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Life-Cycle Assessment of Mineral and Rapeseed Oil in Mobile Hydraulic Systems

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Keywords

biobased products
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Summary

The use of rapeseed oil in mobile hydraulic systems has become more widespread over recent years. This is because of concern about the environment in which the systems work and the perceived benefit of using such fluids. This article examines the major segments of the life cycle of mineral and rapeseed oil as used in mobile hydraulic systems, with case studies of a forestry harvester and a road sweeper. It shows that the systems running on rapeseed oil are not necessarily better for the environment. Many of the environmental issues examined in the study were affected more negatively by the use of rapeseed oil than mineral oil. The main exception to this was greenhouse gas emissions, which are consistently higher for systems using mineral oil because of the use of fossil resources.

This study examines the production of the machinery, the oils, and their use throughout the machines' lives. The poor environmental performance of the rapeseed oil is due mainly to its poor performance in the field. This is because it does not respond as well to high pressure and temperature as mineral oil, causing it to need more frequent replacement during use. This, in turn, influences the definition of the functional unit used in the life-cycle assessment that was conducted. Also, the rapeseed oil has more corrosive qualities than the mineral oil, and more hydraulic components need replacing during the life of a machine running on rapeseed oil than one running on mineral oil.

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Introduction

In recent years, especially in the developed world, there has been a heightened awareness of environmental issues. With this in mind, many companies and organizations have adopted the use of biodegradable fluids with the aim of becoming more "environmentally friendly" and more sustainable; however, analysis is required to determine if this change is better for the environment over the entire life cycle of the fluids.

Mobile hydraulic systems are often used in sensitive areas such as forests and around lakes and rivers. Fluid power systems, although theoretically closed systems, often leak. Most of the time these leaks are small and occur over a number of years. On some occasions the spills are larger, resulting in several liters of oil being spilled. Mineral oil is thought to have a negative effect on the environment if spilled, and for this reason many companies have decided to use biodegradable oils in their systems.

This article describes research undertaken at the University of Bath. A full description of the research project has been reported by McManus (2001) in her Ph.D. thesis. This article briefly describes the environmental assessment method used (life-cycle assessment), the case studies and the results with particular reference to oil use, and the implications for the definition of the functional unit. Because of controversies over the environmental preferability of the two types of oils, and data difficulties associated with assessing the functionality of the two oils, the use of the oils has been examined in more detail and a sensitivity analysis has been included.

The research described here was part of a larger research program in the design of fluid power systems within the Engineering Design Centre at Bath, for which a steering group of senior industrialists with specialist knowledge in fluid power was set up. Part of their role was to review the research every 4 months. The assumptions in the research presented here were discussed with the steering committee.

Life-Cycle Assessment

It is now widely recognized that in order to evaluate the environmental consequences of a product or activity, the impact resulting from each stage of its life cycle must be considered. This has led to the development of a range of analytical techniques known as "life-cycle assessment" (LCA). LCA is an environmental management tool that examines the environmental burden of a product or process over its entire life, from production through use and on to disposal or recycling. The energy and materials used, and pollutants or wastes released into the environment as a consequence of a product or activity, are quantified over the whole life cycle from "cradle to grave" (Graedel and Allenby 1995).

The use of LCA helps avoid the transfer or neglect of environmental burdens that can arise when only one life-cycle stage is examined. LCA requires all the energy inputs; raw materials inputs; emissions to air, soil, and water; and waste to be examined at every stage of the life of the product or system. It is a simple, elegant idea, but it can become convoluted in practice.

The choice of a functional unit is an important aspect of any LCA study. In the present case, the overall functional unit is the use of the machinery over its lifetime.[1] The functional unit, however, was subdivided in some portions of the study to the production of 1 kg of oil[2] or to the production of the machines. This allowed more meaningful comparison during some life-cycle stages. The disposal of the machines and the oils was not considered in this study. This shortcoming of the research arose from the lack of data for this stage of the life cycle.

Mobile Hydraulic Machines: Cases and Data Sources

Two cases are examined: a forestry harvester, used to cut down trees, and a road sweeper. These were chosen because they are both mobile systems and they work in sensitive, but different, environments. The production and maintenance of the whole machines were considered in the study, together with the production and use of the oils and diesel fuel (hereafter referred to as "diesel") used in the machines. Data for the production of the machinery were obtained from the manufacturers. The data were based on production literature and from discussions with the producers and importers of the machinery. Where there were uncertainties in the data, best estimates were made using the experience of the mechanical engineering staff at the University of Bath. Data for the use of the forestry machinery were obtained from the U.K. Forestry Commission. Information about the use of the road sweepers was obtained from the Bath and North East Somerset Council (BANES). Although the study focuses primarily on the comparison of the two hydraulic fluids,[3] it was deemed important to consider machine use, including the use of diesel. Data for the production of the diesel and the emissions associated with its use in such machines were obtained from the IDEMAT database (produced by the Technical University, Delft, Netherlands; ⟨www.io.tudelft.nl/research/dfs/⟩) contained within the SimaPro LCA software ⟨www.pre.nl⟩.

The Purpose and Characteristics of a Hydraulic Fluid

The primary role of a hydraulic fluid in a fluid power system is to transfer energy (Burrows et al. 1999), but there are additional requirements placed upon a fluid in modern high-pressure and high-temperature hydraulic machines. It is important that the fluids have high lubricity and not be corrosive. These requirements resulted in the initial move from traditional water hydraulics toward mineral oil in the twentieth century. Mineral oils are highly flammable and have minimal biodegradation properties. A range of fire-resistant fluids has been developed, but these are often quite harmful to the environment. With the current increase in concern for the environment, the hazardous and recalcitrant nature of mineral oil has led to a surge of interest in "biodegradable" hydraulic fluids. Mineral oils are inherently biodegradable but only over a long period of time, and they do not meet important aspects of environmental acceptability, for example, the absence of aquatic toxicity (Marougy and Helduser 1992). Biodegradable fluids are designed to biodegrade rapidly and have been formulated to meet stringent criteria: They should not pollute groundwater, soil, or surface water when accidentally leaked from hydraulic machines. The use of biodegradable fluids is becoming more common, especially in mobile machines, such as tractors, forestry machinery, and reed-cutting machines.

