LCA Case Studies

Streamlined LCA of Soy-Based Ink Printing

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Abstract. This study provides a benchmark of the life cycle environmental impact characteristics associated with a typical soy-based ink used for sheetfed lithographic printing. The scope included a streamlined Life Cycle Inventory (LCI) and Impact Assessment (LCIA). Materials, processes, and life cycle stages that are the same between different printing inks, or were less than one percent by mass of the printing system input materials, were excluded. The LCIA included identification of specific processes in the life cycle of soy-based ink printing that make the greatest contribution to the overall environmental hazard potential in 13 impact categories for the baseline printing system selected. The LCIA approach included both regional scaling for areas that differ in sensitivity to certain impact indicators and normalization against a reference value. Reduction in the use of tall oil rosin and switching from conventional to low or no-till farming appear to be promising opportunities for reducing the environmental hazard potential.

Keywords: Impact categories; LCI; LCIA; Life Cycle Impact Assessment (LCIA); Life Cycle Inventory (LCI); lithography; sheetfed printing; soy-based ink; soybean oil

Introduction

Soybean oil has been demonstrated to be a viable alternative to petroleum-based middle distillate oils as a vehicle for carrying pigment in many types of printing inks, although soy-based inks still constitute only a small portion of the total potential market for printing inks. According to the United States (U.S.) census of printing inks, the quantity of lithographic and offset inks sold in 1992 amounted to a total of 378.6 million kg, including 48.9 million kg of sheetfed inks. Use of soy oil in inks is limited to paste inks, which are primarily news inks and lithographic inks. Current consumption of soy ink is estimated to be over 23 million kg per year. In order for printers and publishers to display the SoySeal™ on sheetfed material, the American Soybean Association (ASA) requires use of inks containing at least 20% soy oil.

A variety of studies have been conducted on the environmental impacts of selected components of lithographic printing and soy-based ink printing, including evaluations of blanket washes by the U. S. Environmental Protection Agency (EPA 1996) and Tillotson and Demers (1994), an evaluation of shop towel use in printing (PULLMAN et al. 1997), a comparison of soy-based versus petroleum-based ink mileage (ROSINSKI 1995), and a waste reduction evaluation of soy-based ink use at a sheet-fed printer (SIMPSON et al. 1994). In addition, a comprehensive review of all types of printing and typical formulas for printing inks, including soy-based inks, are described in 'The Printing Ink Manual' by Leach and Pierce (1993). Pollution prevention opportunities for the commercial printing industry, including lithography, have been identified by many different studies, for example EPA (1990). However, no Life Cycle Assessment (LCA) has been conducted on an entire printing ink system in the U.S., including extraction of raw materials, manufacturing of printing materials (e.g., ink, solvents, fountain solution, shop towels, paper), printing operations, and disposal of wastes.

From an environmental standpoint, there is an interest in using biologically based products from renewable resources (e.g., soybeans) instead of non-renewable resources (e.g. petroleum), which may become unavailable to future generations. Also, soy-based ink has very low emissions of volatile organic compounds (VOCs) during printing, compared to many petroleum-based ink formulations. Releases of VOCs during printing are a concern for human health in the print shop, as well as creation of photochemical smog, which can cause human health impacts over a broad area.

Prior to the start of this study, no publications were available that focused on an LCA of printing systems using soy-based ink. Although there is still no published LCA that focuses on sheetfed printing using soy-based ink, a recently published LCA on newspaper printing by Rafenburg and Mayer (1998) includes evaluation of an improved printing system (including soy-based ink) as a potential alternative to the baseline printing system using petroleum-based ink.

1 Goals and Scope

The purpose of this study was to document the life cycle environmental impact characteristics associated with the use of soy-based inks by evaluating a typical ('generic') soy-based ink formula currently used in significant quantities for sheetfed printing. This typical soy-based ink printing system will serve as a benchmark for future comparison with alternative ink formulations and other combinations of printing system materials. The Life Cycle Impact Assessment

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(LCIA) included identification of specific processes in the streamlined life cycle (core operations associated with material acquisition, manufacture, use, and disposal) of soy-based ink for sheetfed offset lithographic printing that make the greatest contribution to the overall environmental profile for the baseline soy ink printing system selected. The intent was to identify processes that can be modified to make reductions in environmental impact, thereby enhancing soy-based ink printing as an environmentally preferable choice. It should be noted that an LCIA is a hazard indicator system largely based on resource use and emission loading, and should not be construed to represent actual environmental impacts.

The scope of this project was to select a typical sheetfed printing system using soy-based ink as a baseline and conduct a streamlined Life Cycle Inventory (LCI) and LCIA to benchmark the life cycle environmental characteristics of this system. The LCI and LCIA were streamlined by focusing on the printing system life cycle modules that are potentially different when making comparisons between the baseline soy-based ink and other types of sheetfed ink. Thus, materials, processes, and life cycle stages that are the same between different printing inks, or were less than one percent by mass of the printing system input materials, were excluded.

2 System Description and Boundaries

2.1 Sheetfed lithographic printing

Lithography is currently the most prevalent printing technology in the U.S., with an estimate by A. F. Lewis & Co., Inc. of approximately 49,000 printing establishments using lithographic presses, out of a total of about 53,000 printing shops (EPA 1996). Lithographic printers are primarily small businesses, with roughly 85% of the plants employing fewer than 20 people. Lithographic printing is divided into three separate types: sheetfed offset, heatset web offset, and non-heatset web offset.

Sheetfed offset, which was evaluated here, is a printing process in which the paper is fed into the machine in individual sheets. Sheetfed printing is typically used for the production of publication and packaging work on paper and board (Leach and Pierce 1993, EPA 1996). Sheetfed presses are used primarily for short term printing runs of commercial products at about 92% of the plants with lithographic presses.

