Dunn et al. (2013) shows that miscanthus has the lowest (−10 g CO2e/MJ) land use change GHG emissions under base case modeling assumptions relative to corn, corn stover, switchgrass for biofuel production. Their results show that land use conversion to miscanthus increases carbon sequestration. This result is consistent with miscanthus growth generating additional aboveground and belowground biomass as well as its high yield.

Eutrophication

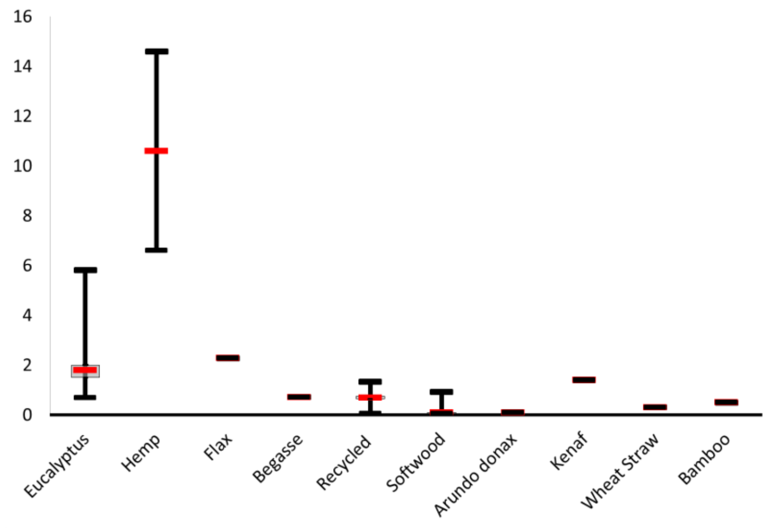

Figure 2: Eutrophication (kg PO_4-eq/ton paper)

Figure 2 shows freshwater eutrophication potential in terms of kilograms of phosphate (kg P) per ton of pulp. Hemp has the largest reported estimate and the principal source of it is the use of fertilizers. While Thomas and Liu (2013) did not find eutrophication to have a significant impact on human health or ecosystems, the values report here for eucalyptus and hemp are higher and may be significant.

Human Toxicity

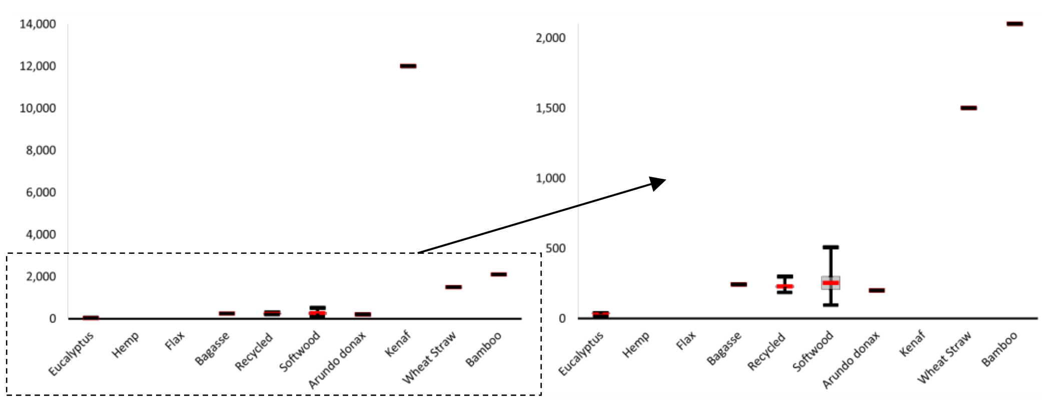

Figure 3: Human Toxicity (kg 1.4-DB eq /ton paper)

Figure 3 shows reported results for human toxicity. The hemp studies did not include human toxicity assessment. Thomas and Liu (2013) noted that their values, for kenaf, wheat straw and bamboo, are primarily from the air and water emissions of agricultural production; data on waterborne emissions from pulp mills and the environmental fate of agricultural inputs used in fiber production limits the completeness of toxicity-related analysis. However, even with these limitations they found that human toxicity, particularly for kenaf, was one of the main contributors to the human health impacts of pulp.

Abiotic depletion

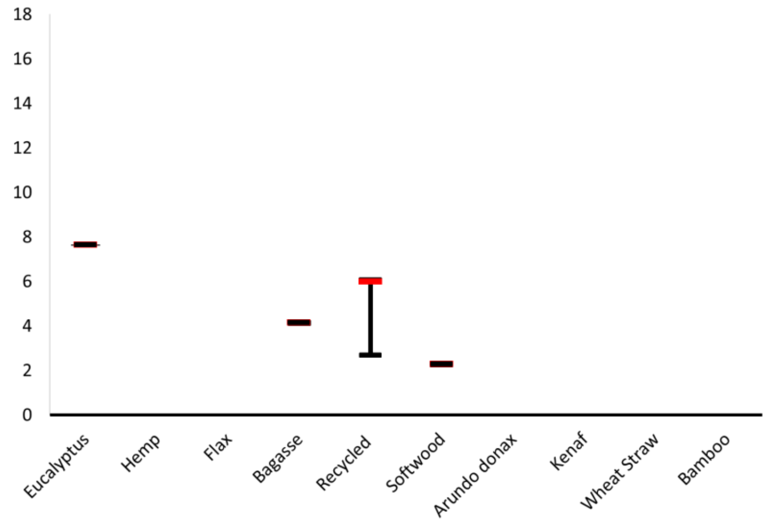

Figure 4: Abiotic Depletion (kg Sbeq /ton pulp)

The abiotic impact category, Figure 4, is a measure of the extraction of minerals and fossil fuels due to inputs in the system. The studies reported here are in units of antimony equivalent Sbeq (Guinée et al. 2002); the values reported are mainly fossil fuel use. The LCA of bagasse surveyed in this study records high level of abiotic depletion because of the intensive use of heavy fuel oil (in this case mazut) for pulp processing; a process which used less fossil fuels would result in lower abiotic depletion. The studies of hemp, flax, arundo donax, kenaf, wheat straw, and bamboo did not report abiotic depletion although fossil fuel consumption was calculated. This indicator is very closely related to the greenhouse gas emissions indicator shown in Figure 1 and is consistent with that figure.

Fresh water toxicity

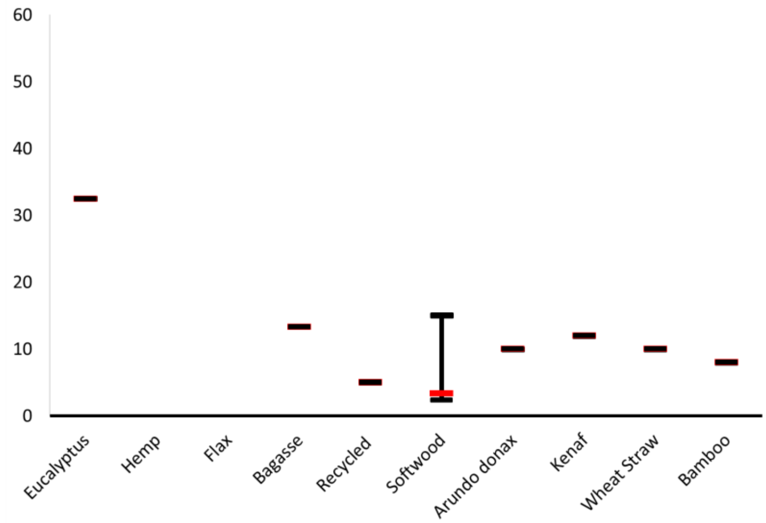

Figure 5: Fresh water toxicity (kg 1,4-DB eq /ton pulp)

Figure 5 shows the results for freshwater toxicity. Thomas and Liu found that most of these impacts are from the pulping process and that the overall ecosystem impact of the measured freshwater impacts was small although not negligible (e.g. ~ 10%). There may be data gaps in the freshwater toxicity analysis.

