The greenhouse and air quality emissions of biodiesel blends in Australia

Tom Beer, Tim Grant and Peter K Campbell
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Enquiries should be addressed to:
Dr Tom Beer
CSIRO
Private Bag 1
Aspendale VIC 3195
Phone: (03) 9239 4546
Fax: (03) 9239 4444
e-mail: tom.beer@csiro.au

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1 EXECUTIVE SUMMARY

The upstream processes of growing and harvesting canola lead to upstream GHG emissions that are approximately 3.5 times higher than upstream emissions from refining the diesel. Tallow has upstream GHG emissions that are approximately 50% higher than the upstream emissions of diesel, whereas those of used cooking oil are slightly lower. Upstream GHG emissions of palm oil depend on whether the plantation was established before 1990, in which case the emissions associated with land clearing and with soil disturbance are not counted as greenhouse gas emissions under present methods of carbon accounting. In this case upstream greenhouse gas emissions are approximately 25% higher than the upstream emissions associated with diesel refining. If, however, rain forest or peat swamp forest is cleared for palm oil growing, then the upstream emissions range from 50 to 136 *times* higher.

When using BD100 produced from tallow, canola, used cooking oil or plantation-based palm oil then the carbon dioxide emissions are offset by the carbon dioxide sequestered during the feedstock production so that the tailpipe GHG emissions are zero, which is to say that the emissions of fossil carbon are zero. However, fossil carbon or other greenhouse gases are emitted during the growth or manufacture of the feedstock. Overall this results in a saving in total life-cycle GHG emissions when the feedstock is canola (422 g CO_2-e/km saving; 49%), tallow (646 g CO_2-e/km saving; 76%), used cooking oil (746 g CO_2-e/km saving; 87%) or palm oil from existing plantations (680 g CO_2-e/km saving; 80%) when compared to XLS diesel, which emits 855 g CO_2-e/km (Table 12.5). GHG emissions from palm oil that is sourced from cleared rain- or peat swamp forest are 8 to 21 times respectively greater than those from diesel.

The extra upstream processing required for reducing the sulfur content results in higher GHG emissions for XLS diesel compared with ULS diesel. The highest savings in GHG emissions are obtained by replacing base diesel with biodiesel from used cooking oil (725 g CO_2-e/km for ULSD to 746 g CO_2-e/km for XLSD).

The large difference between the upstream emission of tallow and used cooking oil are based on the assumption that the tallow is being taken from existing market uses and is not a waste product, whereas the used cooking oil is taken to be a true waste, with no existing market. If low-grade tallow, with no other viable markets, was available, its emission profile would be similar to that of used cooking oil. However, low-grade tallow does require more processing to produce biodiesel than high-grade (edible) tallow.

Blends with 2% biodiesel lead to much smaller GHG savings (when there are savings) or much smaller increases (when there are increases): the savings are 14-15 g CO_2-e/km for used cooking oil blends when using BD2 compared with diesel; 12-13 g CO_2-e/km for tallow biodiesel; and 7-8 g CO_2-e/km for canola oil biodiesel. Palm oil based BD2 produces savings of 12-13 g CO_2-e/km if the palm oil comes from existing plantations, but can lead to increases in GHG emissions that range from 142 to 338 g CO_2-e/km if the palm oil comes from cleared rainforest or cleared peat swamp forest respectively. If palm oil was to be grown in Australia (rather than imported from Asia), the emissions are likely to increase further because of the greater use of mechanisation in Australian agriculture, with its concomitant increase in greenhouse gas emissions.

Life-cycle emissions of CO, NMVOC, and particles are reduced when biodiesel blends are used, but emissions of NO_x may increase slightly.

Summary tables for Greenhouse Gas Emissions for all biodiesel blends can be found in Section 12, with tables and figures describing all emissions for all blends in Section 11.