The lithographic printing process involves the use of an image carrier or plate on which the image and non-image areas are on the same plane (EPA 1996). In this type of single plane printing, the image is maintained by taking advantage of the mutual repulsion of oil and water. Plates are treated so that the non-image area attracts water, while the image area becomes receptive to oil (ink). Water in the fountain solution applied to the hydrophilic (water-loving) portion of the plate confines the ink within the oleophilic (oil-loving) image area. Ink is applied to the plate cylinder from the ink fountain. The image is transferred from the plate to a rubber-covered blanket cylinder, and then to the substrate (e.g., paper or packaging materials).

When changing jobs and to maintain image quality during printing, the intermediate blanket cylinder must be routinely cleaned (EPA 1996). Both manual and automatic methods are used to apply blanket wash for removing ink, paper dust, and other debris from the blanket cylinder of sheetfed presses. Manual cleaning involves wiping down the blanket cylinder with a reusable cloth wipe (towel) or a disposable wipe, dampened with blanket wash solution and water. The reusable cloth wipes are by far the predominant type used by sheetfed printers. Woven cloth wipers are typically cleaned and reused 12 times (Pullman et al. 1997). Automatic blanket cleaners work by applying blanket wash and/or scrubbing the blanket mechanically.

Typical lithographic blanket washes are made primarily of petroleum-based solvents, often mixed with detergent and/or water (EPA 1996). These conventional petroleum-based cleaners typically remove ink quickly and evaporate rapidly, requiring minimal downtime for the press. Petroleum-based cleaners often contain greater than 60% VOCs. While these high VOC washes leave the blanket dry after cleaning, the quick-drying properties come from the high vapor pressure components (e.g., methanol, xylene, MEK) that may pose a potential risk to workers' health and the environment. Still, conventional cleaners continue to dominate the market because of their effectiveness as well as their low cost.

2.2 Generic soy-based ink and blanket wash formulas

Due to the extreme diversity of formulations and large number of manufacturers for soy-based inks and blanket washes, this study was streamlined by selecting a generic or typical formulation of each of these printing materials. A generic formula for soy-based, sheetfed ink was selected based on recommendations from the Graphic Arts Technical Association (GATF) and the manager of the Sheetfed Research Lab at Flint Ink Corporation (**Table 1**). Black ink was selected, because pigments do not differ between soy-based and petroleum-based ink and because black ink is used in a much greater volume than any other color.

Table 1: Generic formula recommended by Flint Ink and GATF

Wt. %	Component	Comments
18	Pigment: Carbon Black	Predominant pigment used in inks for sheetfed printing
0.5	Co drier	Excluded from LCI due to small % and use in other sheetfed inks
1.5	Mn drier	Excluded from LCI due to small % and use in other sheetfed inks
1.5	Polyethylene (PE) wax	
3.5	Reducer: Tung oil	From nuts of Tung tree, primarily from South America
20	100S Type Alkyd[a]	
55	Varnish	50% SBO[b] + 50% PMRR[c]

[a] The 100S Type Alkyd is approximately: 65% (reaction product of 50.7% linseed oil, 9.5% iso-phthalic acid, and later, 4.7% trimethylolpropane), plus 20% [(reaction product of 12.5% tall oil rosin (TOR) and 2.5% Maleic anhydride, and 5% pentaerythritol), plus 15% Aliphatic C14 hydrocarbon)] (personnel communication from Mr. Ludwig Horn, Lawter Chemicals)

[b] SBO = soy bean oil

[c] PMRR = Phenolic Modified Rosin Resin: 66.2% Tall oil rosin, 16.6% Nonyl (or octyl) phenol, 5% Formaldehyde, 2.6% Maleic anhydride (MA), 9.6% Glycerol (or Pentaerythritol), and a trace of alkali catalyst (personnel communication from Mr. J.B. Stansbury, Technical Manager, Arizona Chemical Co.).

Only soy-based inks meeting the requirements of the ASA for the SoySeal™ were considered for this study.

The generic blanket wash was selected to be 50% aliphatic hydrocarbon and 50% aromatic hydrocarbon, based on discussions with three of the major blanket wash manufacturers, GATF, cooperating print shops, and an EPA (1996) report on lithographic blanket washes.

2.3 Life cycle modules and components excluded

As part of the streamlining for this benchmark soy-based ink printing system LCI, several life cycle modules were excluded, because they are expected to be the same regardless of the ink type used (**Table 2**)[1]. For this reason, the following modules were not included in the LCI:

(1) packaging for the printed product,
(2) manufacture of paper used for printing,
(3) distribution/ transportation of printed matter,
(4) burdens contributed by capital equipment and/or by human operators,
(5) color pigments other than black.

Additional components of the printing system were excluded from this evaluation, because they contribute very little environmental burdens due to their extensive life or because they were found to comprise less than 1% of the total system mass balance.

2.4 Functional unit

All life cycle studies require the definition of the functional unit (FU), which is the measure of performance that the system delivers. Based on the units of measure typically used by ink estimators, the functional unit selected for this LCI and LCIA is the quantity of inventory items required for printing 645 m^2 (one million in^2) of substrate at 100% coverage (opacity). Since the inventory is based on black ink, the usage information from cooperating printers involved allocation of resources and emissions based on the percentage of each job printed in black. The quantities of materials (e.g., black ink, blanket wash, fountain solution, paper) used and emissions released per job were calculated based on one FU. For example, calculations on the data supplied by cooperating printers for this study indicated that one FU required 14.1 kg of black, soy-based ink for sheetfed lithographic printing on average for a variety of substrates.

3 Data Collection and Quality

3.1 Selection of cooperating print shops

An initial and follow-up survey of GATF member print shops was used to identify shops that were willing to cooperate in filling out survey forms, have only sheetfed presses, and use only ASA-approved, soy-based ink. After the initial identification of potential cooperators, a second survey was designed to obtain information on quantity and types of printing materials purchased during the last year and to insure that the data supplied would be restricted to sheetfed printing with soy-based ink.