Hydraulic systems operate with relatively large volumes of oil (on the order of 100 liters [L][4] and upward) under high pressure, and so, if there is a spillage, oil may escape and pollute the environment. For this reason, many forestry machine users, particularly in Scandinavian and Germanic countries, are now using the more readily biodegradable oil.

Hydraulic Oil Production

Production of the mineral and rapeseed (canola) oils was examined in detail. Figures 1 and 2 show the stages considered in each of the production processes. This section describes the LCA of the production of the two oils in a cradle-to-gate example. The data for this stage of the LCA were collected from several sources. Data for the production of the mineral oil are not available in as detailed form as the data for the rapeseed oil. As a result, the description of the rapeseed oil that follows is longer than that for the mineral oil. This does not mean, however, that the data provided for the mineral oil are any less accurate than those provided for the rapeseed oil.

Mineral Oil Production Data

Information about mineral oil production processes was obtained through personal communications with representatives of oil companies and through the industrial liaison group at the University of Bath. Published data (Bousted 1993a, 1993b) were also used. Although these data are somewhat old, after a review of the data and results by experts and other stakeholders, it was concluded that the data are representative of current conditions.

The main stages in the production of mineral oil are shown in figure 1. The environmental impacts associated with oil exploration, development, and extraction have not been taken into account because of a lack of data. The energy used in transporting crude oil is included. Refining is used to distill the crude oil into a series of fractions with a molecular mass less than that of the original oil, to remove impurities, and to re-

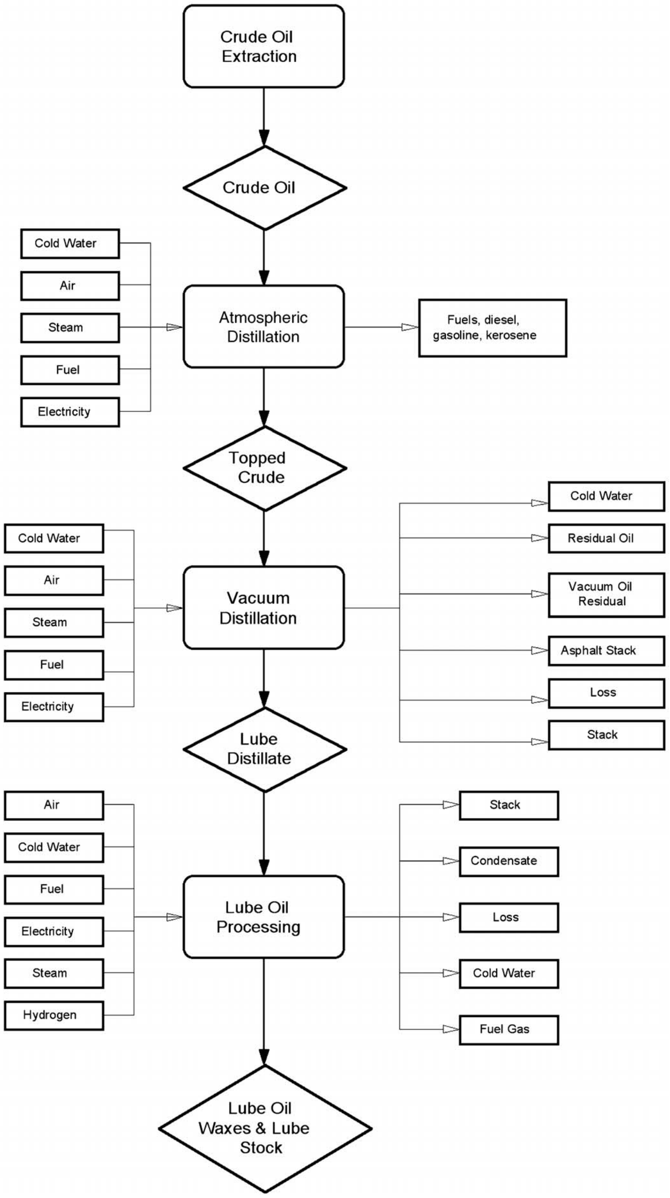

Figure 1 Stages in the production of mineral oil.

cover trace metals that were present in the oil. In general, crude oil yields four basic groups of products: gas and gasoline, middle distillates (gas oil), fuel oil, and residue cuts. The middle distillates are used to produce kerosene, light gas oil, heating oil, diesel oils, waxes, and light lubricating oils. Light lubricating oils are used as hydraulic fluids. Data for the light lubrication fluids were published by Bousted (1993a). These data were used in this study and were also slightly updated after steering group discussion. Table 1 shows the inputs and outputs for 1 kg of refined mineral oil.

Rapeseed Oil Production Data

The data for rapeseed oil production were obtained from Ceuterick and Spirinckx (1997). These were augmented, updated, and compared with some data obtained from Cargill (Allen 1997, 1998) for the crushing stage. The main stages in the production of rapeseed oil are shown in Figure 2. The production of rapeseed oil re-