Table 1.1: Summary of Greenhouse Gas Emissions (g CO_2-e/km) from BD2 for various feedstocks

	Diesel	Canola	Palm oil from existing plantation	Palm oil from rain-forest	Palm oil from peat swamp forest	Tallow	Used cooking oil
ULSD	834	827	822	976	1172	822	820
Difference		-7	-12	142	338	-12	-14
% change		-0.89%	-1.49%	17.02%	40.54%	-1.46%	-1.69%
XLSD	855	847	842	996	1193	842	840
Difference		-8	-13	142	338	-13	-15
% change		-0.92%	-1.51%	16.56%	39.51%	-1.47%	-1.70%

Figure 1-1: Full life-cycle GHG emissions from 100% biodiesel - BD100 (per km NEPM rigid truck) (truncated Y axis)

2 SCOPE OF WORK

In December 2006, CSIRO was requested by Caltex Australia to undertake a life cycle analysis for greenhouse gas (GHG) and criteria pollutants on a blend of 2% biodiesel in diesel (BD2) and to compare its emission characteristics with ultra low sulfur diesel (ULSD, being a maximum of 50 ppm sulfur) from the Kurnell refinery and extra low sulfur diesel (XLSD, being a maximum of 10 ppm sulfur) from the Lytton refinery. Biodiesel feedstocks to be considered in this analysis are canola, tallow, used cooking oil, and palm oil.

It was originally intended to compare these emission calculations with those given by Beer. (2001, 2003). However, during the course of the study it became apparent that there have been significant changes in feedstock prices and availability since these earlier studies so that the upstream modelling assumptions that were used then need to be updated.

In order to provide a consistent set of data for ULSD, XLSD, BD2, BD5, BD10, BD20 and BD100, in May 2007 CSIRO was requested to extend the study to include blends of 5%, 10%, and 20% biodiesel in diesel (BD5, BD10 and BD20 respectively) as well as to provide information in relation to pure biodiesel (BD100) so as to update the biodiesel emissions information given by Beer (2001, 2003). The Department of the Environment and Water Resources agreed to fund this extra component of the study.

The report contains an introductory section that discusses the feedstocks. This is followed by a brief review of the use of biodiesel in vehicles. The report then provides the results of the life-cycle emissions calculations.

3   GENERAL INFORMATION ON BIODIESEL

3.1   Introduction

Biodiesel is a fatty acid ester with combustion properties that are similar to those of diesel. Biodiesel can be made from a large range of feedstocks. In Australia the most common feedstocks are used cooking oil (UCO, the cheapest), tallow, imported palm oil, and canola (a proprietary derivative of rape seed). Any product containing fatty acids, such as vegetable oil or animal fats, can be used as a feedstock.

Table 3.1 compares some of the physical and chemical properties of diesel, the biodiesel feedstocks canola oil and tallow, and their methyl esters (i.e. biodiesel). Vegetable oils have higher density than diesel, but lower energy content (gross calorific value). Vegetable oils have lower carbon contents than diesel, which means lower CO_2 emissions per litre of fuel burnt. CO_2 emissions per kilometre travelled may not be lower, however, due to the lower energy content of the vegetable oils and a higher proportion of multi-bonded carbon compounds.

The major difference in physical characteristics between a typical vegetable oil such as canola oil and diesel is in the viscosity. Canola is more than 12 times as viscous as diesel at 20°C, and remains more than six times as viscous even after heating to 80°C. Straight beef tallow is solid at NTP and as such not suitable for use within diesel engines, hence the lack of a cetane number or viscosity measurement.

Table 3.1: Comparison of typical properties of diesel, oils and fats and their methyl esters.

	Diesel	Canola	Canola methyl ester	Palm oil	Palm oil methyl ester	Beef Tallow	Tallow methyl ester
Density (kg/L) at 15.5^{o}C	0.835	0.91	0.875-0.900	0.92-0.93	0.859-0.875	0.92	0.877
Gross calorific value (MJ/kg)	45.9	39.78	40.07	39.3	41.3	40.05	39.9
Viscosity (mm^2/s @ 37.8^{o}C)	3.86	37.7	3.5-5.0	36.8-39.6	4.3-6.3	N/A	4.47-4.73
Cetane number	40-58	39-44	49-62	42-62	50-70	N/A	58

Source: Adapted from Table 6.1 of BTCE (1994), EERE (2006), Clements (1996), Prateepchaikul and Apichato (2003), Mittelbach and Remschmidt (2004).