Five cooperating print shops were identified, which are located in the following five U.S. states: Arizona, Illinois, Minnesota, Pennsylvania, and Washington. Each of the five print shops uses soy-based ink made by a different manufacturer, but all of the sheetfed lithographic inks contain at least 20% soybean oil. These five print shops are representative of the small, lithographic printers who use only sheetfed presses and ASA approved soy-based ink. Data from the five coop-

Table 2: Summary of system boundary decisions

Processes Outside Scope (Similar Between Soy- and Petroleum-based Inks)	Insignificant as Inputs (Materials Consumed at less than 1 percent of Total Inputs)	Data Unavailable (No Readily or Publicly Available Data Source)
• Colored Soy Ink • Roller Manufacture • Plate Manufacture • Blanket Manufacture • Manganese Drier Manufacture • Cobalt Drier Manufacture	• Cloth Wiper Mfg. & Recycling • Paper Wiper Manufacture • Fountain Solution Manufacture • Acetic Acid Manufacture • Butyl Cellosolve Manufacture • Ethylene Glycol Manufacture • Cotton Fiber Manufacture • Polyester Fiber Manufacture • Nylon Manufacture • Insecticide Manufacture (Cotton) • Herbicide Manufacture (Cotton) • Cotton Agriculture & Ginning • Cattle Production • Gum Arabic Manufacture • Acacia Tree Silviculture • Butanol & Methanol Manufacture • Ethylene Oxide Manufacture	• Blanket Wash Manufacture • Pentaerythritol Manufacture • Acetaldehyde Manufacture • Phthalic Acid Manufacture

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[1] A detailed system flowsheet showing the life cycle processes included and excluded from the soy-based ink printing system can be viewed at the website http://www.battelle.org/environment/LCM/soyflow.stm.

erating printers represented twelve different sheetfed press types made by eight different press manufacturers. The cooperating print shops recorded the following: press description, blanket log, fountain solution log, and daily press log of individual print jobs.

3.2 LCI data collection

Data collection for the LCI included site-specific primary data, site-specific secondary data, and generic secondary data. Site-specific primary data were collected during 1997 at the five cooperating printers described above. Site-specific secondary data were obtained from EPA databases on emissions from Kraft pulp manufacture (includes production of TOR) and carbon black manufacture. The Kraft pulp mill data came from 11 mills for five of the top ten companies producing Kraft pulp. The carbon black data came from all 19 facilities operating in the U.S. in 1995. Information for both processes was taken from the Toxics Release Inventory (TRI 1997) database for the 1995 submission year and criteria air pollutant data from the Aerometric Information and Retrieval System (AIRS 1996) database for the 1996 submission year.

Generic secondary data were drawn from Battelle's archives or from publicly available data sources. Battelle has compiled information on crude oil extraction and refining, natural gas extraction, hydrogen production, and electricity production. Other generic secondary information were developed from data taken from publicly available data sources such as the U.S. Geologic Survey (USGS 1997), Minerals Information Center for minerals extraction information for the 1996 submission year, the U.S. EPA's TRI (1997) and AIRS (1996) databases for emission data, or Battelle's LCAD database.

Data on soybean production and soybean oil extraction and refining were supplied by the National Renewable Energy Laboratory (NREL), U.S. Department of Energy (DOE) from the front end of their LCI on biodiesel (NREL 1996). This information covered emissions and resource consumption in the fourteen largest soybean producing states and was cumulative for all life cycle stages from raw materials acquisition through delivery of soybeans to a processor. These modules included ancillary materials and energy, such as fertilizer manufacturing, pesticide manufacturing, and electricity production.

The NREL data for soybean agriculture were originally calculated using 1990 cropping practices, when significantly more conventional tillage was practiced. These data were updated to more closely reflect the 1995 cropping practices and match the data age for most of the other LCI modules. The first adjustment was to the number of hectares planted in soybeans, by applying a ratio of 1995 to 1990 hectares planted. A second adjustment was to change the data to reflect changes in cropping practices. Here Battelle relied on data listing the average cost of fuels in 1990 and 1995 per hectare of soybeans under conventional and alternative cropping practices, and as a composite. The composite fuel costs per hectare were both first adjusted to a 1990 basis by using data on the costs of fuels compiled by the U.S. Department of Energy, Energy Information Administration (DOE/EIA 1997). The ratio of 1995 to 1990 composite costs was used as a multiplier for fuel consumption data compiled by NREL to adjust it to 1995 cropping practices.

Agrochemical and fertilizer consumption data were also adjusted to better reflect the change in cropping practices from 1990 to 1995. Data from USDA, which tabulated data on fertilizer and agrochemical use in kg per hectare planted for both 1990 and 1995 were used to adjust the fertilizer and agrochemical consumption and upstream production information embedded in the NREL soybean agriculture LCI.

4 Life-Cycle Inventory Methods

The LCI was compiled following the applicable guidelines described by ISO 14041, in conjunction with the U.S. EPA's (1992) document on Life Cycle Assessment: Inventory Guidelines and Principles. The Battelle-developed software LC*Advantage*™ Plus was used for inventory compilation and calculations.

4.1 Allocation procedures

Allocation was based primarily on mass output of products and co-products. Exceptions included crude oil refining and natural gas processing, where a volume-based allocation process was used. Modules allocated and the approximate proportion of the module inputs and outputs attributed to the soy ink system include: cattle slaughtering – including 15%, which are fats for rendering into glycerol, in addition to meat, hides, and hooves; crude oil refining – including 5% of various refined petroleum products used throughout the system as both products and feedstocks; flax seed processing – including 35%, which is linseed oil for incorporation into alkyd resin, in addition to flax meal or linseed cake; formaldehyde production – including 80%, which is formaldehyde, which is used to produce pentaerythritol, and trimethylolpropane used in making alkyd for the ink; Kraft pulp production – including 2.7%, which is black liquor for refining into Tall Oil Rosin (TOR), in addition to Kraft pulp for paper production; soybean crushing – including 29%, which is soy bean oil, in addition to hulls and soybean meal; TOR manufacture – including 20.7%, which is TOR, in addition to distilled tall oil, pitch, and various other resinous products; and tung nut milling – including 50%, which is tung oil, in addition to tung nut meat. These were generally applied allocations. However, for processes like Kraft pulping, some emissions or inputs were attributable only to selected products and not to others. In those cases, item-specific allocation factors were used.