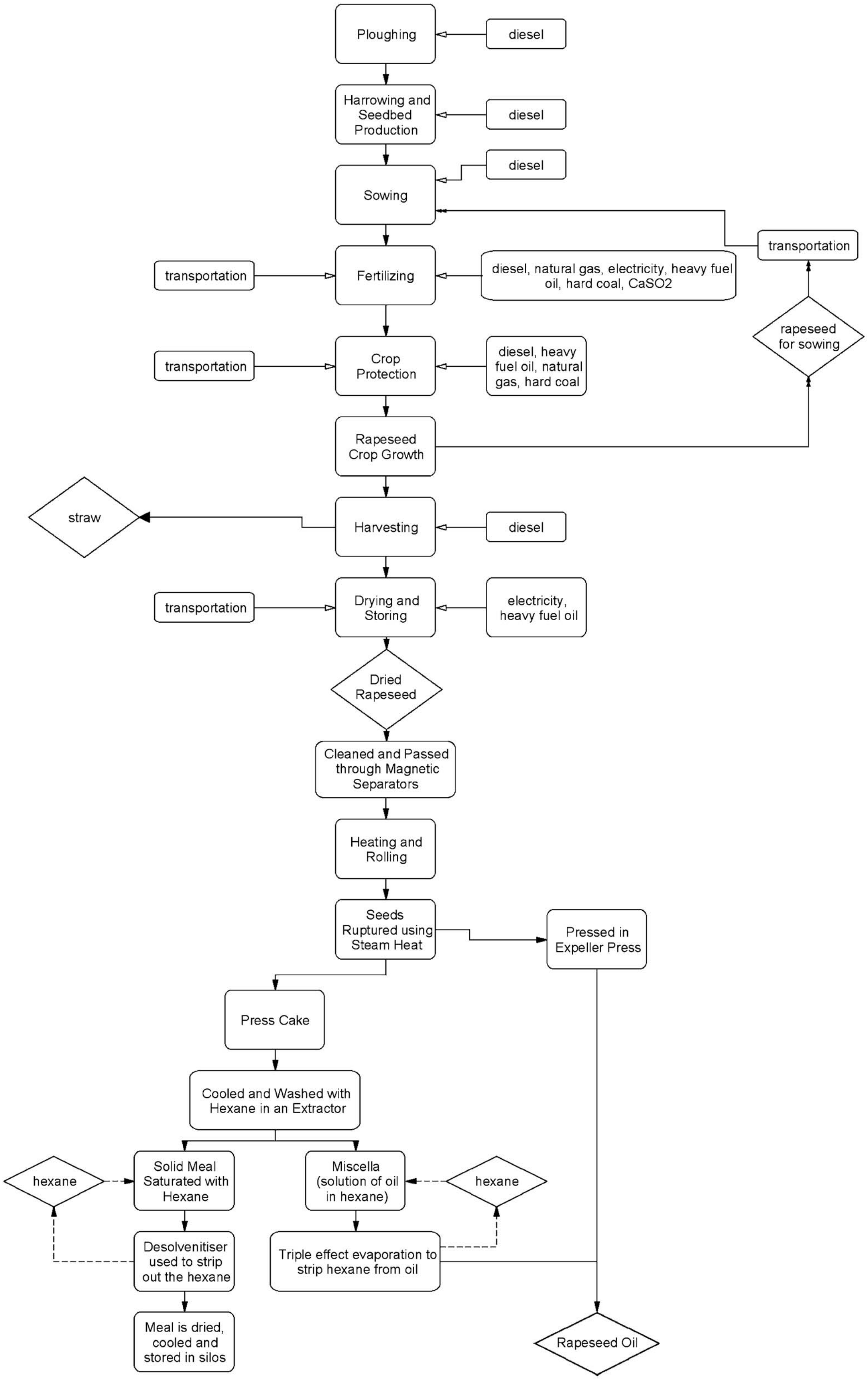

Figure 2 Stages in the production of rapeseed oil.

quires seedbed preparation, sowing, fertilizing, crop protection (pesticide use), rapeseed growth, harvesting, drying and storing, and crushing and refining. For a field of 10,000 square meters[5] approximately 34 kg of diesel is used in the plowing, fertilizing, harrowing, and seedbed preparation stages. Data for the diesel production and use were taken from the IDEMAT database contained within the SimaPro software. Four kilograms of seed are applied per hectare. We assumed that the seed is used from the field product, and therefore the weight of this is deducted from the final produce. This may not, however, always be the case, as farmers often want to change the variety of crop they grow. The use of fertilizers has various environmental effects; the impacts are localized, and they are not considered in the LCA. The amount of fertilizers used is based on recommendations of agricultural associations and is shown in table 2.

Pesticides are also required for the growth of rapeseed. They are utilized in the form of herbicides, fungicides, and insecticides. Data on the amount of pesticides used on the crops were obtained from the Pesticide Usage Survey Report (Thomas et al. 1996), which was produced by the U.K. Ministry of Agriculture, Fisheries, and Food (now the Department for Environment, Food, and Rural Affairs) and the Scottish Office of Agriculture (Environment and Fisheries Department). European data used by VITO, the Flemish Institute for Technological Research (Ceuterick and Spirinckx 1997), vary greatly from those obtained for the United Kingdom. The U.K. data were used in this study; relative to the U.K. data, the European data suggest that far more pesticides are used on crops. A comparison is shown in table 3.

Soil is always undergoing gas exchange of some sort, and this is difficult to assess for the purposes of an LCA because the exchange depends on the soil moisture, soil type, and vegetation. Discussions with P. S. Wightman (1999), and other soil science academics, along with referenced material (Jarvis and Pain 1999; Bouwman 1990), provided the basis for an estimate of the emissions caused by the rapeseed. This estimate was based on soil conditions needed by the crop and its growing patterns. Estimated total emissions from the soil and those associated with the rapeseed are shown in table 4.

Table 1 Inputs and outputs associated with the production of 1 kg of refined mineral oil

Category	*Inputs/outputs*	*Amount*
Fuels (input)	Coal	0.15 MJ
	Oil	1.41 MJ
	Gas	3.34 MJ
	Hydroelectric	<0.01 MJ
	Nuclear	0.01 MJ
	Other	0.00 MJ
	Total fuels	4.92 MJ
Feedstock (input)	Oil	45.00 MJ
Raw materials (input)	Iron ore	140 mg
	Limestone	140 mg
	Water	210,000 mg
	Bauxite	320 mg
	Sodium chloride	140 mg
	Clay	30 mg
	Ferromanganese	<1 mg
Air emissions (output)	Dust	340 mg
	Carbon monoxide	80 mg
	Carbon dioxide	284,000 mg
	Sulphur oxides	1,800 mg
	Nitrogen oxides	2,900 mg
	Hydrogen chloride	5 mg
	Hydrocarbons	2,900 mg
	Metals	1 mg
Water emissions (output)	COD	10 mg
	BOD	5 mg
	Acid as H+	30 mg
	Nitrates	1 mg
	Metals	5 mg
	Ammonium ions	1 mg
	Chloride ions	10 mg
	Suspended solids	60 mg
	Hydrocarbons	20 mg
	Other nitrogen	1 mg
Solid waste (output)	Industrial waste	310 mg
	Mineral waste	2,200 mg
	Slags and ash	2,500 mg
	Nontoxic chemicals	170 mg

Note: COD = chemical oxygen demand; BOD = biological oxygen demand.