These high viscosity levels create problems for the use of pure vegetable oils as an unmodified fuel. The flow of the fuel from tank to engine is impeded, which can result in decreased engine power. Fuel filter blockages may also occur. The multi-bonded compounds pyrolyse more readily and engines can suffer coking of the combustion chamber and injector nozzles, and gumming, and hence sticking, of the piston rings. This causes a progressive decline in power. If left unchecked, dilution of the crankcase oil can lead to lubrication breakdown. Long-term tests have verified that there is a build-up of carbon deposits in the injection nozzles and cylinder heads.

The viscosity problem can be mitigated by preheating the oil and using larger fuel lines, by blending diesel and vegetable oils, or by chemical modification (e.g. producing methyl esters, i.e. biodiesel). Apart from the viscosity difficulties, vegetable oils may result in starting difficulties due to a high temperature being required before the oil will give off ignitable vapours. They also have a relatively slow burn rate as a result of the low cetane rating, which makes vegetable oils unsuitable for high speed engines.

Biodiesel can be used in a diesel engine without modification. The fuel consumption of biodiesel per kilometre travelled is similar to that for diesel when biodiesel is used as a diesel blend. The commercial biodiesel available in the US has lower energy contents than diesel which leads to increased fuel consumption when pure biodiesel is used (Taberski 1999). As is evident from Table 3.1, the energy content can vary considerably depending on the feedstock and the processing method.

Knothe (2005) has reviewed the dependence of biodiesel fuel properties on the structure of fatty acid alkyl esters. The cetane number decreases with increasing unsaturation and increases with increasing chain length, is largest for esters containing 16 carbon atoms (such as palmitic methyl ester) and decreases if there are more or fewer carbon atoms. In general, the heat of combustion increases with chain length and for an ethyl ester is greater than the heat of combustion for a methyl ester.

3.2   Transesterification

Biodiesel is obtained by transesterification of a vegetable oil. Figure 3-1 depicts a flow chart of the esterification process.
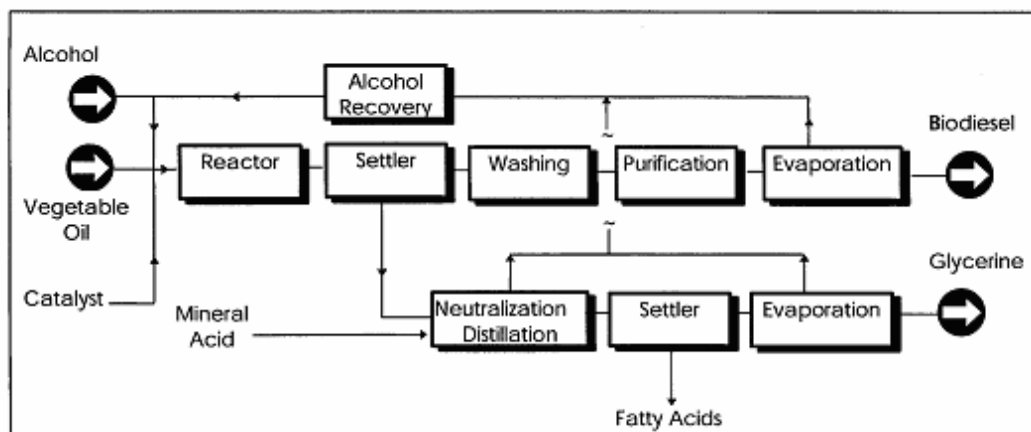
Figure 3-1: Flowchart of the process of esterification to create biodiesel fuel.
Source: National Biodiesel Board production