4.2 Assumptions about electricity production

For processes with an explicit input of electricity, the U.S. national average grid model prepared by Battelle was used. These processes included: soy-based ink manufacture, printing, pulpwood production, natural gas processing, alkyd resin manufacture, tung nut milling, flax seed processing, PMRR manufacture, carbon black manufacture, crude oil refining, crude oil extraction, and TOR manufacture. The soybean agricultural modules included electricity generation within the module boundaries, no further information is available, but the electricity is assumed to be a national average grid. For other modules, either no electricity was used within the module, or no information was available on electricity consumption.

4.3 Limitations of LCI

There are a number of limitations with the LCI. The first limitation has to do with the processes that were eliminated from the LCI because of a lack of available data (Table 2). These are all petroleum-based materials or manufacturing processes. Their inclusion would be expected to produce a small increase in the environmental effects potential associated with the petroleum-based components of this soy-based ink printing system.

A second limitation is the lack of information on transportation of products between processes in the latter stages of the LCI. For the Raw Materials Acquisition (RMA) stage of the LCI, transportation of products from point-of-production to point-of-use was not readily available.

The U.S. national average grid model was used for electricity, because most of the modules using electricity had facilities throughout the U.S. However, local grids can vary substantially in the proportion that comes from coal, nuclear, hydroelectric, and other electric generation methods. Also, some minor processes, such as manufacturing tung oil or linseed oil, may take place outside the U.S.

The majority of the site-specific secondary data and generic secondary data are based on technologies and TRI emission information for 1995. Data for soybean agriculture obtained from NREL was updated to be consistent with the 1995 timeframe for most of the inventory modules. However, updated information was not readily available to bring a few of the minor modules up to the 1995 timeframe. For example, data for formaldehyde production and flaxseed processing included energy data for 1985 and production data for 1993. Data for the polyethylene module were all from 1993.

Data on emissions from manufacture of fertilizer applied to soybeans were included in the soybean agriculture module, since it is the predominant crop for this LCA. Data on emissions from manufacture of fertilizer applied to the three minor crops (pulpwood, tung trees, and flax) were not included in the analysis.

5 Summary of Life Cycle Inventory Results

5.1 Results across all life cycle stages

5.1.1 Electricity generation

Electricity Generation involves the off-site generation of electricity, including fuel consumption and emissions. Aside from the normal energy carriers, no other inputs were recorded for off-site electricity generation within the printing system. Air emissions from electricity generation are dominated by CO_2 emissions at 96 kg per FU, with SO_x and NO_x the next most prevalent types of emissions (**Table 3**). The emissions of CO_2 more than offset the sequestration of CO_2 due to growing soybeans, so that the printing system is a net generator of CO_2. Fossil fuel combustion by-products [fly ash, bottom ash, and flue gas desulfurization (FGD) sludge] were the most significant solid wastes. The only other solid waste was spent nuclear fuel. Of the total electricity consumption for all processes during the life cycle, Printing consumes approximately 86%.

Table 3: Summary of electricity generation LCI module (kg per FU)

Input/ Output Type[a]	Resource	Electricity Generation
I	Coal, Bituminous	2.31E+01
I	Coal, Lignite	1.27E+01
I	Coal, Subbituminous	4.26E+00
I	Natural Gas	2.70E+00
I	Residual Oil	1.32E+00
I	UO_2	1.30E-04
RA	CO_2	9.63E+01
RA	SO_x	7.28E-01
RA	NO_x	3.82E-01
RA	PM10	4.47E-03
RA	TNMOC[b], Unspeciated	1.81E-03
RA	Methane	8.32E-04
RS	Ash, Fly	2.39E+00
RS	Flue Gas Desulfurization Sludge	7.56E-01
RS	Ash, Bottom	7.50E-01
RS	Spent Fuel, Nuclear	2.27E-04

[a] I = Inputs, RA = Air Releases, and RS = Solid Releases

[b] TNMOC = Total Non-Methane Organic Carbon

5.1.2 Embodied energy

Embodied energy is the calculation of the energy expended or lost to society to produce a product or service. It is significant because the embodied energy has been expended, and; therefore, represents the opportunity cost of the product expressed in energy terms. The concept of system energy used herein (see Section 5.1.3) is the cumulative energy expended to deliver the functional unit. It is the sum of the embodied energy and the energy required during the printing operation in and of itself. (Note that this definition is inconsistent with some uses of system energy where the system energy is the sum total of the embodied energy and the inherent energy – the energy content of the product which might be reclaimed upon combustion.)

The total approximated embodied energy was calculated as 5.07 GJ per FU. Two processes appear to consume or contribute most of the embodied energy: Electricity Generation at 28.5 percent, and TOR Manufacture at 41.8 percent. Soybean Agriculture contributes 0.58 percent, which includes a quantity of both embodied and inherent energy. The numbers for Electricity and TOR are completely embodied energy; thus, the actual contribution of these processes to the system embodied-energy would be expected to increase if a corrected calculation could be prepared.

5.1.3 System energy

System energy calculations were prepared using a process similar to that used for the embodied energy calculations. All of the energy flows and energy carriers in the LCI were tabulated. For each process, flows were eliminated from the calculation if they were exclusively used as *feedstock*. The remaining flows were summed by process and for the system, and the contribution was calculated (**Table 4**). The difference between these calculations and the embodied energy calculations is that here the energy associated with Printing is included, whereas in the embodied Energy it is not.