One hectare of land yields a total of 3,500 kg of rapeseed and 7,000 kg of straw. The percentage water content varies in seed and straw. The dry weights produced are 2,975 kg rapeseed and

Table 2 Fertilizers used for growing 1 hectare of rapeseed oil

Fertilizer	*Amount (kg)*	*Comment*
Potash fertilizers	130	These are produced from potash ores and occur as sylvanite, carnalite, rock salt and kainite. Sylvanite can be used directly as a fertilizer.
Magnesium fertilizers	80	These are mainly produced from keiserite, which is a constituent of raw potash salt.
Nitrate fertilizers	187	This is produced from ammonia, which is processed by steam reforming of natural gas. Approximately 0.46 kg is needed to produce 1 kg of NH_3.
Phosphorous fertilizers	70	Phosphate rock is the raw material used in the production of this fertilizer. Approximately 14.7 kg of the rock is needed to produce 1 kg of the fertilizer.
Lime	500	Lime production relies on the mining, crushing, and calcining of limestone in furnaces. For 1 kg of CaO, 1.89 kg of lime has to be mined. Dust emissions are serious, but local, and thus difficult to incorporate into LCAs.

Source: Adapted from Ceuterick and Spirinckx (1997).

3,500 kg straw. Allocation of the impacts from the previously described stages is made according to the dry weight because this is the weight of useful product.

Prepress solvent extraction is the most common and economical process of oil extraction (Salunkhe 1992). When rapeseed arrives at a mill, metallic residue is removed by passing the seeds over a magnet. The seeds are dehulled through a rolling process, and the seeds are commuted (ground) and thermally pretreated. Conditioning deactivates the enzyme myrosinase and improves the quality of the oil. Then the seeds are flaked and pressed, which separates 60% to 70% of the oil from the meal. These processes are shown in figure 2. To extract more oil, the meal then undergoes solvent extraction using hexane. With the introduction of the U.K. Environmental Protection Act (in 1990), there is a legal requirement to keep the hexane use below 2 kg/ton of seed processed.[6] On average, about 0.2% to 0.3% of this hexane is lost; the rest is recycled (shown by the dashed lines in figure 2). In this study the maximum hexane usage is considered, with a loss rate of 0.2%. The production of the hexane was assumed to be comparable to naphtha production, as the production processes are very similar. After the solvent extraction with hexane, the seeds can be desolventized by toasters heated with steam. After drying and cooking, this meal can be used as an animal feed component. The crushing process produces 1,188.4 kg of oil and 1,782.6 kg of meal (40% and 60% of total mass, respectively). Using mass-based allocation, 40% of the environmental burdens associated with rapeseed production and processing are allocated to the rapeseed oil. The oil is then refined to remove impurities such as water, dirt, phosphatide gums, and free fatty acids.

Comparison of Impacts of Production of Oils

Data were entered in the SimaPro software (McManus et al. 1999; McManus 2001), which was used to characterize the impacts associated with 1 kg of each of the oils. EcoIndicator 95 was used for impact assessment in this study, and the results are shown in table 5.

The SimaPro LCA impact results show that the production of mineral oil has a larger environmental impact than rapeseed oil in the categories of greenhouse gases, acidification, heavy metals, and winter smog. The drilling and extraction stages have a large impact on the greenhouse gases and acidification categories. When mineral oil is extracted, natural gas is sometimes

Table 3 Pesticide used on a 1 hectare rapeseed crop

	Source	
	Ceuterick and Spirinckx (1997)	*Pesticide usage survey report 141 (Thomas et al. 1996)*
Herbicide	2.20 kg	0.87 kg
Insecticide	0.7 kg	0.04 kg
Fungicide	1.85 kg	1.2 kg
Growth regulators		0.06 kg
Molluscicides		0.07 kg
Mixed seed treatments		0.09 kg

Table 4 Soil emissions per hectare per year

	Total soil emissions	*Estimated rapeseed emissions*
Emissions to air		
N_2O	3,140 g	1,000 g
Methane	2,190 g	1,000 g
Ammonia	10 kg	5 kg
Emissions to water		
Nitrate	50 kg	25 kg
P_{tot}	0.35 kg	0.17 kg
K	20 kg	10 kg

Note: P_{tot} = total phosphorus; K = potassium.

flared, releasing methane (CH_4) and carbon dioxide (CO_2), and this results in large impacts in the greenhouse gases category. The impact on greenhouse gases is far larger for mineral oil than for rapeseed oil. Rapeseed oil has a larger impact on ozone-depleting gases, eutrophication, carcinogens, summer smog, pesticides, and energy. The crushing stage in rapeseed oil production requires considerable energy. This is reflected not only in the levels of energy consumption but also in high impacts in the categories of acidification and global warming. The use of fertilizers has a large impact on eutrophication and also on the energy use category. One way to see the significance of these impact data more clearly is to normalize them by total European emission on a per capita basis, as shown in table 6. The normalization method used in this research is the "people emission equivalent" approach determined as follows:

$$\text{European Emissions per Capita} = \frac{\text{Total European Output in Each Emission Category}}{\text{Population of Europe}}$$

$$\therefore \text{People Emission Equivalents} = \frac{\text{Emissions from the Process Studied}}{\text{European Emissions per Capita}}$$

This method is used within the SimaPro LCA software. The results indicate that the impact on greenhouse gases from the production of mineral oil far outweighs any of the other impacts in either of the production stages.

The data in table 6 indicate that the environmental impacts of the production of the two oils are very different, and it is not possible to say that one is better than the other overall. The much larger contribution to greenhouse gases made by mineral oil, however, may lead to the view that mineral oil has the larger overall environmental effect. This inconclusiveness is typical of LCA when a valuation stage is not carried out. A valuation stage could produce a single environmental impact score that could be used to claim that one type of oil is better than another. The result of this type of comparison, however, is highly dependent on the choice of impact category weightings. The valuation process is, therefore, very subjective and is not carried out in this study.