The alcohol that is input into the transesterification process can be methanol or ethanol. Generally methanol is used. There are three reasons for this. Firstly, the reactions proceed at lower temperatures if methanol rather than ethanol is used. Secondly, in general methanol is cheaper than ethanol. Typical prices[1] (based on estimated production costs and thus ignoring excise or fuel taxes) are 62c/L for methanol compared to 82c/L

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[1] http://www.afg.asn.au/resources/pdfs/Grower/Grower26,1/Grower26,1-p27-38.pdf

for ethanol and 37 c/L for petrol. The third reason is that the European standards only allow for the use of methanol as the reacting alcohol and they also specify iodine number, which acts to limit feedstock to rapeseed or canola oil[2]. Because most of the world's biodiesel production emanates from Europe the installation of European plants in other countries will tend to perpetuate the use of methanol as the alcohol to be used. The catalyst used in the transesterification process is generally caustic soda (Sodium Hydroxide, NaOH) though potassium hydroxide (KOH) can also be used.

The greenhouse gas emissions arising from the process depicted in Figure 3-1 depend on the amount of fossil fuel involved in the production of the alcohol. If methanol is used then this process is described by the equation.

$$C_3H_5(OOCR)_3 + 3CH_3OH \rightarrow 3RCOOCH_3 + C_3H_5(OH)_3$$

(Triglyceride)   (Methanol) $\rightarrow$ (Methyl ester) (Glycerine)
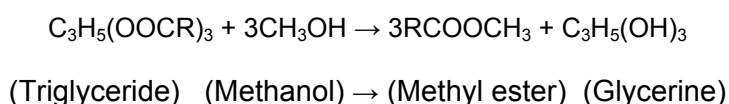
The term "triglyceride" in the equation may be either vegetable oil or tallow. From a chemical point of view, the differences between various plant and animal derived fats are due to the structural variations of fatty acids contained in fat molecules.

In most fats, the length of the fatty acid carbon chain ranges between C16 and C18. There are also differences in the degree of saturation (number and position of double bonds) in acid molecules. Saturation is the major factor determining physical properties of fats. Highly unsaturated vegetable oils are low viscosity liquids, while fully saturated animal fats are solid at ambient temperature.

From the point of view of the transesterification process itself, these differences in molecular structure are insignificant in terms of process parameters or energy demand. The greenhouse gas emissions arising from the process depicted in Figure 3-1 depend mostly on the amount of fossil fuel involved in the production of the alcohol as given by Sheehan (1998), who estimates that 5% (by mass) of the carbon emissions are fossil-fuel carbon.

For example, if methanol is used, overall emissions will be higher because the current commercial production method of methanol involves solely using fossil-fuel feedstocks such as natural gas or coal. By contrast, if the use of ethanol produced from renewable resources (biomass) using bioprocesses is contemplated, greenhouse emissions will be lower. Methanol can be produced by the gasification of biomass but this is currently not done in Australia on a large scale. To determine the overall differences in greenhouse gas emissions would require a dedicated study, which is outside the scope of this report.

Another source of differences in life-cycle emissions of biodiesel arises at the stage of oil and tallow production. In the case of oil-seed crops, there needs to be accounting for energy and raw materials inputs into fertiliser production, land cultivation, materials transportation, harvesting and oil extraction. Similarly, when tallow is used as a feedstock, energy expended in farming activities needs to be accounted for. In both cases appropriate allocation procedures for multiple product streams need to be observed.

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[2] http://www.deh.gov.au/atmosphere/fuelquality/publications/submissions/pubs/epa-vic.pdf

4   AUSTRALIAN PRODUCTION

4.1   Production capacity

Table 4.1 reproduces the Australian proposals for biodiesel production presented to the Biofuels Task Force (Biofuels Task Force report[3], page 41). The production capacities range up to 150 ML per year.