.Terrestrial eco-toxicity

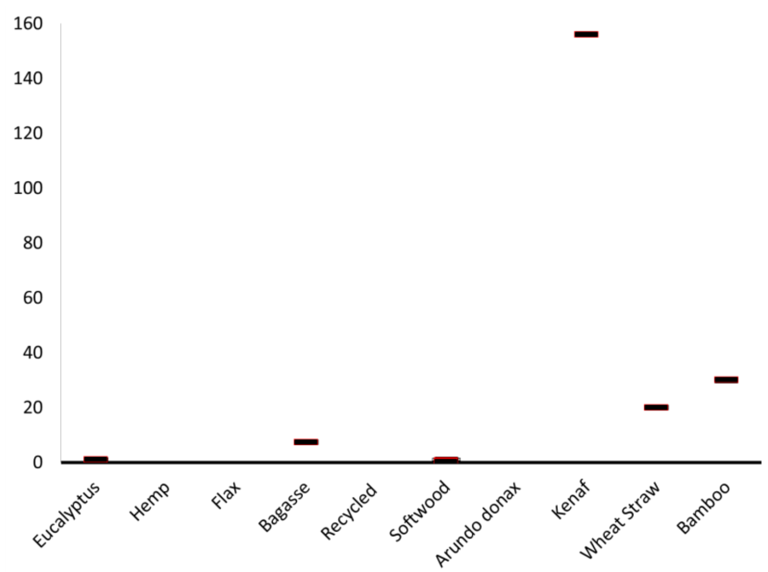

Figure 6: Terrestrial Eco-toxicity (kg 1.4-DB eq /ton paper)

Figure 6 shows the terrestrial eco-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). Kenaf is reported as having the highest value, which is caused primarily by the air and water emissions from agricultural production; this value comprised about 30% of the overall human health life cycle impact of kenaf pulp (Thomas and Liu, 2013). The studies of hemp and flax did not include assessment of terrestrial eco-toxicity, and since these are also agriculturally produced fibers they may have non-negligible impacts in this category.

Particular Matter

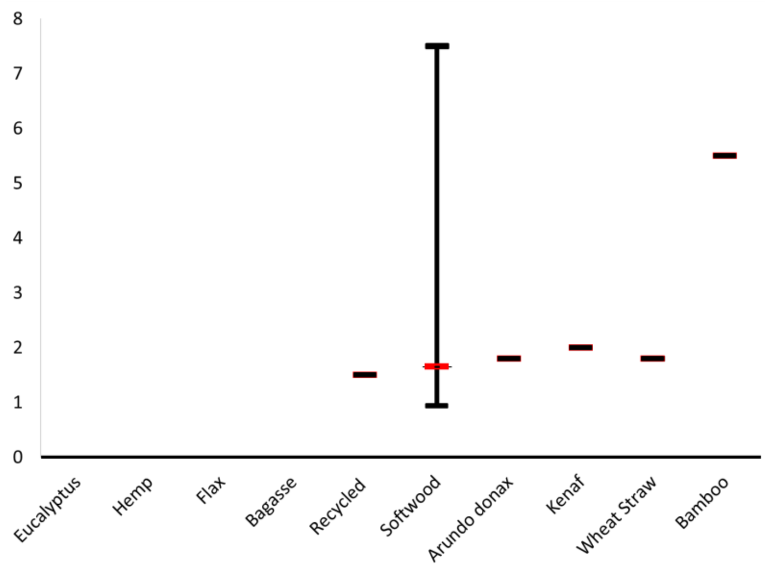

Figure 7: Particulate matter (kg PM 10 eq /ton pulp)

Figure 7 shows particulate matter emissions per ton of pulp. The measure used here is particulate matter of diameter 10 microns or less. PM 2.5 is now generally recognized as a better measure of health impacts and could be used if the data were available. 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 estimated by Thomas and Liu (2013) may reflect the relative age of the pulp mill studied, and also reflects the relatively long transportation distance from that pulp mill to the paper mill. Thomas and Liu (2013) found that these particulate emissions comprised a significant portion of human health impacts of pulp production (~30% for bamboo). It should also be noted that these emissions mainly reflect the characteristics of the pulp mill rather than the type of pulp. Particulate emissions values for eucalyptus, hemp, flax and bagasse were not reported.

5.3.2 Hot spots

Among the pulp life cycle stages, **pulp manufacturing** is the source of most of the environmental impacts, across all of the studied impacts. Half of the studies surveyed identified pulp production for most of the environmental impacts in categories related to the use of fossil fuel.

Fiber cultivation was the second largest contributor, particularly for eutrophication and global warming, and transport was the third and last contributor particularly for fibers with long transport distances (see table for qualitative-comparison).

The analyses included in this review are from different authors and for different fibers. As with all meta-analyses, the surveyed studies were not all carried out to the same degree or including the same types of data. For this reason, if a high impact in one study is the result of inclusion of an activity that was not included in other studies, it might be an impact that can also occur for other fiber types. For example, herbicides are used in softwood production even though it has not typically been reported in environmental assessments of softwood, whereas the careful environmental assessment surrounding consideration of potential new fibers (e.g. bamboo for US plantings) includes potential herbicide use even though its growers insist it will not be needed. Conversely, a reported high impact for one fiber type may be due to consideration of a specific practice and not indicative of a general feature. And it is of course possible that errors have been made.

However, overarching findings indicate that hot spots for fibers *per se* include:

- **Land use change** to establish plantations; this can have large greenhouse gas impacts as well as impacts on other environmental endpoints.
- Production in **high value conservation areas**.
- **Slow growing fiber** sources, such as northern softwood, for which the greenhouse gas impacts of harvesting are slow to recover.
- **Farming** impacts associated with annual plants (hemp, kenaf, linen, etc) including use of fertilizers, pesticides, and plowing and harvesting energy use.
- **Co-products** that can mitigate impacts – for example use of northern softwood for saw timber with associated chips for pulp production could have a much lower greenhouse gas impact than whole tree use of northern softwood for pulp production. Similarly wheat straw or other agricultural residues may have low impact because it is a minor co-product. Linen, kenaf and other alternative fibers could have co-products that might substantially mitigate their impacts. In particular, fiber hemp cultivation also produces woody core and dust (Gorchs and Lloveras, 2003) while fiber flax cultivation yield also seeds, which are used for sowing and the surplus, is sold for other aims (oils, animal feed, flours) (González-García et al. 2010a).
- **Invasiveness**, which may be a function of location.

Because the pulping and paper making processes are recognized as being substantial contributors to the overall life cycle environmental impact of paper, a complete evaluation of alternative fibers would include consideration of the pulping and paper making processes. Manufacturers that can achieve lower than average impacts from pulping, transportation, and paper making processes may be able to provide papers with substantially lower environmental impacts than the average for their fiber type.

5.3.3 Cold spots

We are not convinced that any **type of alternative fiber** reviewed here has inherently low environmental impact compared to moderate to low impact standard wood fibers. The environmental impacts of pulp and paper depend strongly on the energy efficiency of the entire supply chain, and also depend strongly on low use of agricultural inputs and low emissions from the manufacturing facility. While there are some fibers that appear to have higher impacts (hemp, northern softwood, and kenaf) than others, the environmental impacts of pulp made from other alternative fibers are similar to the environmental impacts of pulp made from wood or recycled fibers.

Although the environmental impacts of transportation are consistently evaluated in LCAs, transportation is generally not found to be a major contributor to the environmental impact. An exception is an assessment that compared consumption of printing and writing paper in Germany versus Portugal; higher impacts were found for larger transport distances (Dias et al. 2007). Thomas and Liu (2013) also found that transport of northern softwood pulp from central Canada to the US southeast by a combination of truck and rail made a significant contribution. Few of the reviewed LCAs included substantial transcontinental transport of pulp or paper; although inclusion of these scenarios could result in higher transportation impacts, ocean transport is one of the most efficient modes of transport. Thomas and Liu (2013) also found that numerous impact categories (ozone depletion, photochemical oxidant formation, acidification, etc.) have little quantified impact on the life cycle impacts of pulp.

Figure 8 is a conceptual map of our views of fiber impacts with respect to both the fiber itself and the pulp production.