Analysis of Use-Phase Impacts

The Performance of Rapeseed and Mineral Oil within Hydraulic Systems

Mineral and rapeseed oils do not have the same performance characteristics when used within hydraulic systems. This is a controversial issue, with some manufacturers claiming that rapeseed oil does not need to be replaced any more frequently than mineral oil and some users claiming that the fluid needs to be replaced 3 times as often as mineral oil. As the use of rapeseed oil is still relatively new and uncommon, it is difficult to obtain accurate performance data.

Marougy and Helduser (1992) from the company Vickers Hydraulics carried out wear tests on environmentally acceptable fluids. Two antiwear tests were carried out based on standardized vane pump tests. These tests showed excellent anti-

Table 5 Characterized data for mineral and rapeseed oil production

Category	*Units*	*Rapeseed oil*	*Mineral oil*
Greenhouse gases	Kilograms CO_2 equivalent	0.3	3.56
Ozone-depleting gases	Kilograms CFC-11 equivalent	4.25×10^{-10}	8.90×10^{-12}
Acidification	Kilograms SO_4^2 equivalent	0.00327	0.00383
Eutrophication	Kilograms PO_4^3 equivalent	0.00102	0.000378
Heavy metals	Kilograms Pb equivalent	3.75×10^{-07}	5.02×10^{-07}
Carcinogens	Kilograms B(a)P equivalent	6.52×10^{-11}	1.62×10^{-12}
Winter smog	Kilograms SPM equivalent	0.000976	0.0018
Summer smog	Kilograms C_2H_4 equivalent	0.000479	1.61×10^{-08}
Pesticides	Kilograms Act. S equivalent	1.43×10^{-05}	0
Energy	Megajoules LHV equivalent	6.18	5.94
Solid waste	Kilograms	0.00773	0.00519

Note: CFC-11 = tricholoromethane; B(a)P = benzo(a)pyrene; SPM = suspended particulate matter; Act. S = active substance; LHV = lower heating value.

wear properties for the rapeseed oil; the results showed that rapeseed oil could perform as well as mineral oil. These tests were carried out with new (previously unused) rapeseed oil, and there was no testing done on the oil performance when the fluid starts to age or becomes contaminated. The total lifetime of the fluid was not addressed in their study. Marougy and Helduser (1992) stated, however, that if the vegetable oil were contaminated with a few percent of a highly dispersible lubricant, then the hydraulic system would fail as a result of a loss of lubricity. Field trials were carried out by Vickers Hydraulics, which tested a PVE35 piston pump with rapeseed oil. After 3,500 hr of service, there was no obvious wear of the pump.

Cheng and colleagues (1992) also carried out tests on a vegetable oil. Their tests showed excellent properties for the oil in most cases, apart from the durability tests. The results indicated that if vegetable oil were to be used in a system where the fluids were expected to work over a long period of time, there might be problems with the wear pattern of the hydraulic fluids. These tests were performed at a temperature of 70°C. Many applications run at a higher temperature than this. Eichenberg (1994) concluded that rapeseed oil is an acceptable hydraulic fluid, but that the high-temperature stability is critical. According to Eichenberg, high-temperature operation causes oxidation, oil deterioration, and an increase in viscosity. Low temperatures cause thickening of the oil, which reduces its capability to flow in the machine.

Few studies have directly compared the use of mineral and rapeseed oils (or any biodegradable fluids) in hydraulic systems. Some have compared the use of biodegradable fluids with each other, but few have included the use of mineral oils (with the exception of Hudson [1999]). For this reason, it is very difficult to determine the comparability of the fluids. A large amount of information has been gathered informally through conferences and meetings, however. Many analysts, for example, Lämsä (1999) and Wightman and colleagues (1999), have stated that rapeseed oil performs as well as mineral oil in hydraulic systems. Although we requested documented evidence for this, none was received. Some users (for example, in the Forestry Commission, National Trust for Scotland, and BANES) have stated that they need to replace rapeseed oil and some of the hydraulic components more frequently than they would if they were using mineral oil—anywhere from 1.5 to 3 times more frequently. This is because rapeseed oil is more corrosive on the hydraulic systems than mineral oil.

Sauer Sundstrand, a leading hydraulics component manufacturer, performed a comparison of the use of mineral oil, rapeseed oil, and synthetic esters in hydraulic pumps as part of a product development program (Hudson 1999). The performance of the mineral oil varied little across

Table 6 Normalized data for the production of 1 kg of mineral oil and 1 kg of rapeseed oil

	Total (people emission equivalents)	
Category	*Mineral oil*	*Rapeseed oil*
Greenhouse gases	2.73×10^{-4}	2.30×10^{-5}
Ozone-depleting gases	9.61×10^{-12}	4.59×10^{-10}
Acidification	3.41×10^{-5}	2.91×10^{-5}
Eutrophication	9.89×10^{-6}	2.68×10^{-5}
Heavy metals	9.23×10^{-6}	6.90×10^{-6}
Carcinogens	1.49×10^{-10}	5.99×10^{-9}
Winter smog	1.91×10^{-5}	1.03×10^{-5}
Summer smog	8.96×10^{-10}	2.67×10^{-5}
Pesticides	0	1.48×10^{-5}
Energy	3.73×10^{-5}	3.89×10^{-5}
Solid waste	0	0

the tests and was satisfactory in all tests. Two off-the-shelf rapeseed oils were tested. One was successful when tested at 50°C, one failed. Neither type of rapeseed oil met performance requirements when tested at temperatures above 50°C. Thus, laboratory testing showed that rapeseed oil did not perform as well as mineral oil at high temperatures and pressures (Hudson 1999). Rapeseed oil was shown also to degrade faster than mineral oil. Some manufacturers stated that the oil performed as well as mineral oil but did not substantiate their claims with data. Informal meetings with hydraulic system users elicited the information that systems operated on rapeseed oil can use very different amounts of oil than those run on mineral oil.