Table 4.1: Current and proposed biodiesel production capacity, 2004/05 to 2009/10 (ML)

Biodiesel capacity	2004/05	2005/06	2006/07	2007/08	2008/09	2009/10
Biodiesel Industries Australia, Rutherford	0.5	20	20	20	20	20
Australian Biodiesel Group, Berkeley Vale NSW	15	40	45	45	45	45
Biodiesel Producers Australia	0	0	60.2	60.2	60.2	60.2
Australian Renewable Fuels, Adelaide SA	0	44.7	44.7	44.7	44.7	44.7
Riverina Biofuels	0	0	44.7	44.7	44.7	44.7
Australian Renewable Fuels, Picton WA	0	0	44.5	44.5	44.5	44.5
AJ Bush	0	0	60	60	60	60
Australian Biodiesel Group Queensland	0	0	40	40	40	40
Natural Fuels	0	0	150	150	150	150
(South) Australian Farmers Fuel	0	0	15	15	15	15
Total biodiesel	**15.5**	**104.7**	**524.1**	**524.1**	**524.1**	**524.1**

In actual fact, the situation in 2006/2007 was exceptionally volatile with ambitious expansion plans being proposed in early 2006 followed by a marked scale-back in 2007. Thus our estimate of production capacity for the financial year is only 323 ML, but it is expected to be 570 ML over the 2007 calendar year. In addition, the BP refinery in Bulwer is presently producing a biodiesel-like product that they call "renewable diesel" by hydrogenating tallow (rather than using transesterification).

The 2006 annual report of the Australian Biodiesel Group Limited states that the Narangba plant commenced operation in July 2006 and had produced 5 ML in the second half of 2006. The annual report also states that the Berkley Vale plant is mothballed.

It would appear that the plans by AJ Bush did not eventuate. A company in Brisbane called Ecotech operated a 30 ML plant during 2006 but this has also apparently been

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[3] http://www.dpmc.gov.au/biofuels/final_report.cfm

closed. The Biofuels Task Force listing fails to mention the 20 ML facility in Laverton, Victoria run by Vilo Asset Management, which is part of the Victor Smorgon Group of companies. There are also plans by Axiom Energy to establish a 150 ML capacity biodiesel plant near Geelong, Victoria. It is unclear when the plant is likely to be operational, though in September 2006 the company indicated that the plant was to be operational in the third quarter of 2007.

4.2 Feedstock

The Australian oilseed processing industry is small by international standards, with approximately 3000 kilotonnes of annual capacity.

Table 4.2: Australian oilseed production (kt)

	98/99	99/00	00/01	01/02	02/03	03/04	04/05	05/06	06/07
Canola	1685	2402	1681	1607	790	1622	1531	1439	512
Sunflowers	195	125	72	70	25	58	62	98	106
Soybeans	107	102	76	63	18	74	54	55	54
Cottonseed	950	980	1082	1054	546	494	912	844	680

Table 4.2 provides estimates of Australian oilseed production according to ACIL Tasman[4] and ABARE[5]. In 2000/2001 Australia produced 1607 kt of canola and about 500 ML of canola oil.

Table 4.3: Biodiesel feedstock prices and volumes.

Feedstock	Price ($/tonne)	Annual Production (kt)
Waste oils	200-350	60 – 80
Tallow – low grade[6]	280	260 (mostly exported)
Tallow – high grade	400-500	240
Canola grain	260-400	1,400 of which 1,300 is exported

Table 4.3 reproduces a table of domestic biodiesel feedstock prices and production. The prices in this table refer to the average range from 1995-2001 and have been chosen in

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[4] http://www.ipa.org.au/files/A9_part1.pdf
[5] http://www.abareconomics.com/interactive/AC_june_2006/excel/table20.xls
[6] Low grade tallow has a high fatty acid content