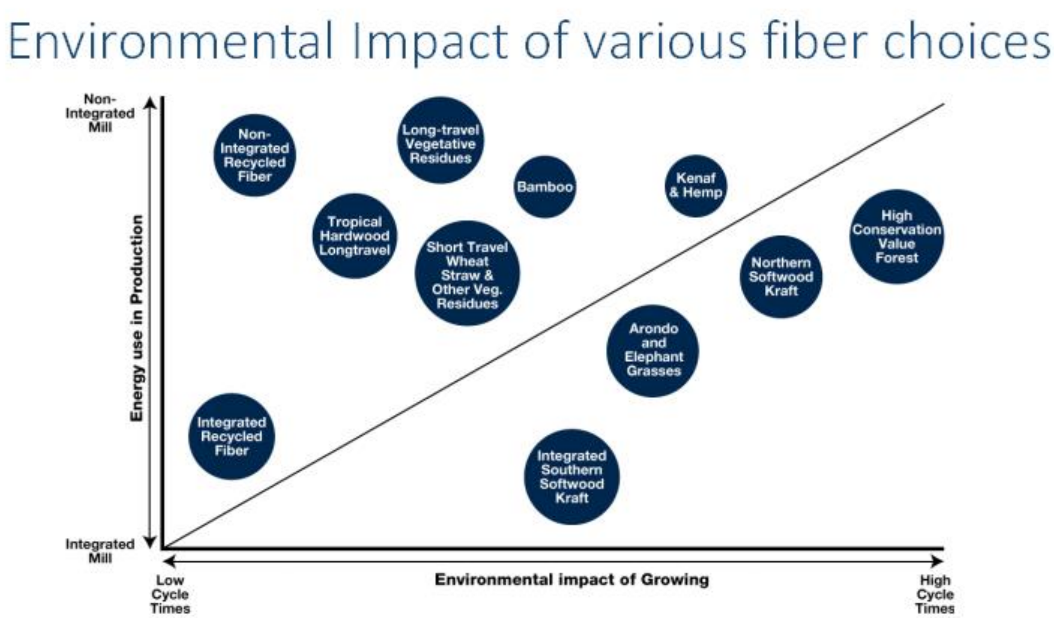

Figure 8: Conceptual map of fibers with respect to both environmental impact of growing and energy use in production, both of which are key areas of potential environmental impact.

5.3.4 Uncertainty analysis

Among all the studies analyzed only Thomas and Liu (2013) and Forte et al. (2015) provide uncertainty analysis. As discussed above, there is substantial uncertainty associated with comparing across these studies.

6 Market Review

The global production of paper and board increased—with two exceptions (1975 and 1982)—continuously over the last few decades from 125 million tons in 1970 to 365 million tons in 2006. (Jahan et al. 2009).

In 2011, the most recent year with data available, the five highest world producers of pulp for paper were the U.S. (50.2M tonnes), China (21.1M), Canada (18.3M), Brazil (13.9M), and Sweden (11.7M). In 2011, the five highest world producers of paper and paperboard were China (103.1M tonnes), the U.S. (77.4M), Japan (26.2M), Germany (22.7M), and Canada (12.1M) (Modak et al. 2015). Bleached hardwood kraft pulp prices fell by roughly 30% from 2010 to 2016 (Schafer 2016), due mainly to increasing supply. Pulp and paper production has been prevalent in the U.S. since the early 1900s, and continues to contribute significantly to the U.S. economy.

Global demand for printing and writing paper peaked in 2007 at 120 million metric tons per year and declined to slightly 100 million metric tons in 2016. The world demand for paper and paperboard products is projected to reach 490 million tonnes by 2020 with an average annual growth rate of 2.8%. Most of this growth is due to the growing demand for packaging; slowly growing tissue demand also contributes (Schafer 2016). In particular, it is projected that the market for paper and paper board will continue to grow globally at 2.3 percent per year until 2030, with particularly sharp increases in developing countries (due to increases in population, literacy rates, and quality of life) and a slight decline in the most advanced industrialized counties (due to advances in electronic communications) (Sheikhi et al. 2010).

South America is the major exporter of bleached hardwood kraft pulp; Asia and Europe are substantial importers, and North America has a small positive net import. Demand for printing and writing papers in North America fell by 5.7% in 2014, 5.2% in 2015, and was projected to fall a further 3.3% in 2016 and another 3.2% in 2017 (Schafer 2015, 2016).

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 the Far East (Thomas and Liu 2013). Recycled fiber from an integrated recycled fiber mill is about twice as expensive, on the basis of delivered cost per ton, as softwood kraft from an integrated kraft mill ($30 vs $60)[3].

Among traditional fibers, **eucalyptus** represented 50% of the global pulp fiber traded internationally in 2007 and its market share has increased since then (FAO 2007). Brazil is the largest producer of eucalyptus with more than three million hectares of eucalyptus plantations (Holland, 2009) and production of 14 million tons of pulp, comprising 40% of the global short-fiber market (Modak et al. 2015; The Economist 2016). Fibria[4] recently installed the largest pulping line in the world, producing 4000

[3] The current price for U.S. southern softwood pulp is about $30 per delivered ton; this includes both stumpage and harvesting costs (Timbermart South 2015).

[4] http://www.fibria.com.br/en/

million tons per day, and running only eucalyptus. All Brazilian exported eucalyptus pulp is from FSC, PERC or Cerflor certified plantations (Paper Industry World 2012). Its use as a fiber for paper is well established and it is the wood fiber against which non-wood fibers have been compared in some of the LCAs reviewed here. The fibers are short and are used in newsprint, tissue, and also for printing and writing paper (Paper Industry World 2014), and may also be mixed with other (e.g. longer) fiber types. The cost of transporting eucalyptus to North American is increasingly balanced by lower production costs of larger scale and newer production facilities I South America.

Acacia is a fast growing species used in forest plantations in Indonesia and elsewhere in Asia (Rosli et al. 2009) as well as southern Africa. The market is well established as short but flexible fiber for consumer product grades to impart softness. Unfortunately, early harvesting was often of rain forests and old growth. Now, however, there are plantations of rapidly growing trees that can be harvested within 6 years of re-planting and good fiber obtained. We believe these markets are growing globally at 3-5% annually and paralleling the consumer tissue markets in each region. As of 2014 Sumatra had 1.5 million ha of acacia plantation, which had become the source fiber for most of Sumatra's pulp industry. For instance, together Asia Pulp and Paper (APP) and Asia Pacific Resources International (April) produce 6.2 million tonnes of pulp and acacia represents 80% of this[5]. Acacia plantations were initiated in 2003 and difficulties with maintenance of the plantations (problems due to disease and pests) have been reported (McBeth 2014). Vietnam is also a substantial producer of acacia, which is largely exported to China for pulping. Vietnam exported 400,000 tons in 2001 and was up to 5.4 million tons in 2011 (Pulp and Paper News 2012). APP is scheduled to open a new pulp mill in Sumatra in 2017.

Non-wood fibers play a smaller role in the paper market, accounting for about 10% of the world's pulp production (Jahan et al. 2009). According to FAO statistics (FAOSTAT Forestry 2010), in 2009 the total worldwide production of the "other fiber pulp" was 19.1 million tonnes, while total pulp production for paper totaled 178.1 million tonnes.

At the global level about 2.5 billion tonnes of non-woods are available annually, from both agricultural residues and some fiber crops for pulp and paper production (Kozlowski and Mackiewicz-Talarczy, 2009; Hurter, 2015). Figure 9 shows the availability of the non-wood fibers reviewed in this study; additional fibers with substantial availability include residues from rice, corn, sorghum, barley and others.

[5] http://www.nationmultimedia.com/news/opinion/aec/30230786

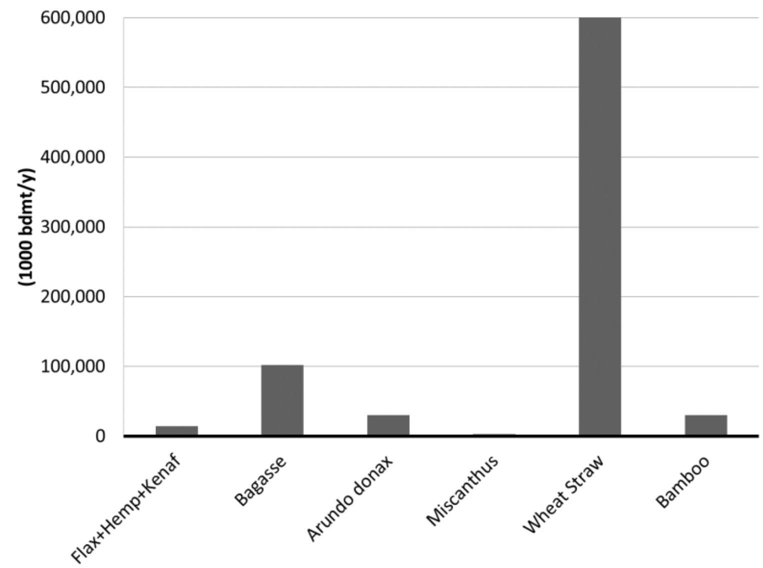

Figure 9: Global availability selected non-wood fibers (data from Hurter, 2015)

The most widely used non-woods for paper-making are straw, reed, bamboo and bagasse (Leponiemi et al. 2011). China produces more than two-thirds of the non-wood pulp worldwide, while non-wood production is relatively insignificant in Europe, America and Africa (FAOSTAT Forestry 2010). In particular, most non-wood pulp is produced from wheat straw in China and India. These two countries account for about 80 percent of the total nonwood pulp production (Jahan et al. 2009). Among the non-wood plants, straw has been used in Asia, Africa, Eastern Europe and Latin America for the production of paper pulp as well as in Spain and other European countries for manufacturing of high-quality pulps for specialty papers (Gonzales-Garcia et al. 2010)

In the United States, with regard to fine papers, there has not been a significant market buzz or acceptance of alternative fibers, perhaps because of quality issues. However, in 2012, Kimberly-Clark announced that 50% of its wood fiber would be sourced from alternative fibers by 2025 (Wong 2012).