The differences in opinion concerning the performance of rapeseed oil arise for several reasons. These fluids are not always consistent in performance because of the additives and the quality of the base oil. Additives are used in base oil to enhance its hydraulic qualities. The precise mix of additives can vary from one batch of oil to another, but the testing by Hudson (1999) tried to ensure that the additive packages included in the various batches of rapeseed oil were as similar as possible. Base oil quality can vary from one crop to another and from one year to the next, depending on weather, storage, and treatment conditions. Also, the performance of the rapeseed oil depends on the way in which it is used within a system. Although manufacturers of fluids and equipment set out maintenance schedules, it is probable that in many situations these are not strictly adhered to. If a system running on mineral oil is not maintained according to specification, in many cases this does not lead to operational problems. It is likely, however, that a system running on rapeseed oil may only be able to perform to the same specifications as mineral oil (causing no operational problems) when maintained properly and used at low temperatures and pressures.

In this study, we assumed that rapeseed oil must be replaced twice as often as mineral oil when used in a hydraulic system. We also assumed that the components in a hydraulic system are replaced once for a system running on mineral oil and twice for a system running on rapeseed oil. This is an oversimplification, as some components in the system are replaced more frequently than this and some not at all; however, this is thought to be an adequate representation of a practical maintenance schedule.

Local Impacts

Local impacts associated with the running of the machinery can be severe and depend on local conditions. Such impacts are not reflected in the LCA process both because of the difficulties of aggregation over space and time and also because some of the acute impacts of a hot oil spill do not fall into any of the standard environmental impact categories used in LCA assessments.

Note that a spill of either type of oil results in ecological and environmental damage. Oil is often released at high temperature and pressure; therefore, plants and animals may be burned or scorched with a significant spill of oil of any type. The use of rapeseed oil within a system is not a license to minimize maintenance procedures and worry less about spillage into the environment. Spillage of rapeseed oil may result in a faster recovery, but it still causes environmental damage.

Case Studies of Oil Use

For the case studies of both the forestry harvester and road sweeper, the impact of the production and maintenance of the machines was considered together with the use of the hydraulic fluids and the diesel used over the lifetime of the machines. The specific purpose of the LCA study was to compare the use of the different hydraulic oils within these systems. The production of the whole machines has been included for completeness. Figure 3 shows the normalized results of the comparison of the two oils used in the harvester over its lifetime. It shows the impacts of the production of the machinery and the oils. The impact on greenhouse gases of the system run on mineral oil far outweighs any of the other impacts considered. For every other category, however, the impact of the system using rapeseed oil is greater than the impact of the system run on mineral oil.

The lifetime of the sweepers is shorter than that of the forestry machinery. Therefore, the impact of different oils takes on less of a significant role compared with the production of the sweeper. Figure 4 shows the normalized results for the comparison between the use of mineral and rapeseed oils in the sweeper. The impact of greenhouse gases from the use of the mineral-oil-run system is far less pronounced than when used in the forestry harvester; however, the sweeper shows the same trend as does the harvester. Impact in the greenhouse gas category is larger for the system running on mineral oil. For every other category, the system running on rapeseed oil has a greater impact.

Sensitivity Analysis of Oil Use

Machine manufacture has a varying significance in the overall life-cycle impact of the systems; for example, as noted earlier, the sweeper machine manufacture has a larger impact on the life cycle of the sweeper than the production of the forestry harvester has on its life cycle.

Given conflicting opinions about oil performance, we have studied the effect on the overall result if the performance of the mineral oil were taken to be equal to, 1.5 times better than, and 2 or 3 times better than the rapeseed oil. Included in this sensitivity analysis is an equal replacement rate for the parts that are commonly affected by problems with oil.

Figure 5 shows the use and manufacture of the harvester with different oil performance scenar-

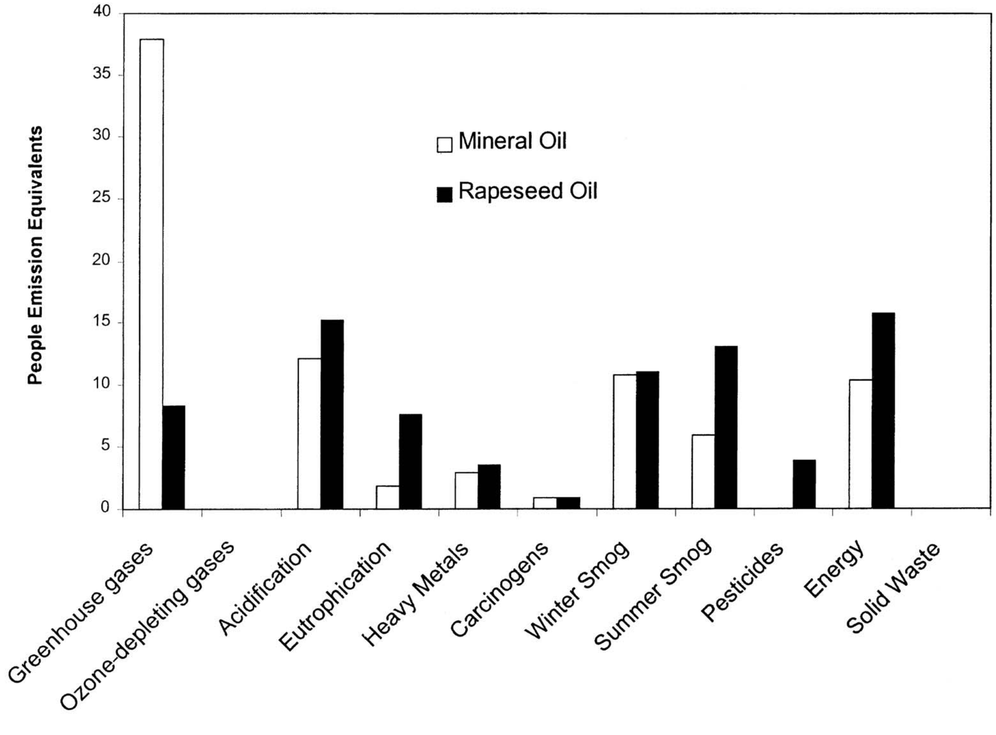

Figure 3 Comparison of normalized data for the use of the harvester.