order to obtain a representative average value for feedstock prices that can be used in subsequent life-cycle calculations. The reason for this, as described in Appendix D and Appendix E is that life-cycle assessment requires data on which to base co-product allocation. This data should be relatively stable, but biodiesel feedstock prices are volatile and strongly influenced by international market prices. Drought also increases the market price of canola.
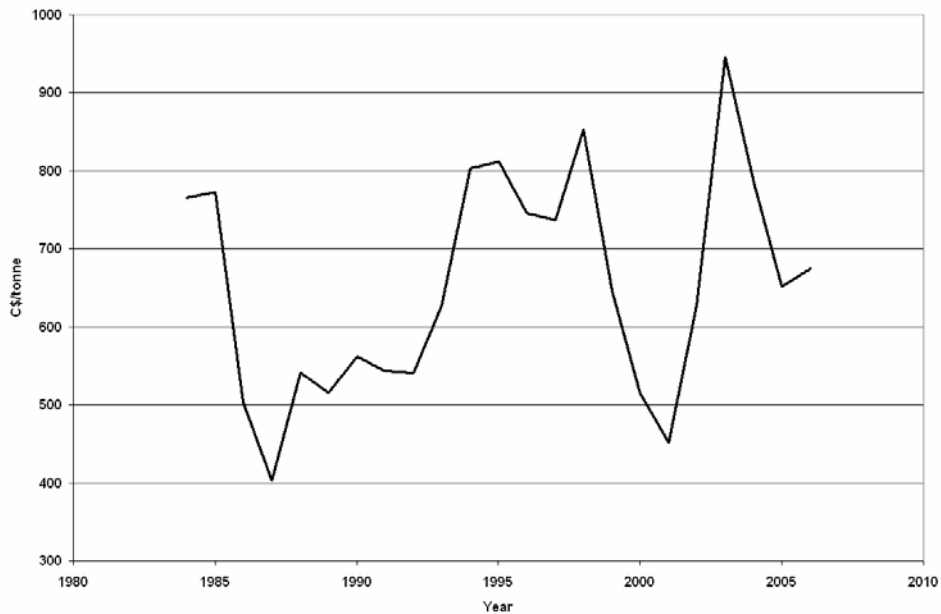
Figure 4-1: Average annual price of Canola Oil in C$/tonne. Data from Canola Council of Canada[7]

Figure 4-2: Crude Palm Oil Prices in US$/tonne

Estimated feedstock costs and by-product revenue streams for biodiesel production using different feedstocks are presented in

Table 4.4. The options examined in more detail include the production of biodiesel from:

- used cooking oil using new capacity
- tallow using new capacity
- whole grains or oilseeds (such as canola) using new capacity
- imported palm oil.

4.2.1 Used Cooking Oil

Used cooking oil (UCO) is also known as used vegetable oil, waste vegetable oil, waste cooking oil or yellow grease[8]. In this document the terms are used interchangeably, with a preference to avoid the use of the term "waste". Although considered a waste product in the past, due to its use in biodiesel the accepted term is now "used".

The biodiesel yield from all oil in liquid form (including UCO) is assumed to be 80%. Given the specific gravity of 0.92, a tonne of cooking oil yields 870 litres of biodiesel. The NSW Dept Energy, Utilities and Sustainability (whilst still the Sustainable Energy Development Authority) estimated that feedstock costs for biodiesel vary from 20 to 90c/L. In this case it is assumed that the low end of this range refers to UCO while the upper end of the range is likely to refer to commercially grown oil seeds or vegetable oil. As with waste starch, it is difficult to determine the true economic value of UCO as no transparent market exists. Some businesses incur costs associated with the disposal of the used cooking oil while others are paid for theirs. At this stage in Australia this is an undeveloped market. The Australian Tax Office estimated the price of UCO to be $170/tonne (Australian Tax Office, personal communication). On this basis the cost of UCO feedstock is estimated to be approximately 20c/L.

The total cost of chemicals used in the production of biodiesel, mainly alcohol and a catalyst, depends on the production process, as well as the current chemical prices. The continuous flow process requires the stoichiometric amount of chemicals (that is, the exact proportions required for the chemical reaction), whilst the batch process requires an excess of alcohol to drive the reaction to completion. However, in the batch process, most (over 90%) of the excess alcohol can be recovered for use later such that the difference in costs between the two processes are small enough to be ignored (McAloon 2000).