Table 4: Summary of system energy calculations

Process/Segment	Quantity (J/FU)	Percent
TOR Manufacture	1.92E+09	37.81
Electricity Generation	1.31E+09	25.75
Pulpwood Production	1.21E+09	23.86
Printing	4.83E+08	9.53
Carbon Black Manufacture	8.70E+07	1.72
Soybean Agriculture	2.67E+07	0.53
Ink Production	1.70E+07	0.34
PE Production	8.06E+06	0.16
Crude Oil Extraction	5.66E+06	0.11
PMRR Manufacture	3.33E+06	0.07
Alkyd Resin Manufacture	2.25E+06	0.04
Flax Seed Processing	2.27E+06	0.04
Formaldehyde Production	1.55E+06	0.03
Tung Nut Milling	4.36E+05	0.01
Crude Oil Refining	1.15E+05	0.00
Natural Gas Field Operations	5.17E+03	0.00
Natural Gas Processing	1.06E+02	0.00
Total	**5.07E+09**	

In summary, TOR Manufacture accounts for almost 38% of the system energy consumption, Electricity Generation over 25%, Pulpwood Production almost 24%, and Printing about 9.5%. These four processes account for almost 97% of the system energy consumption. Soybean agriculture accounts for only 0.53% of the total system energy consumed. Most importantly these results are consistent with the other LCI results in that TOR and Electricity Generation appear to be the primary causative agents.

5.1.4 Inventory results compared by life cycle stage

For the total LCI of soy-based, sheetfed, lithographic printing ink, water input dominates the input resources consumed per FU (**Table 5**). The next four largest inputs are steam, pine trees, CO_2, and crude oil. The water, pine trees, and CO_2 inputs are primarily used during the Resource Extraction (Raw Materials Acquisition Stage). The steam is primarily used during the Intermediate Materials Manufacturing Stage.

Air emissions for the total LCI are dominated by emissions from the combustion of fossil fuels (i.e., SO_X, NO_2, CO, CO_2, VOCs, and Particulates). These air emissions are primarily released during the Intermediate Materials Manufacturing and Raw Materials Acquisition Stages.

The water emissions released in greatest quantity for the total LCI include nitrates, phosphorus, and triglycerides. Nitrate emissions are primarily associated with Kraft pulp manufacture. Triglycerides are primarily associated with soybean crushing. Phosphorus is primarily associated with farming.

The solid wastes released in the greatest quantity during the total LCI are wood waste and tung nut shells. These wood wastes are released during the Intermediate Materials Manufacturing Stage, while the tung nut shells are released during Resource Processing (Raw Materials Manufacturing Stage). Other important solid wastes are unspeciated non-hazardous wastes and mineral processing wastes, which are primarily released during the Intermediate Materials Manufacturing Stage

5.2 Results in selected life cycle stages

5.2.1 Soybean farming

The soybean farming LCI module was provided by NREL and updated with 1995 data. It is an aggregated module covering all agriculture-related operations from acquisition of raw materials necessary for soybean farming through production of the soybeans. This includes production of agrochemicals, off-site electricity generation for the upstream modules, fertilizer manufacture, production of fuels used on-farm, and the agricultural operations proper.

Water input, associated with irrigation in states with low rainfall, dominates the resources consumed as 4,808 kg per FU. The next largest input, at 16.5 kg per FU, is CO_2 sequestered by the soybean plants. The primary components of agrochemicals and fertilizers are the next largest inputs – crude oil, phosphate rock, and potassium monoxide.

Air emissions are dominated by CO_2 emissions from the combustion of fossil fuels. Other fossil fuel combustion-related emissions are the next most significant, the exception being ammonia, which is significant and a remnant of the production of ammonia-based fertilizer.

Total Suspended Solids (TSS) dominates waterborne emissions from soybean field runoff. The next most significant emissions are Total Kjeldahl Nitrogen (TKN) also from soybean field runoff. Phosphorus emissions are the next most significant, relating to the runoff from phosphate-based fertilizer.

5.2.2 Soy-based ink printing

The LCI data for the soy ink printing module are given in **Table 6**. The most significant inputs are black soy ink, a second color of soy ink, blanket wash, and roller wash. Blanket and roller washes are an order of magnitude lower than the two ink colors mentioned. Fountain solution is the least used compound within the system. The only emission attributable to printing was the release of VOCs. Just over 0.11 kg of VOCs were emitted per FU, in comparison to over 23.9 kg of system inputs (ignoring wipers), for a VOC yield of 0.47 percent.

Table 5: Ten largest inputs and releases for total LCI and percentages by life cycle stage