There has been no movement of which we are aware for sanitary products such as diapers, adult incontinence and feminine care products, as southern pine fiber length and coarseness continue to be the hallmark for product quality. Wheat straw in bath tissue, however, makes sense to companies because the short and stiff fibers are not easily recyclable again, and therefore a good end-of-life scenario is to flush the used product away.

Below we summarize additional market information of the most important non-wood fibers: hemp, flax, bamboo and elephant grass (Miscanthus).

Total world **hemp** fiber production in 2003 was approximately 77,450 tonnes (representing only 0.15 per cent of world fiber production) with five main producers: China (45 per cent), Spain (19 per cent), Peoples' Republic of Korea (16 per cent), Russia (8 per cent) and Chile (5 per cent) (Cherrett et al., 2005). In 2008, estimated global production volume was 0.10 mill tonnes (van Dam, 2008). In addition, China has announced plans to substantially increase the hemp production for textiles in the coming years to 1.5 million tonnes of fiber per year (van Dam, 2008).

Several bamboo-producing countries, such as China and India, use **bamboo** for pulp and paper. In 2005 China produced 300,000 tonnes of bamboo for pulp production while in Myanmar bamboo use for pulp and paper amounted to 43,245 tonnes in 1990, 103,597 tonnes in 2000 and 60,412 tonnes in 2004. Long fiber such as bamboo has been used for towels to add strength. Since 2015 Kimberly-Clark has been selling a number of products containing bamboo, including paper towels made of 20% bamboo. Disposable plates made from bamboo are available from other countries.

In 2014, estimated global **flax** production volume was 320,043 tonnes (FAOSTAT, 2017). As of 2016, Georgia Pacific is marketing industrial flax cloths (Georgia Pacific 2016). These are marketed as replacements for rags and rental towels, and their benefits include lower cost, less water use compared to cloths that are laundered, and lower potential exposure to metals and other contaminants.

Finally, the Swedish firm SCA has announced the potential to use ***miscanthus*** in tissue papers as a substitute for eucalyptus (SCA 2015). However, there is currently no shortage of eucalyptus so the near-term prospects for elephant grass appear limited.

The U.S. DOE's 2016 Billion Ton Report (US DOE 2016) analyzes availability of biomass for production of biofuel and other products. A number of the biomass feedstocks analyzed in that report can also be used for production of paper, providing an integrated and consistent analysis of U.S. feedstock availability and price. The study has developed scenarios for U.S. paper and paperboard production, all in the range of about 40 million dry short tons by 2040 (US DOE 2016, Figure 3.12).

The study (US DOE 2016, Table 4.8) has estimated the supply as a function of price for elephant grass (miscanthus) and wheat straw with prices at $40, $60, and $80 per dry ton delivered. The study indicates that little miscanthus can be delivered for less than $40 per dry ton; at $40 per dry ton miscanthus production is estimated to be less than 1 million tons in 2022, from 2-5 million tons in 2030 and from 7 to 65 million tons in 2040. For prices up to $60 per ton, which is the baseline price estimate to achieve U.S. biofuel goals, production of miscanthus is estimated to reach 28 to 45 million tons in 2022 and increasing amounts in the out years.

The **wheat straw** market is relatively well-researched, due to its potential as a biofuel feedstock. It is estimated to be available in 2017 in quantities of 6 to 7 million dry tons at a price of less than $40 per dry tonne (US DOE 2016, Table 4.7). The total quantities of wheat straw that could be available are limited by the wheat crop; at prices of $60 or $80 per dry ton the largest the market can get is 37 million tons per year.

7 Conclusions

The analysis above indicates what has been published regarding the environmental impacts of different paper fibers. The overall life cycle impact of a type of paper will depend strongly on the pulping and paper making processes. In some cases those processes can be more important to the overall environmental impact than the type of fiber used. In particular, several of the LCA studies analyzed show that forest activities and the type of fiber contribute very little to almost all environmental impact categories compared with pulp mill operations (Dias et al. 2006, Jawjit et al. 2006, Gonzalez-Garcia et al. 2009). For instance, the two studies for hemp provide very different results because different stages were included in the analyses: while Gonzales-Garcia et al. 2010a (Spain) includes only fiber cultivation and transportation to the pulp mill da Silva Vieira et al. 2010 (Portugal) includes also pulp production increasing the overall hemp's contribution on Global Warming, Photochemical Oxidant Formation, Acidification and Eutrophication (freshwater). Below we summarize the environmental impacts that can be attributed specifically to each fiber.

Hemp vs. flax and eucalyptus:

Comparing **hemp and flax**, González-García et al. (2010a) report that the production of hemp fiber has higher values for all the LCA impact categories analyzed. Production and use of fertilizers as well as the stage of scutching (fiber separation) were identified as the hot spots in both crops. With regard to **energy resources use**, hemp scenario is more intensive than flax. Agricultural activities (field operations) are highly mechanized and have high energy consumption, up to 48% and 89% of total in hemp and flax scenarios respectively. Specifically, scutching and harvesting stage appear as main contributors in hemp system, while the high electricity consumption due to irrigation (71% of the total) dominates the energy use for flax production González-García et al. (2010).

Comparing **hemp and eucalyptus**, da Silva Vieira et al. (2010), show that hemp presents higher environmental impacts than eucalyptus paper in all environmental categories analyzed. The main differences are in the crop and the pulp production stages. This is because hemp makes use of more mechanical operations and larger amounts of fertilizer in the former and larger amounts of chemical additives in the latter; finally, hemp requires larger areas than eucalyptus per unit of output.

On the other hand, Xu and Becker (2012) shows that eucalyptus plantation management methods in China, especially the application of fertilizer, should be an important concern for plantation management in the future.

Softwood or Bamboo?

Thomas and Liu (2013) underlines how the location of fiber production plays a key role in assessing whether bamboo pulp has lower fossil fuel consumption than northern softwood pulp. In a situation in which bamboo and northern softwood pulp production facilities are located at the same distance from the tissue mill, bamboo could potentially have equal or greater requirements for fossil fuels than northern softwood.

Finally, in order for a paper to have outstanding environmental features, both the fiber choice and the pulp and paper and supply chain choices should meet high standards. This study does not identify or determine those standards. Hot spots for fibers can stem from the carbon, ecosystem or biodiversity impacts of fiber production, particularly in unmanaged forests and high conservation value areas. Land use impacts can be reduced by producing fibers intensely in cultivated areas, however this created potential for environmental impacts due to fertilizers, pesticides, irrigation, cultivation and harvesting.

Bottom Lines: As discussed in the section on hot spots and cold spots: We are not convinced that any alternative fiber type has a definitive environmental advantage over every type of wood fiber in general. Specific pulps from individual producers with low inputs and efficient production processes can be better than other pulps. Life cycle environmental assessment and market data specific to alternative fiber fine papers for the US market are very limited. Production of paper from alternative fibers is relatively new for the US market. First generation production systems may have higher costs and environmental impacts established production systems and these systems might nevertheless be supported for their potential to provide future environmental benefits.

As new data become available, major issues to consider for fiber production are the energy and chemical inputs to production, the management of the agricultural processes to protect soil, water, carbon and ecosystems, and the potential for invasiveness or ecosystem impacts. In supply chains in which fiber or pulp will be transported long distances, the efficiency and emissions from transportation can be important. In general, the energy and environmental impacts of both pulping and paper-making can dominate the overall environmental impacts; these impacts can matter more than the choice of fiber and should be considered in an overall evaluation.