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[7] http://www.canola-council.org/industry_stats.html
[8] http://www.meatupdate.csiro.au/whats-new/whats-new2007-2.pdf

Table 4.4: Biodiesel feedstock costs and by-product revenues

Feedstock			Chem –icals [bc]	Glycerol revenue [d]	Meal revenue			Net required revenue [e]
Name	yield [a]	price	cost			yield	price	revenue	
	L/t	$/t	c/L	c/L	c/L	kg/L	$/t	c/L	c/L
Waste oil	870 [f]	170	20	9	6	—	—	—	35
Tallow	894 [g]	450	50	9	6	—	—	—	66
Canola seed	370	353	95	9	6	24	140	36	76
Canola oil	875 [h]	910	104	9	6	—	—	—	119

a. The yield of biodiesel per litre of oil is 0.8 litres. b. Methanol costs of $800/t at a specific density of 0.791 with 125ml/L of biodiesel required gives 8c/L input cost. c. Catalyst cost of $200/tonne at a ratio of 0.5% by weight equates to a 1c/L input cost. d. Glycerine yield of 8% per litre of biodiesel sold at $850/t with a specific density of 1.112. e. Assumes operating costs of 7.5c/L and capital costs of 4.5c/L. For this analysis, it has been assumed that plants do not qualify for the capital subsidy. Applying the subsidy would reduce the net revenue required by approximately 1c/L (depending on the size of the plant). f. At a specific density of 0.92. g. At a specific density of 0.895. h. At a specific density of 0.914.

The amount of alcohol required for the reaction varies depending on the type and quality of the feedstock (in particular, the amount of free fatty acids in the oil) and the process. The amount required varies between 9 and 15% by volume. This analysis assumes that 125ml of methanol are required for every litre of biodiesel produced. Methanol is assumed to cost $800/t. This equates to approximately 8c/L of biodiesel produced.

The amount of catalyst required is assumed to be 0.5% by weight and is assumed to cost $200/t. This equates to approximately 1c/L of biodiesel produced.

Combining both the cost of alcohol and catalyst, the total cost of chemicals is assumed to be approximately 9 cents for each litre of biodiesel produced.

As mentioned previously, glycerine (or glycerol or glycerin) is a by-product of the production of biodiesel. It is commonly used as a solvent, plasticiser and softening agent in a wide range of industries such as cosmetics, tanning and dying, food processing, chemicals and explosives. With a yield of 8% per litre of biodiesel produced and a price of around $850 a tonne, revenue from glycerol sales is estimated to be around 6c/L of biodiesel produced.

Taking all this together, the total cost of biodiesel production based on used cooking oil feedstocks is estimated to be 35c/L.

It is difficult to assess the quantity of UCO produced in Australia. On the basis that UCO is produced at a rate of between 10–12 litres per person (Australian Tax Office, personal

communication), total Australian supplies would be between 220 and 260 ML in 2010 (assuming a population of 22 million). SEDA estimates that 120,000 tonnes of UCO is currently produced in New South Wales alone (personal communication). On the assumption that 50% of 264 ML of used cooking oil[9] is recoverable (and assuming a yield of 80%), this resource could be used to produce between 90 and 105 ML of biodiesel.