Input/ Output Type[a]	Inputs or Releases	Total for all LCI Stages (kg/FU)	Geologic & Biotic Resource Extraction (% of total)[b]	Geologic & Biotic Resource Processing (% of total)[c]	Intermediate Materials (% of total)[d]	Printing (% of total)[e]
I	Water	5.12E+03	94.43%	<0.01%	5.56%	
I	Steam, High Pressure	3.15E+02			100.00%	
I	Tree, Pine	5.39E+01	100.00%			
I	CO_2	2.38E+01	99.88%		0.12%	
I	Crude Oil	7.70E+00	96.98%		3.02%	
I	Natural Gas	1.59E+00	31.84%	22.63%	45.53%	
I	Phosphate Rock	1.01E+00	100.00%			
I	Calcium Oxide	9.46E-01			100.00%	
I	Nonyl Phenol	6.89E-01			100.00%	
I	Cattle, Beef	3.56E-01		100.00%		
RA	CO_2	2.90E+01	85.33%	0.09%	14.59%	
RA	Particulate	1.95E+01	0.03%	98.57%	1.41%	
RA	Water	1.08E+01		5.56%	94.44%	
RA	CO	3.58E+00	23.12%	26.22%	50.67%	
RA	SO_x	1.42E+00	0.55%	49.67%	49.78%	
RA	VOC, Unspeciated	1.18E+00		18.14%	72.32%	9.54%
RA	NO_x	1.02E+00	99.74%	0.01%	0.25%	
RA	Ammonia	8.05E-01	1.74%	97.11%	1.14%	
RA	NO_2	7.32E-01		49.29%	50.71%	
RA	SO_2	3.18E-01		38.70%	61.30%	
RL	POTW Wastewater, Unspeciated	3.18E+01			100.00%	
RL	Total Suspended Solids	2.05E+01	100.00%		<0.01%	
RL	Water	3.11E+00		20.16%	79.84%	
RL	Produced Water	2.70E+00	100.00%			
RL	Total Kjeldahl Nitrogen	7.37E-01	100.00%			
RL	Phosphorus	1.59E-01	100.00%			
RL	Nitrate, Unspeciated	1.44E-02	0.01%	49.99%	50.00%	
RL	Triglycerides	1.02E-02		100.00%		
RL	Methanol	6.23E-03		50.00%	50.00%	
RL	Total Dissolved Solids	3.73E-03	97.73%		2.27%	
RS	Wood, Waste	1.74E+01			100.00%	
RS	Tung Nut Shells	1.23E+00		100.00%		
RS	Non-Hazardous Solid Waste	3.71E-02	100.00%		<0.01%	
RS	Mineral Solid Waste, Unspeciated	4.65E-03			100.00%	
RS	Zinc	3.83E-03		50.00%	50.00%	
RS	Ash	3.01E-03	50.89%		49.11%	
RS	Methanol	1.10E-03		50.00%	50.00%	
RS	Solid Waste, Refinery Residual	2.73E-05		100.00%		
RS	Chloroform	2.27E-05		50.00%	50.00%	
RS	Acetaldehyde	2.02E-05		50.00%	50.00%	

[a] I = Inputs, RA = Air Releases, RL = Liquid Releases, and RS = Solid Releases
[b] Geologic & Biotic Resource Extraction corresponds to the Raw Materials Acquisition life cycle stage
[c] Geologic & Biotic Resource Processing is considered part of the Manufacturing life cycle stage
[d] Intermediate Materials Manufacturing is considered part of the Manufacturing life cycle stage
[e] Printing is considered part of the Use/Reuse/Maintenance life cycle stage

Table 6: Summary of soy-based ink printing LCI module (kg per FU)

Input/ Output Type[a]	Resource	Printing
I	Ink, Soy-based, Black	1.41E+01
I	Ink, Soy-based	9.55E+00
I	Blanket wash	1.24E-01
I	Roller wash	7.87E-02
I	Wiper, Reusable, Cotton/Poly-blend	8.39E-03
I	Fountain solution	1.84E-07
RA	VOC, Unspeciated	1.13E-01

[a] I = Inputs, RA = Air Releases

6 Life Cycle Impact Assessment Methodology

The LCIA methodology used to evaluate inventory data for the benchmark printing system follows the steps recommended by the Society of Environmental Toxicology and Chemistry (SETAC 1993a and 1993b) and the recommendations submitted by the U.S. delegation to the International Organization for Standardization (ISO 1998). The approach includes both regional scaling for areas that differ in sensitivity to certain stressors and normalization against reference values as described by Tolle (1997). As indicated previously, the equivalency models used are assessments of potential hazard and not a representation of actual impacts.

6.1 Scoping, impact criteria selection, and classification

Scoping included an evaluation of the data available from the LCI, a preliminary determination of the impact categories of concern, and whether additional data were needed for evaluating specific category indicators (stressors). As a result of the scoping exercise, a special effort was made during LCI data collection to get as much chemical-specific emission data as possible.

The classification step involved linking or assigning data from the LCI to individual impact categories within the three major impact categories of human health, ecological health, and resource depletion recommended by SETAC (1993a, 1993b, and 1997). These are similar to the Swedish 'safeguard subjects' (Steen and Ryding 1992), but do not include consideration of aesthetics or cultural impacts. Category indicators (emissions and resources used) identified in the LCI were assigned to the 13 impact categories identified during scoping. Although the potential exists for other impact categories, this set corresponds to the types of category indicators identified in the LCI, minimizes overlap among category indicators, and has science-based equivalency factors appropriate for characterization.

6.2 Characterization modeling with equivalency and regional scaling factors

The characterization phase involved a site-independent evaluation of the magnitude of the impact potential associated with individual category indicators. This involved development of equivalency factors based on the physical, chemical, or toxicological properties of each chemical to determine the potential hazard of that chemical relative to others in the same impact category. Quantitative (full) or semi-quantitative (partial) equivalency factors were used to characterize category indicators assigned to 11 of the 13 impact categories that had the potential to include more than one category indicator per impact category. The equivalency factor approach follows recommendations by SETAC (1993a and 1997), which has been described in more detail by Tolle (1997).

Regional scaling factors were incorporated into the partial equivalencies for three of the categories (Acid Deposition, Smog Creation, and Eutrophication), because previously available equivalency factors reported in Heijungs (1992) do not account for differences in regional sensitivity resulting from different environmental conditions (e.g., pH buffering capacity or increased smog formation from VOCs by presence of NO_X). Regional scaling factors for the three partial equivalencies and for the two impact categories that did not require equivalency factors (Water Use and Suspended Particulates) are reported in Tolle (1997).

6.3 Normalization by reference values

Normalization using reference values is recommended after characterization of LCIA data, because aggregated sums per impact category need to be expressed in equivalent terms (SETAC 1993a, Guinée 1995, Tolle 1997). The normalization step helps to put in perspective the relative contribution that a calculated characterization sum, which is called a category indicator by ISO (1998), makes relative to an actual environmental effect. The normalization approach used in this study, which is discussed in more detail in Tolle (1997), involves the determination of factors that represent the total, annual, geographically relevant impact for a given impact category. Impact categories were assigned to one of three spatial perspectives, global, regional, or local. The normalization value for each global, regional, or local impact category was based on the annual impact potential, respectively, for the entire world, the maximum annual state emissions (in the U.S.) after multiplying by the regional scaling factor, and the maximum annual facility emissions (in the U.S.) after multiplying by a factor of 1.5 to account for facility clusters.