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9 Appendix

Eucalyptus

Table 5: Eucalyptus - Global warming

	Lopes et al. (2003)	Dias et al. (2007)	Gonzalez-Garcıa et al. (2009)	Jawjiy et al. (2006)	da Silva Viera et al. (2010)	Lopes Silva et al. (2015)
Global warming (GWP) or climate change	• Most of GWP results from the final disposal of printing and writing wastepaper. • Contribution is mainly from CH_4 emissions during wastepaper landfilling. o Although total CO_2 emissions are 8 (natural gas) to 15 (heavy fuel oil) greater than CH_4 emissions, CH_4 has a bigger role because its GWP is 24.5 times greater CO_2 • The second contributor is onsite energy production in paper production, due to CO_2 emissions. • The replacement of oil by natural gas originates a reduction	*German market:* • The most important contributor to the GWP is the paper production stage due to nonrenewable CO_2 emitted. • The final disposal stage contributes to 15% of the total GWP. o This is due to CH_4 emitted during paper landfilling *Portuguese market*: • It is unfavourable for the GWP because landfilling is the main final disposal alternative for wastepaper, resulting in CH_4 emissions, as	• Only the CO_2 originated during non-renewable fuel combustion was included • The combustion of fuel oil in lime kiln stands for 65% of the impact followed by chemicals production (31%). • GWP could be reduced by displacing the consumption of fossil fuels by renewable in the chemical recovery system.	• Among the three main GHG – CO_2, CH_4 and N_2O –CO_2 accounts for almost all of the emissions • Activities that generate GHGs are: biomass combustion in the energy production unit (65%) and lime burning (30%). o These activities become less significant if CO_2 emissions from biomass combustion can be excluded since the carbon is derived from trees o The major contributor to GHGs becomes bunker oil use with the amount of total emission reduced to 0.13	• Fertilizers' contribution to GWP either through the energy requirements for their production or through N_2O emissions from the soil contribute little compared to the pulp stage. • Chemical additives used for pulp production, contributes to GWP due to the energy requirements for their production.	• Paper manufacturing showed the highest contribution to GWP (52%), and it is mostly due to CO_2 emissions (43.9% of impacts) from electricity production. • The pulp extraction and bleaching showed 41% of GWP impacts, mainly due to CO_2 emissions (33.7% of impacts) from the generation of electricity using nonrenewable sources such as coal and oil. • The total biogenic CO_2eq emissions were 3198.0 kg per ton of offset

	in the GWP of about 20%, because of a decrease in CO_2	landfill gas is not burned.		Mton CO_2-eq/year. ○ including the sequestration of CO_2 by eucalyptus (0.6 Mton CO_2-eq/year) timber production can be considered a minor contributor		paper in the cradle-to-gate system, and the remaining part is stored into the paper as carbon embedded, accounting for 871.5 kg

Table 6: Eucalyptus - Photochemical oxidant formation

	Lopes et al. (2003)	Dias et al. (2007)	Gonzalez-Garcıa et al. (2009)	da Silva Viera et al. (2010)	Lopes Silva et al. (2015)
Photochemical oxidant formation (POF or POP)	• The final disposal of wastepaper contributes almost 100% to the overall POP potential due to the CH_4 emissions from wastepaper land filling.	*German market:* • The final disposal of wastepaper is the major contributor as a result of CH_4 emissions from wastepaper landfilling. *Portuguese market:* • It is unfavourable for the POF because landfilling is the main final disposal alternative for wastepaper, resulting in important CH_4 emissions, as landfill gas is not burned.	• The main contributor of POP is the production of energy in the mill (more than 60%) due to the chemical recovery unit • SO_2 emissions represented more than 83% of total emissions, principally derived from recovery boiler (black liquor as fuel) and lime kiln.	• Mechanical operations used during the farming/forestr y stage contribute to POF due to the emission of hydrocarbons.	The forest production and industrial production contributed to 35% and 65% of all PO impacts. • The forest production hotspot was volatile organic compounds (VOC) emissions from wood harvesting and transportation activities. • Most of the impacts caused by the industrial production are due to the processes of pulp extraction and bleaching (42%) and offset paper manufacturing (37%). • The production of thermal energy used in the industrial production was responsible for most of the PO impacts, due to carbon monoxide (CO) and VOC emissions from burning diesel and biomass.

Table 7: Eucalyptus - Acidification and Eutrophication

	Lopes et al. (2003)	Dias et al. (2007)	Gonzalez-Garcıa et al. (2009)	Jawjit et al. (2006)	Lopes Silva et al. (2015)

Acidification (AP)	• Paper production is the most important contributor to the overall AP due to SO2 emissions from on-site energy production.
	• Transport, eucalyptus pulp production and electric energy production are important contributors.
	  ○ In the transport subsystem the contribution is dominated by NOx emissions while in the two other subsystems, SO2 emissions are mainly responsible.
	• In the natural gas scenario a reduction of almost 75% of the overall AP is observed. This happens as a result of the paper production contribution reduction to nearly zero, and of the "avoided" emissions by the surplus electricity production in paper manufacturing.
		German Market:
		• Paper production stage has the largest contribution because of SO2 emissions generated during energy production.
		Portugese market:
		• the APs are smaller (2-15%) when the printing and writing paper is consumed in Portugal because the decrease achieved in the paper distribution stage exceeds the increase observed in the final disposal stage.
			• Energy production related processes represented roughly 67% of total emissions.
			• The chemical recovery unit is the major contributor to SO2 emissions due to the use of Na2SO4 and the use of fuel oil in the lime kiln.
			• SO2 emissions contribute to 69% of total emissions, followed by NOx (31%) which comes mainly from combustion in the boilers and from fuel oil in the lime kiln.
				• The kraft pulp production subsystem generates acidifying agents through the production process and chemical recovery since many sulfur-containing chemicals (sodium sulfate and sodium sulfide) are used.
				• The combustion of fuel in the pulp mill is the main source of NOx emissions, although fertilizer use also contributes to the emission of this pollutant.
				• The total annual acidifying emissions from SO2 and NOx were calculated to be 3.6 kton SO2-equivalents.
				  ○ The chemical recovery unit was found to be the major contributor to SO2 emission due to the use of Na2SO4 in the chemical make-up process and the use of bunker oil in the lime kiln.
				  ○ The emission of NOx comes mainly from combustion in the biomass boiler and recovery boiler and from bunker oil in the lime kiln.
				    ▪ The chemical
					• The chemical recovery process contributed to the most to AC (62%)
					  ○ This is due to inorganic air emissions of hydrogen sulfides (47.8%) from total reduced sulfur (TRS) emissions.
					  ○ 10% of the impacts are related to the consumption of diesel fuel in industrial boilers,
					• The extraction and bleaching process contributed to 24% of AC impacts due to nitrogen oxides (NOx) and sulfur dioxide (SO2) emissions from the production of thermal energy, which uses diesel fuel in industrial boilers.

				recovery unit contributes the largest proportion to the total emissions ▪ Another NOx contributor is biomass combustion (34%). ▪ The eucalyptus forestry subsystem exhibits only a very small contribution (3%) since there is a small NOx emission from diesel and fertilizer use.	
Eutrophication (EP or E) or Nutrient enrichment (NE)	• The largest contribution comes from the eucalyptus pulp production, mainly as a result of its COD emissions. • Transport and paper production contribute to this impact category. • In the transport subsystem this is mainly due to NOx emissions • . • The overall EP is reduced by more than 20% with the replacement of heavy fuel oil by natural gas.. .	*German market:* • The greatest contribution comes from the pulp production mainly as a result of COD and NOx emissions. The paper production stage has also a remarkable contribution mainly due to NOx emissions. *Portugese market:* • The EP is smaller (between 2 and 15%) when the printing and writing paper is	• Waste treatment, energy production and waste water treatment plant (WWTP) represented 35%, 29% and 25% of EP • emissions to water represented more than 62% due to COD emissions (from WWTP and disposal in landfill of	• Fertilizer use in the eucalyptus forestry and pulp production unit (cooking, washing and bleaching) at the kraft pulp mill are the most important activities causing the emission of nitrogen and phosphorus. • Among the six pollutants of EP agents – NO3, NOx, PO4 from fertilizer use; N and COD from the pulp production unit; P from the wastewater treatment unit –COD was proportionally the most abundant pollutant discharged (12,240 ton/year in total). • When considered EP	Forest production and industrial production subsystems each contributed to 50% of all NE impacts. • 47.2% of all NE impacts are attributed to the emissions ammonia and NOx emissions due to forest management activities of NPK fertilizing, and the use of diesel in wood harvesting, processing, and transportation activities. • The contribution of NE impacts from the industrial production shows the extraction and bleaching process being the highest results (42%), followed by the offset paper manufacturing process (36%), due to air emissions of NOx from

		consumed in Portugal because the decrease achieved in the paper distribution stage exceeds the increase observed in the final disposal stage.	green liquor dregs). • NOx emissions contributed to 33% of the total EP from energy production	agents as nutrient potential (NP) substances in terms of PO4-equivalents, P in the effluent was the most abundant (1,573 ton PO4-eq/year), followed by COD from the pulp production unit (269 ton PO4-eq/year) and PO4 from fertilizer use in eucalyptus plantations (211 ton PO4-eq/year).	burning diesel and biomass in the production of thermal energy. • Total NOx emissions generated by the extraction and bleaching process and the offset paper manufacturing process accounted for approximately 40% of all NE impacts.