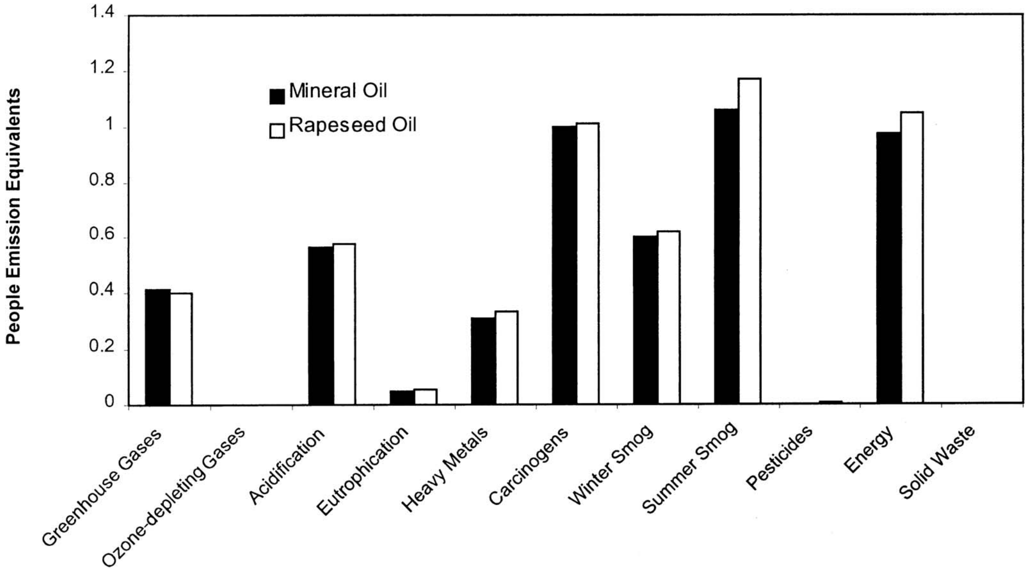

Figure 4 Comparison of normalized data for the use of the sweeper.

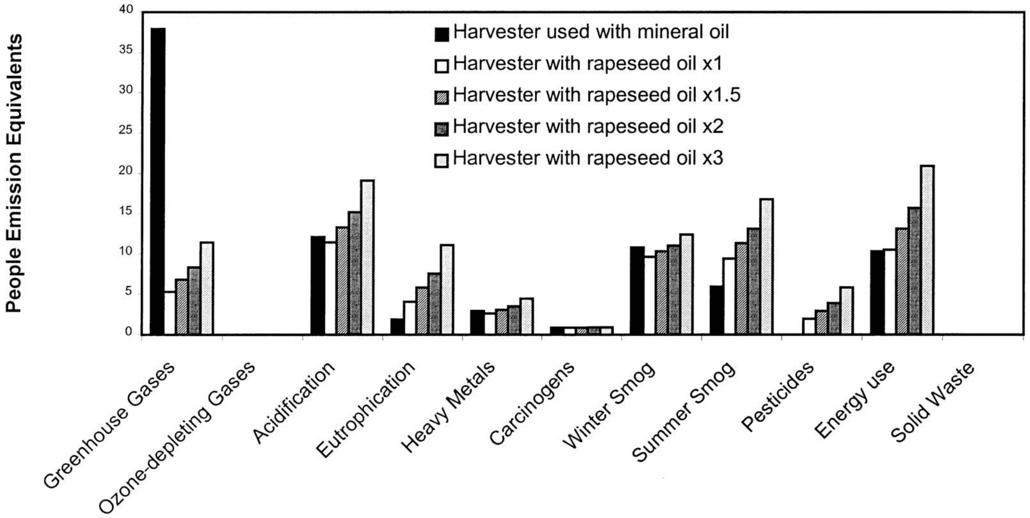

Figure 5 Normalized sensitivities for the oil performance scenarios for the harvester.

ios. For each of the different rapeseed oil performance scenarios, the impact of the mineral oil on greenhouse gases remains by far the most significant. When the rapeseed is changed as frequently as the mineral oil, the impacts on ozone-depleting gases, eutrophication, summer smog, pesticides, and energy use are larger for the system running on rapeseed oil. The impacts on greenhouse gases, acidification, heavy metals, and winter smog are greater for the system running on mineral oil. The impacts in the carcinogen and ozone-depleting gas categories are very similar for both oils.

When the rapeseed oil is replaced 1.5 times as often as the mineral oil, once again the impact on greenhouse gases is dominated by the mineral oil. Impacts on ozone-depleting gases, acidification, eutrophication, heavy metals, carcinogens, summer smog, pesticides, and energy use are greater for the system running on rapeseed oil. The impact on greenhouse gases and winter smog is greater for the system running on mineral oil.

When the scenario used in the case study is adopted, and the mineral oil is deemed to perform twice as well as the rapeseed oil, the impact on ozone-depleting gases, acidification, eutrophication, heavy metals, carcinogens, winter smog, summer smog, pesticides, and energy use is greater for the system running on rapeseed oil. Only the impact on greenhouse gases is larger for the system running on mineral oil. Again, with the mineral oil assumed to perform 3 times as well as rapeseed oil, only the environmental impact on greenhouse gases is larger for the system running on mineral oil.

Figure 6 shows the sensitivity of the sweeper's life-cycle environmental impact to the different oil performance scenarios. Mineral oil's contribution to greenhouse gases is not nearly as profound for the road sweeper as is it was for the harvester. Because of the sweeper's shorter life, the manufacture of the machine makes a far greater relative contribution to the total life-cycle impacts of the machine. When the two oils are replaced at the same rate, the environmental impacts are very similar for most of the issues considered. The rapeseed system has a greater impact on eutrophication, summer smog, and pesticides. The impact on greenhouse gases, ozone depletion, heavy metals, and carcinogens is the same for both fluids. Mineral oil has a greater impact on acidification, winter smog, and energy use. All the results for both oils are very similar in this scenario, however. This is because of the machine production and the fact that the sweeper uses a lot less oil during its lifetime than the forestry harvester does.