7 Life Cycle Impact Assessment Results

The results of the LCIA are presented as raw impact scores (inventory quantity per FU times equivalency factor) and normalized impact scores (raw impact score divided by the geographically relevant normalization factor). The two impact categories PM_{10} Effect Potential and Water Use Effect Potential are not multiplied by an equivalency factor, since there is only one possible inventory item. For five impact categories, the inventory quantities associated with each state in the U.S. have also been multiplied by the appropriate regional scaling factor. None of these scores represent actual impacts; rather, they indicate the potential hazard of the individual and combined inventory items associated with each impact category.

Normalized impact scores for a particular impact category for two different processes or stages were not considered different unless one was two or ten times as large as the other, respectively, for impact categories calculated by full or partial equivalency factors. This margin of error was considered appropriate, due to inaccuracies and assumptions in both the LCI data and quantification methods for the impact potentials. With the exception of the primary data from the print shops, the LCI data were primarily secondary data and most were generic rather than site-specific data. Even with the best site-specific quantification methods, ecological data typically varies by more than 20 percent. Since this study relied on equivalency factors without use of site-specific risk assessments or background data, the margin of error was expected to be substantially higher. This is a judgement call based on training in environmental sciences and life cycle studies, but is not a statistically derived value. Full equivalency factors had international agreement and were almost entirely science based, while partial equivalency factors were semi-quantitative, including some approximation and assumptions.

7.1 Description of results by impact category

The total normalized impact score by impact category and raw impact score by individual inventory item were calculated for each of the impact categories potentially involving more than one inventory item. The individual scores for each natural resource were individually normalized, because no

Table 7: Summary of impact scores for total LCA and selected modules

	Total LCA		Normalized[a] Impact Scores for Selected Modules				
Impact Category	Raw Impact Score	Normalized Impact Score	Soybean Oil Solvent in Varnish	Petrochemicals to Manufacture Resin	Soybean Agriculture	Tall Oil Rosin Manufacture	Printing with Soy-Based Ink
Smog Creation Potential[c]	1.25E+00	5.32E-10	4.90E-12	2.05E-13	4.90E-12	6.49E-13	4.21E-11
Ozone Depletion Potential[b]	1.53E-05	3.22E-15	0.00E+00	0.00E+00	0.00E+00	3.22E-15	0.00E+00
Acidification (Acid Rain) Potential[c]	1.00E+01	1.86E-10	1.71E-12	1.64E-13	1.71E-12	1.54E-12	0.00E+00
Global Warming Potential[b]	2.77E+02	5.24E-12	8.83E-14	1.36E-14	8.83E-14	1.16E-15	0.00E+00
Eutrophication Potential[c]	2.45E+00	1.05E-09	7.57E-10	4.15E-16	7.57E-10	3.30E-19	0.00E+00
Carcinogenicity Potential[c]	6.53E-02	2.70E-12	9.54E-14	5.96E-15	9.54E-14	3.12E-16	0.00E+00
Human Inhalation Toxicity Potential[d]	1.42E+02	1.22E-08	5.59E-11	1.61E-11	5.59E-11	3.56E-11	3.22E-10
Terrestrial (Wildlife) Toxicity Potential[d]	2.21E+01	3.49E-07	8.76E-08	7.45E-12	8.76E-08	4.85E-09	0.00E+00
Aquatic (Fish) Toxicity Potential[d]	5.35E+00	5.46E-09	5.38E-09	1.17E-15	5.38E-09	1.74E-11	0.00E+00
Solid Waste Land Use Potential[c]	8.66E-01	1.66E-08	2.04E-12	0.00E+00	2.04E-12	9.09E-10	0.00E+00
Natural Resource Depletion Potential[b]	0.00E+00	1.83E-11	2.65E-13	2.49E-12	2.65E-13	0.00E+00	0.00E+00
PM_{10} Effect Potential[c]	2.08E-04	1.07E-13	8.35E-16	8.12E-17	8.35E-16	0.00E+00	0.00E+00
Water Use Effect Potential[c]	5.09E+03	1.93E-11	1.81E-11	7.15E-14	1.81E-11	4.39E-12	0.00E+00

[a] Normalization follows the procedure and measurement quantities described by Tolle (1997), which involves the determination of factors that represent the total, annual, geographically relevant impact for a given impact category. Impact categories were assigned to one of three spatial perspectives, global, regional, or local.

[b] Each global normalization value was based on the total, annual impact potential for the entire world.

[c] Each regional normalization value was based on the maximum, annual state impact potential (in the U.S.) after multiplying by the regional scaling factor.

[d] The local normalization value was based on the maximum annual facility impact potential (in the U.S.) after multiplying by a factor of 1.5 to account for facility clusters.

appropriate method was determined to combine normalization data for each resource into a total normalization factor for the entire impact category. A summary of the total normalized scores for all 13 impact categories is shown in **Table 7**.

The primary inventory items contributing to the total raw or normalized impact potential for each of the 11 impact categories with multiple inventory items are as follows:

- Smog Creation Potential – unspeciated VOC and unspeciated hydrocarbon air emissions
- Ozone Depletion Potential – trichlorofluoromethane air emissions
- Acid Rain Potential – Ammonia, NO_2, and SO_x air emissions
- Global Warming Potential – CO_2 air emissions
- Eutrophication Potential – ammonia air emissions, and phosphorus and total Kjeldahl nitrate water emissions
- Carcinogenicity Potential – acetaldehyde and formaldehyde air emissions
- Human Inhalation Toxicity Potential – CO, NO_x, and unspeciated VOC air emissions
- Terrestrial (Wildlife) Toxicity Potential – ammonia air emissions and phosphorus water emissions
- Aquatic (Fish) Toxicity – phosphorus water emissions
- Solid Waste Land Use Potential – land use for disposal of spent nuclear fuel and wood waste sent to landfills from Kraft pulping operations
- Natural Resource Depletion Potential – uranium ore, coal, crude oil, and natural gas based on individually-normalized resource use