Table 8: Eucalyptus - Land use

	<u>Lopes Silva et al. (2015)</u>

Land use	• Under the framework for LCIA of land use, two types of interventions can be distinguished: land use (occupation) and land use change (transformation).
	  o The study only addresses the occupation impacts due to limitation of data on the previous land use state.
	• it was observed a great reduction in the corresponding soil ecological function potential, mainly due to a long period of occupation, except for Groundwater Replenishment (GWR).
	  o GWR results indicated a credit for the performance of the soil functional potential.
	• The erosion of 2.49Eþ03 kg of soil eroded exceeding restoration conditions during the occupation process of the field.
	• Physicochemical Filtration (PCF) indicator was 1.02Eþ03 (cmol*m2*a)/kgsoil, which represents the amount of cations that could not be fixed into the soil due to the forest operations
	• The impact in the ability to filter pollutants fixed in the soil was 2.05Eþ06 cm*m2, expressing the amount of water that could not be filtered due to the forest production subsystem.
	• GWR represents the soil's ability to recharge groundwater in order to regulate peak flow through the magnitude of runoff and aquifer recharge.
	  o GWR value showed an improvement of the soil functional performance of 4.84Eþ03 mm*m2 in comparison to Potential Natural Vegetation (PNV).

Table 9: Eucalyptus - Ozone depletion and Human and Eco-toxicity

	Gonzalez-Garcıa et al. (2009)	Jawjit et al (2006)	Lopes Silva et al. (2015)
Ozone depletion (OD)	• The production of energy stands for two thirds of this impact category, mainly due to the production of fossil fuels used to strike the boilers and lime kiln. o Halon 1301 and 1211 from the production of the fuel oil used in the lime kiln represented 76% and 13%of the total contributing emissions (CFC-11 equivalent) • Tthe production of chemicals used in cooking and bleaching stages (specifically H2O2) is the other important element (29%).	• Among the four main components of tropospheric ozone precursors – NMVOC, CO, CH4 and NOx –CO accounts for almost all of the emissions. • There are only two main important sources of the smog problem: biomass combustion and the chemical recovery unit. o Biomass combustion in the energy production unit ranks the first, with a share of almost 80%. o For the chemical recovery unit emission share is 14% • Eucalyptus forestry subsystem emits a very small proportion (<1%) of the total tropospheric ozone precursor compounds and can be considered to be negligible with respect to this problem.	• 57% of the OD impacts occurred in the offset paper manufacturing process due to the electricity supply chain, and are attributed to organic halogenated air emissions of R11 and R144 from the electricity supply chain. o Air emissions of R11 and R144 accounted for approximately 84% of the OD impacts. • 36% of the OD impacts occur in the pulp extraction and bleaching, also due to R11 and R144 emissions generated when electricity is consumed.
Human and Eco-toxicity	• The pulp production process in the study is totally chlorine free so chlorinated compounds are not used as bleaching agents. • AOX emissions are really low due to the absence of chlorinated compounds and are associated to the waste water treatment plant. • The production of chemicals seems to be the main responsible (61%), mainly due to H2O2 and NaOH, followed by energy production *Human toxicity* • it is mainly caused by water and airborne emissions such as PAH (15%) and nickel (10%) to air and,	• TRS, which is mainly emitted through the chemical recovery unit causes a bad odor and can harm the human respiratory system. • Emissions of particulates, SO2, NOx also contribute to human toxicity problem. • The total emissions of human toxicity compounds are about 6.9 kton C6H4Cl2-eq/ year. • Among the four pollutants considered – TRS, AOX, SO2, NOx and particulates – AOX emission from pulp bleaching is the highest 1.84 kton/year). • in terms of C6H4Cl2-equivalents, NOx emissions from biomass combustion exhibit the highest amount (2.07 kton C6H4Cl2-eq/year), followed by AOX from pulp	• The industrial production subsystem contributed to 38% of all EC impacts, o the chemical recovery (49%) and offset paper manufacturing (46%) o EC impacts occur during the production of thermal energy, which uses biomass and diesel fuels generating NOx (from burning biomass and diesel) and heavy metal air emissions (from the electricity cradle-to-gate life cycle). • the forest production was responsible for 62%. o EC impacts are caused by glyphosate air emissions (48.8% of all EC impacts) due to the use of glyphosate herbicide in forest management activities.

	PAH (10%) and barium (10%) to water, mainly from the chemicals and fuels production.
	Fresh water aquatic ecotoxicity (FE):
	• FE potential is mainly divided between chemicals production and the treatment of waste generated in the process.
	• Three substances are the main contributors: copper (31%), vanadium (25%) and nickel (18%) from both processes.
	Marine aquatic ecotoxicity (ME)
	• Chemicals production was mainly responsible for the contributions to this category (75%), followed by waste treatment (13%) and energy production (8%).
	• The emission of hydrogen fluoride to air represented 56% of total, followed by vanadium (11%) and beryllium (8%) to water, mostly from O2, NaOH and H2O2.
	Terrestrial ecotoxicity (TE)
	• With a contribution of more than 92%, chemicals production dominates this impact, specifically NaOH (60%) and H2O2 (18%) consumed in the cooking and bleaching processes.
	• The main emissions were mercury to air (73%) from NaOH production and vanadium to air (22%) related to H2O2 production
		bleaching in the pulp production unit and NOx from the chemical recovery unit.
		• Odorous TRS is emitted as a result of pulp cooking and the chemical recovery unit at amounts of 1530 and 30 ton TRS and 337 and 7 ton C6H4Cl2- equivalents, respectively.
		• For the eucalyptus forestry subsystem, emissions of human toxicity compounds were found as a result of diesel use and fertilizer use, but these only account for about 1% of the total emissions.
			Human toxicity
			• Chemicals emitted through anthropogenic activities can contribute to human toxicity by exposure to the environment if the substances are poisonous and humans are exposed to them
			  ○ The chemical recovery (55%) and offset paper manufacturing (41%) processes were the greatest contributors to human toxicity in cancer effects (HTC) .
			  ○ The chemical recovery (54%) and offset paper manufacturing (41%) were the main contributors to Human toxicity, non-cancer effects (HTNC) resulting mainly from heavy metal air emissions (65.4%) in the electricity supply chain.
			  ○

Table 10: Eucalyptus - Particulate matter formation

	Jawjit et al. (2006)
Particulate matter formation	• The combustion of fuel during the pulp production process and transportation of eucalyptus timber causes the emission of VOCs, CO, CH4 and NOx, which are considered to be tropospheric ozone precursors.

Table 11: Eucalyptus - Non-renewable resource depletion

	Lopes et al. (2003)	Dias et al. (2007)
Non-renewable resource depletion	• Paper production is the subsystem contributing most to non-renewable resource depletion consuming exclusively non-renewable fuels (heavy fuel oil or natural gas) for on-site steam and electricity production. • The second most important contribution is transport coming from the consumption of diesel oil and heavy fuel oil by the several modes of conveyance throughout the paper life cycle. o The overall potential to this impact category is reduced by more than 45% in the natural gas scenario, mainly due to the surplus of electricity generated in the paper production process.	*German market:* • The non-renewable resource depletion potential is largely due to the consumption of heavy fuel oil in the paper production stage, about 70% is used for on-site energy generation almost 20% is used to produce the electricity from the grid consumed in the paper production process. *Portuguese market:* • Non-renewable resource depletion potentials are smaller (between 2 and 15%) when the printing and writing paper is consumed in Portugal because the decrease achieved in the paper distribution stage exceeds the increase observed in the final disposal stage.