When rapeseed oil is replaced 1.5 times more often than mineral oil, there is a more noticeable difference: The impact of the machine using rapeseed oil is somewhat greater for eutrophication, carcinogens, summer smog, and pesticides. The impacts on ozone depletion, carcinogens, and energy use are the same, and the mineral oil has a greater impact only in the greenhouse gases category. When the rapeseed oil is changed twice as often as mineral oil, the environmental impact for the system running on rapeseed oil is greater for all the environmental categories. This is repeated when the system needs 3 times more rapeseed oil than mineral oil.

For all the systems studied, when the performance of mineral oil is taken to be 3 times better than that of rapeseed oil, the systems running on rapeseed oil are shown to have a greater impact than mineral oil in every environmental category, except greenhouse gases. When twice as much rapeseed oil is used as mineral oil, most of the impact categories in each system (and all categories in the sweeper's case) have a larger impact from the rapeseed-run system.

When the oil performance is taken to be the

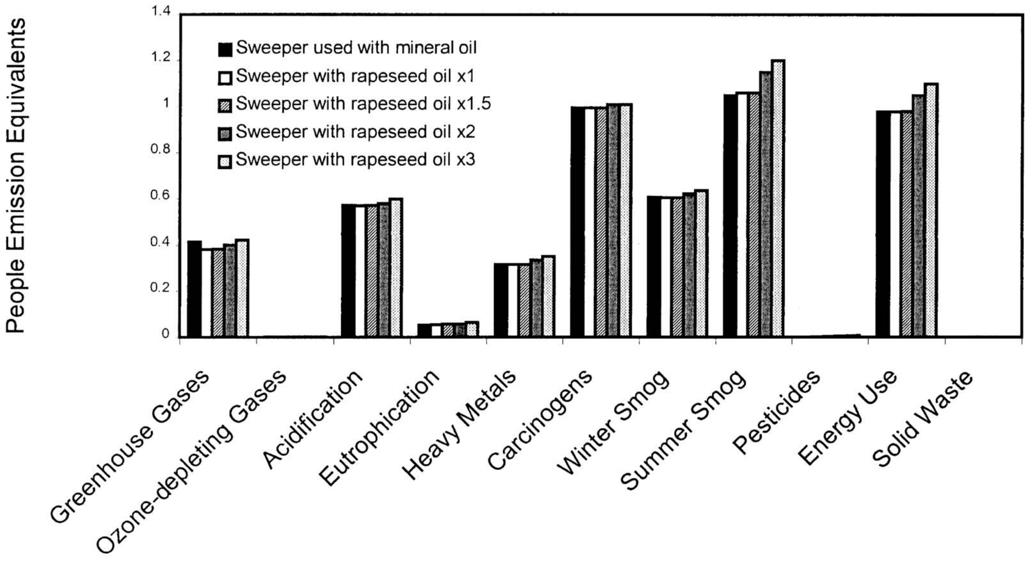

Figure 6 Normalized sensitivity for the oil use scenarios in the sweeper.

same in the sweeper case, the results are very similar and there would be no relative benefit in using one oil rather than the other. When the oil performance is assumed equal in the harvester case, then the environmental impact is lower when using rapeseed oil. This suggests that the results from this study cannot automatically be carried over to other mobile hydraulic systems. It also shows that the results are sensitive to the assumptions made about oil performance.

Concluding Remarks

Despite an expectation that systems operated on biorenewable rapeseed oil should be better for the environment, this is not necessarily the case. A surprising result is that the environmental impact of the systems running on rapeseed fluid is often greater than that of those running on mineral oil. This is because of the performance characteristics of the rapeseed oil. Rapeseed fluids do not last as long when subjected to high pressure and temperature as mineral oils do. They also have a more destructive effect on some hydraulic components (for example, rubber seals and hoses), which have to be replaced more frequently, causing more of an environmental burden.

LCA is a powerful tool, but it obviously has limitations. This includes data availability and accuracy. As the use of LCA becomes more widespread, however, it is hoped that databases will be compiled and maintained so that this is not a lasting problem. Decisions are often made about the environment as a result of incomplete or misguided information. LCA allows a more complete environmental story of the product or system to be told. This should improve decision making.

No information about the disposal of the machines or the fluids was included in this study. Although this is a shortcoming in the research, it should not have a detrimental effect on the comparative power of this study. In the United Kingdom, at present both oils are disposed of in a similar manner. Much of the oil is recycled or reused as lower grade oils or used as a heating oil in the process of road building and maintenance. Currently, in the United Kingdom, there is so little rapeseed oil used that it is simply mixed with other oil, and thus both are burned or reprocessed together.

This article shows that it is not necessarily better to operate systems using rapeseed oil in place of mineral oil when the whole life cycle is considered; however, continuing to promote the use of mineral oil is unsustainable because the oil is derived from a nonrenewable resource. Therefore, the results of this study should be used to improve the performance of the rapeseed oil in the areas where weaknesses have been identified. For example, production methods should be modified to reduce environmental impact. Materials such as seals and hoses within the hydraulic system should also be designed to be compatible with the rapeseed oil so that they do not degrade so quickly. In the meantime, machine users should consider their choice of oil based on its whole life impact.

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Notes

1. Definition of the functional unit as *x* hours of successful operation of the equipment was considered. Because this is a huge number, however, when it was used it was said to be confusing and unintelligible. Therefore, we used the definition described in the text because it was thought to be more meaningful.
2. One kilogram ≈ 2.204 lb.
3. Editor's note: For a sustainability assessment of a biolubricant in the *Journal of Industrial Ecology*, see the article by Cunningham et al. (2003) in this issue.
4. One liter ≈ 0.264 gallons.
5. One square meter = 0.0001 ha ≈ 0.000247 acres.

6. Unless otherwise noted, “ton” refers to metric ton. One metric ton = 1 Mg. [SI] ≈ 1.102 short tons.

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