All but seven of the inventory items listed above that are the main contributors to the total raw or normalized impact potential scores are substantially the result of processes in the Intermediate Material Manufacturing Stage (Table 5). The life cycle stages serving as the primary sources of these seven inventory items are as follows: Resource Extraction (CO_2 and unspeciated hydrocarbon air emissions, uranium ore input resources, and phosphorus and total Kjeldahl nitrogen water emissions); Resource Processing (ammonia air emissions); and Power Generation (land use for disposal of spent nuclear fuel). Crude oil use is about equal for the Resource Extraction and Intermediate Materials Manufacturing stages. SO_X, NO_X, acetaldehyde, and formaldehyde air emissions are each about equal for the Resource Processing and Intermediate Materials Manufacturing stages. CO air emissions are about equal for the Resource Extraction, Resource Processing, and Intermediate Materials Manufacturing stages.

Three of the five life cycle modules compared in Table 7 contribute substantially (>50%) to the total normalized impact score for one or more of the impact categories. The Soybean Agriculture module contributes 72%, 98%, and 94% of the normalized impact score, respectively, for Eutrophication Potential, Aquatic (Fish) Toxicity Potential, and Water Use Effect Potential. Soybean agriculture is the source of all of the impact potential for these three impact categories included in the Soybean Oil Solvent in Varnish module. The Nuclear Power Generation module contributes 52% of the normalized impact score for Natural Resource Depletion Potential. The TOR Manufacture module contributes 100% of the normalized impact score for Ozone Depletion Potential.

7.2 Sensitivity analysis

A sensitivity analysis was conducted to determine the impact of omitting minor processes with emissions or resources used that had high equivalency factors, to see if they make a significant contribution to the total impact potential for any impact categories. Since this was a streamlined LCA, some very minor processes were omitted either because their input mass was less than one percent of the total mass input to a downstream process or because no manufacturing data could be determined where multiple products with similar emissions were made at the same facility. Processes contributing a total mass of nearly eight percent of the generic ink were omitted. Thus, two sensitivity analyses were conducted which involved increasing the mass of an emission or resource used by eight percent to determine the resulting change in the normalized impact score for relevant impact categories. In the first case, the mass amount of methane air emissions released for the total LCI was increased by eight percent. This change only increased methane's contribution to the total impact score for Global Warming from 0.1 to 0.2 percent, resulting in virtually no change in the total Global Warming impact score before or after normalization with a reference value. In the second case, the mass quantity of crude oil used for the total LCI was increased by eight percent. This change only increased crude oil's contribution to the total impact for Natural Resource Depletion from 16.3 to 17.3 percent, resulting in an increase in the total normalized impact score from 3.01E-11 to 3.05E-11. This extremely minor change in the resulting impact score for both impact categories would be true whether it was due to inclusion of omitted processes or due to a similar increase in these emissions and resource use to compensate for under reporting by data sources for processes already included in the inventory.

7.3 Interpretation and limitations of results

This LCIA of soy-based ink printing involves evaluation of the hazard potential associated with 13 selected impact categories. The results can be used to identify processes in the life cycle with the greatest potential for minimizing impacts.

Equivalency factors for the three toxicity or carcinogenicity impact categories could not be determined for some chemicals or unspeciated chemical groups/compounds due to the lack of appropriate LD_{50}, LC_{50}, or carcinogenicity test results. This was not considered to be a major deficiency in the LCIA, since most of the chemicals or materials without equivalency factors were present in relatively small quantities in the LCI. Thus, even if the missing equivalency factors were large, the contribution to the normalized impact score would be small.

The Global Warming impact category is primarily influenced by release of CO_2. Of the four renewable crops (soybeans, pine trees, tung trees, and flax) included in this streamlined LCA, a carbon balance involving sequestration in soil was only established for soybeans, since they are the dominant crop of the four evaluated. Thus, CO_2 sequestration considerations were not calculated for the other three crops.

8 Improvement Opportunities for Impact Reduction Potential

Depending on which impact categories are considered to be of greatest concern, changes in the percentages of different components in the generic sheetfed lithographic ink formula (assuming it did not significantly affect performance) could reduce the impact score for selected impact categories, even though it may slightly increase the score in other impact categories. For example, reducing the quantity of TOR used in the formula by replacing it with soy oil could reduce the Ozone Depletion Potential, but it would be likely to increase the impact scores for Eutrophication Potential, Aquatic (Fish) Toxicity Potential, and Water Use Effect Potential, which are associated with Soybean Agriculture (see Section 7.1). In the typical formula for soy-based ink used in this study, TOR is 33.1% of the varnish and 20.7% of the total ink by weight. Another alternative is to make ink with TOR supplied by manufacturing facilities with reduced emissions.

Since the Soybean Agriculture life cycle module makes a substantial contribution to the impact potential for three impact categories (Eutrophication Potential, Aquatic (Fish) Toxicity Potential, and Water Use Effect Potential) evaluated for the generic soy-based ink formula, using no-till farming (the soil is left undisturbed from harvest to planting) for growing the soybeans could substantially reduce the potential impacts for these categories. Soybean Agriculture is responsible for essentially all of the normalized impact score for 12 of the impact categories with scores greater than zero in the column Soybean Oil Solvent in Varnish (see Table 7). Switching from conventional or low till to no-till farming would reduce the number of trips across the field and thus reduce the emissions from farming equipment. Although this would require an increase in the use of herbicide in place of tilling to control weeds, there are herbicides available with extremely low environmental impact potential. A comparative LCA has not been published comparing conventional tillage with no-till farming. However, most long-term field studies have shown slightly higher no-till yields on well-drained to moderately well-drained soils or on sloping land, particularly with crop rotations, compared with conventional tillage (USDA 1995). Experienced no-till farmers claim greater yields due to increased water infiltration and improved soil properties in 4-7 years from when the system becomes established.

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