Hemp

Table 12: Hemp: Global warming, Photochemical oxidant formation and Eutrophication

	Gonzales-Garcia et al. (2010a)	Gonzales-Garcia et al. (2010b)	da Silva Viera et al. (2010)
Global warming (GWP) or climate change	• the production (specifically ammonium nitrate) and use of fertilizers were identified as the principal elements (70%) of total GWP • N_2O (58%) and CO_2 fossil (42%) emissions dominated the contributions to GWP mainly due to the application of nitrogen to soil, nitric acid production and combustion of fossil fuels to the generation of electricity required.	• Only the CO_2 originated during non-renewable fuel combustion was considered because the CO_2 released from renewable sources is assumed to be balanced with CO_2 absorption in the photosynthesis stage. • The results indicated a release of 7 tonnes of equivalent CO_2 per tonne of pulp. • The emissions of fossil CO_2 presented the greatest contributions (approximately 74%) to this impact category,followed by N_2O (25%). • Hemp fibers production, followed by electricity production were observed as responsible systems to GWP. • Production of chemicals (specifically, NaOH production) and on-site energy production were also identified as important contributors. • the production of steam from fossil fuel (mainly natural gas) contributed to more than 19% of total CO_2 equivalent emissions •	• The values estimated are 140 $kgCO_2$-eq/t paper o It included N_2O emissions from the fertilizer applied to the soil, which greatly contribute to global warming. • More than 80% of GWP is from pulp production • About 20% is from fiber production
Photochemical oxidant formation (POF or POP)	• Field operations contribute to 50% of POP, being scutching process the main contributor to this category • Fertilizers production involves almost the 40% of total contributions, specifically P-based fertilizer production. • POP shows important contributions from energy-related emissions: SO_2 and CO, which represent 71% and 17% of the total emissions,	• The electricity production subsystem had the largest contribution to the potential impact of POF (36%), followed by agricultural activities (30%) and the subsystem of chemicals production (27%). • The POF of the system under analysis was mainly caused by energy related emissions from the electricity subsystem and agricultural machinery. • The contributions to SO_2 emissions from NaOH and fertilizers production SO_2 represented more than 78%, followed by CO emissions (11%).	• 55% is from pulp production and 45% is from hemp production • Mechanical operations used during the farming/forestry stage contribute to POF due to the emission of hydrocarbons.

	respectively.		
Eutrophication (EP or E)	• The use of fertilizers is the principal source followed by fertilizers production • Nitrate (NO_3^-) leaching, nitrogen and also phosphate emissions contribute to approximately 90% of the whole effect.	• Nitrate leaching and Phosphate emissions to water as well as Nitrogen and NOx emissions to air contributed to 72%, 8% and 7% respectively, of the total eutrophying emissions. • Agricultural activities were the responsible of 88% of the total contributions, specifically, hemp cultivation (77% of total). • Emissions to water represented more than 75% due to COD, P and N related emissions.	• Fertilizer use in hemp production contributes highly (more than 50%) to EP(nitrates and phosphates) resulting in high field emissions for hemp production

Table 13: Hemp - Acidification and Non renewable resources depletion

	Gonzales-Garcia et al. (2010a)	Gonzales-Garcia et al. (2010b)
Acidification (AP)	• AP was mainly due to mineral based fertilizers production and use (57%), and the scutching process (field operation) • Energy related emissions are also main contributors: Sulphur dioxide (SO_2) originated from combustion of sulphur-containing fossil fuels (41%), ammonia (NH_3) emissions associated to fertilizers use and production (34%), as well as nitrogen oxides (NOx) from combustion (25%).	• Hemp fibers production were the most important contributors to A and figured approximately 43%, followed by electricity and chemicals production (30% and 19% respectively). • Emissions to air of SO_2 (59%), NOX (26%) and NH_3 (15%) were mainly responsible for acidifying emissions.
Non renewable recourses depletion	• Oil crude, natural gas and uranium are the main energy resources (79%). • Total energy use of the hemp system (agricultural production, straw processing and transport subsystems) is 13.2 GJ t^{-1} (13.2 GJ ha^{-1}). • Fertilizers production is an important element for hemp crop representing 39% of energy use • Scutching and harvesting stage mean the 17% and 11%, respectively.	• The production of chemicals was the major contributor (64%), specifically H_2O_2 manufacture followed by electricity production (33%).

Table 14: Hemp - Ozone depletion and Human and Eco-toxicity

	Gonzales-Garcia et al. (2010b)
Ozone depletion (OD)	• The production of natural gas used for heat production showed the highest contribution to OD (roughly 25% of the total impact). • The production of chemicals used in cooking, bleaching and chemical recovery stages (specifically NaOH) was observed as a significant process contributor to OLD (more than 19%). • Hemp fibers production contributed to 15% of total contributing emissions respectively due to the use of diesel in agricultural activities.
Human and Eco-toxicity	*Human toxicity:* • 29% was associated to the electricity production subsystem. • Agricultural activities related to fibers production represented more than 46%, mainly due to fertilizers production and harvesting • Production of chemicals, particularly H2O2 and NaOH is another hot spot. *Fresh water aquatic ecotoxicity (FE):* • 39% of FE potential was linked to chemicals production (H2O2 and NaOH) followed by electricity production on national grid (25%) • Agricultural field operations to produce the raw material contributed to roughly 19%. ○ Emissions to water dominated the contributions to this impact category (approximately 96%), specifically the emissions of Va (32%) and Cu (24%). *Marine aquatic ecotoxicity (ME):* • Electricity production was the main responsible of the contributions to this category (42%), followed by agricultural operations (35%) and chemicals production (22%). • H2O2 and NaOH were the main chemicals contributing to this impact category • The emission of HF to air represented 82%, followed by emissions of Beryllium to water (6%). *Terrestrial ecotoxicity (TE):* • the production of chemicals represented more than 58% of total contributions to TE potential • NaOH (around 52% of total), followed by electricity requirements production (22%). • The main emissions contributing to this impact category were the emission of Hg to air (61%) related to NaOH production and the emission of Vanadium (19%) and Chromium VI (11%) to air derived from fertilizers production.

Flax

Table 15

	Gonzales-Garcia et al. (2010a)	Gonzales-Garcia et al. (2010b)
Global warming (GWP) or climate change	• Fertilizers production and use as well as field operations (specifically irrigation process) were the main responsible • This category was dominated by two substances (N_2O (20%) and CO_2 fossil (79%)), which are mainly emitted from energy production, nitrate based fertilizer production and application	
Photochemical oxidant formation (POF or POP)	• Field operations (irrigation and scutching) are the main responsible and their contribution adds up to 67% of total. • SO_2 contribute to 66% of this category followed by CO_2 (26%)	
Acidification (AP)	• Field operations such as irrigation and scutching processes are mainly responsible for the results in this impact category (more than 50% of total contributions), followed by fertilizers production and use • SO_2 and NO_x emissions represent approximately 47% and 20% respectively. • NH_3 emitted as consequence of nitrogen application (volatilization) and nitrate based fertilizer production stands for one third of the acidification impact. ○ NH_3 emissions are strongly dependent on the nitrogen-fertilizer rate: this type of emissions increase with increasing N-fertilizer rates applied, so it will be needed to apply the optimum amount.	• Flax fiber production were the most important contributors to A and figured approximately 43%, followed by electricity and chemicals production (19%). • Emissions to air of SO_2 (59%), NOX (26%) and NH_3 (15%) were mainly responsible for acidifying emissions.
Eutrophication (EP or E)	• Fertilizers usage and production are the main factors responsible • Nitrogen related emissions, phosphate and NO_3 − leaching associated to fertilizing process are responsible of almost 65% of total	
Ozone depletion		• Flax fiber production contributed to 1 16% of total contributing emissions due to the use of diesel in agricultural activities. • The remaining contributions were mainly related to Spanish electricity generation profile (14%). • Halon 1211 and 1301 represented 43% and 42%, respectively of the total contributing emissions (CFC-11 equivalent).
Human toxicity	•	• Agricultural activities related to flax fiber production

		represented more than 46%, mainly due to fertilizers production and harvesting. • Production of chemicals, particularly H2O2 and NaOH is another hot spot. • It is important to mention the emissions of PAH (29%), HF (17%), Ni (8%) and As (6%) to the air.
Non renewable	• Total energy use of the flax system (agricultural production,straw processing and transport subsystems) is 12.4 GJ t−1 (18.6 GJ ha−1). • Field operations are the main contributors in flax scenario (89%), specifically irrigation process which involves 71% of total. • Oil crude, natural gas and uranium are the main energy resources (71%).	

Bagasse

Table 16

	Poopak and Agamuth (2011;2012)
Global warming (GWP) or climate change	• The total impact of global warming is -729.81 kg CO_2 eq (Negative impact means environmental benefits). • Electricity and bagasse contribute lowest impact value because both of these inputs were using renewable sources. o Electricity is using hydroelectric sources, whereas, bagasse is a by-product of sugarcane factory. • The consumption of bagasse as raw material for paper production (instead of virgin wood) may result in reduced deforestation and at the same time increased CO_2 absorption and has the potential to reduce global warming effect.
Photochemical oxidant formation (POF or POP)	• Bagasse gave an impact value in photochemical oxidation of Kg C_2H_4 0.37
Acidification (AP)	• Acidic gases such as sulfur dioxide and nitrogen oxides (released during the burning of fossil fuels) contribute to the acidification of the soil and fresh water ecosystem. • The category indicator was equal to 3.43 KgSO_2 eq.
Eutrophication (EP or E)	• During the combustion of fossil fuels and fuel production high NO_x is produced. This can result in accumulation of nitrates, phosphates and dissolved oxygen content.
Ozone depletion (OD)	• The total impact value contributed by the paper production process to ozone layer depletion was 0.00015 kg CFC-11 eq. o Chlorine contributed the first major impact (62%), Kraft was the second major contributor (16%) while, NaOH was the third (14%). Others made up a small range of impacts which was less than 5% each; starch (4%), mazut (2%), aluminum sulphate (1%), OBA (0.4%), bagasse (0.4%), resin (0.2%) and clay (0.01%).
Human and Eco-toxicity	• The toxicity impact was measured as 1, 4-dichlorobenzene equivalents per kg emission (Kg 1,4-DB eq) and it is equal to 242.14 • From the total impact, kraft contributed the highest impact of about 42%. Aluminum sulphate was in second place with 26% followed by mazut (15%), chlorine (10%), NaOH (4%), bagasse (1%), starch (1%), resin (1%), OBA (0.2%), clay (0.02%) and electricity (0.0005%).
Abiotic depletion	• Mazut (fuel oil) contribute the highest impact value of 85% followed by kraft with 11%, of the total impact. The resin, bagasse, OBA (Optical Brightness Agent), NaOH, corn starch and Aluminum sulphate make up smaller impacts in a range of 0.1-2%. • Clay and electricity contribute very little impact which are 2.90x10-3 kg Sb eq and 2.91x 10-5 kg Sb eq

Photochemical Oxidant Formation

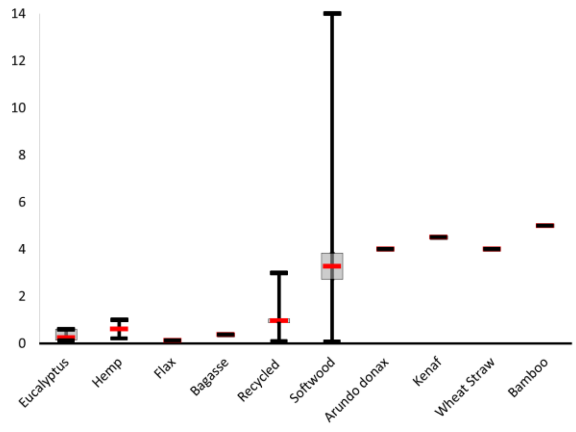

Figure A1: Photochemical Oxidant Formation (kg ethene-eq/ton product)

Figure A1 shows photochemical oxidant formation. The pulp production process is the main source of this impact, so result may reflect the quantification of the pulping process rather than differences in the feedstock itself.

Photochemical oxidant formation for softwood from Thomas and Liu 2013 are particularly high. This study uses a full ReCiPe database that includes background processes (building the roads and power plants for the system). However, that study found that these photochemical oxidant formation levels contributed less than 0.003% of the human health impacts. Therefore we do not consider these emissions to be significant contributors to the impacts of pulp.

Acidification

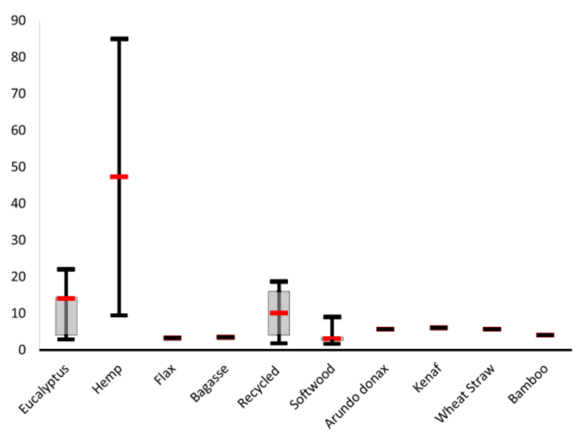

Figure A2: Acidification (kg SO_2/ton product)

For the fibers considered, Figure A2 indicates that hemp paper produces the highest acidification level. This is because the processes that most affect the environment are the mechanical operations required for crop production, emissions from fertilizer use (leaching), and the production of chemical additives used for pulp production, for which hemp presents higher values in all of these. Iosip et al. (2012) assessed the level of acidification under different levels of recycle fiber contamination. Thomas and Liu

(2013) found that acidification contributed less than 0.3% of the ecosystem impacts. Therefore we do not consider these emissions to be significant contributors to the impacts of pulp.

Ozone depletion

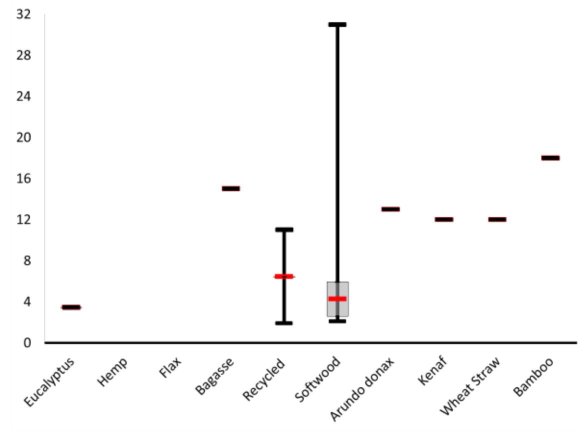

Figure A3: Ozone Depletion (kg CFC-11 eqx10^5 /ton paper)

Figure A3 shows published results for stratospheric ozone depletion. Thomas and Liu (2013) found that ozone depletion contributed less than 0.003% of the human health impact; therefore we consider these emissions to be insignificant to the assessment of the environmental impact of pulp.

Marine aquatic toxicity

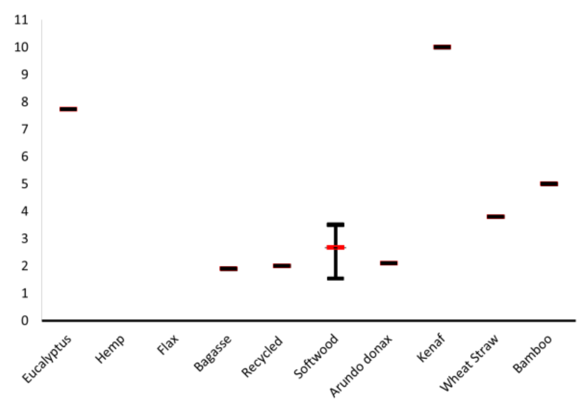

Figure A4: Marine aquatic toxicity (kg 1,4-DB eqx10 $^{-4}$ /ton pulp)

Figure A4 shows marine ecotoxicity potential for all the fibers. Kenaf is reported as having a high value and its main source is chemicals used in agriculture production (Thomas and Liu, 2013). Similar results are reported for eucalyptus, for which chemicals in production were mainly responsible for the contributions to this category (Gonzales-Garcia et al. 2009). However, the overall contribution of marine aquatic toxicity to ecosystem impacts was reported by Thomas and Liu (2013) to be very small (~ 2%) and we therefore do not consider this indicator to be important in the overall impacts of pulp production.