4.2.2 Tallow

Tallow is rendered animal fat and a by-product of the livestock processing industry. Australian tallow production in 2000-2001 was approximately 567 000 tonnes (Australian Renderers' Association, 2002), most of which was exported (68%). The biodiesel yield from tallow is approximately 894 litres a tonne. Since June 1994 tallow prices in Australia have largely been in the range from $400 to $700 a tonne (Figure 4-3). The unit value of exports averaged almost $510 a tonne over the period 1988-89 to 2002-2003. Beer (2003) assumed that the real medium term price of tallow would average $450 a tonne (in real terms). On this basis, and taking into account both fixed and recurrent operating costs as well as by-product revenue, the net revenue required to cover costs is estimated to be 66 c/L. If updated domestic prices from Figure 4-3 (i.e. a long-term average of $550/tonne) and production costs from Toohey (2003) are used costs rise to 82 c/L, and with the latest spike in tallow prices to $860/tonne in June 2007 tallow biodiesel would cost a full 114 c/L.   As this demonstrates, the price of tallow-based biodiesel is quite volatile, being highly dependent upon the cost of the feedstock.
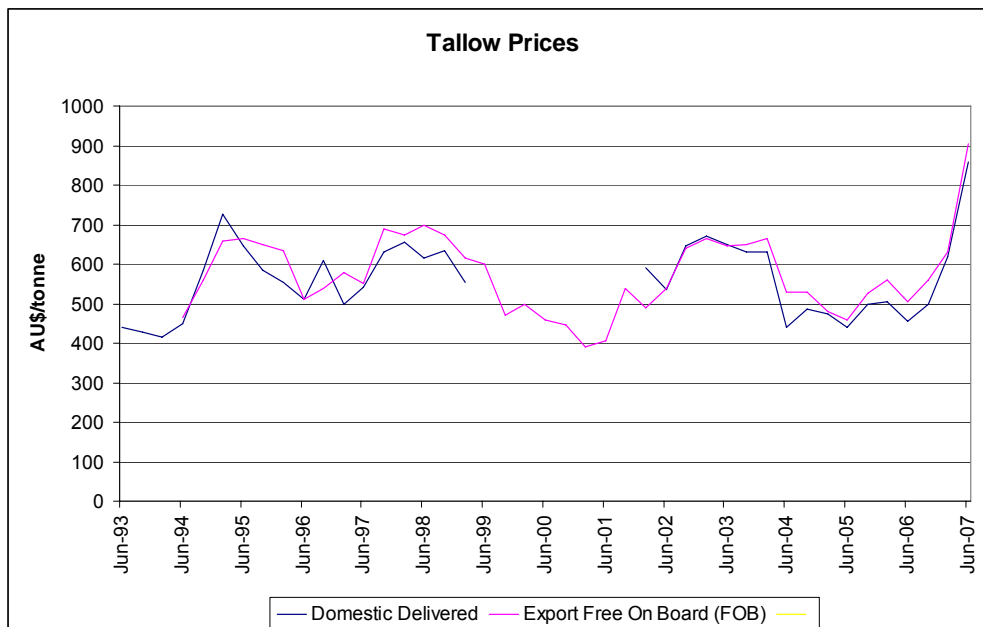
Figure 4-3: Tallow Prices (high grade; maximum 1% FFA). Data from Aginfo, the Australian Bureau of Statistics, and The Jacobsen[10]

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[9] http://www.biodiesel.org/resources/reportsdatabase/reports/gen/19970901_gen-190.pdf claims that in Austria 41% of used cooking oil is relatively easy to collect. A slightly higher figure would apply to Australia, which has a higher proportion of fast-food outlets.
[10] http://www.thejacobsen.com/

Tallow is sold in several different grades, depending mainly upon the percentage of FFA (free fatty acids). Although the naming can change from country to country, it is usually top white (edible) that has under 1% FFA, prime 1-2% FFA, extra fancy 2% FFA, bleachable fancy (good) 2-4% FFA, unbleachable (low grade) 10% FFA, medium gut 10-15% FFA, K grade 21% and low gut (dark) up to 60% FFA. The free fatty acids in tallow are not used to create biodiesel; they must be removed at some point during the process, leading to extra costs (either in pre-processing or extra catalyst). As such biodiesel producers prefer to tallow with a low percentage of FFA, which is the most expensive variety. This is also the type required for food use.

4.2.3 Oil Seeds and Canola Oil

A considerable number of new project proposals are based on the utilisation of whole grain oilseeds, and canola in particular. However, as internationally traded agricultural commodities, oilseed prices vary considerably depending on both domestic market conditions (i.e. drought) and international market developments. On 9 December 2002 the Australian Financial Review quoted a closing price, in Canadian dollars, of C$431.60 per tonne for January 2003 canola seed futures on the WCE exchange. Three years later, on 9 December 2005 the same price was C$237.10 for January 2006 canola seed futures. Since this low, prices have risen to approximately C$400/tonne[11]. Crushed grain meal is also a valuable co-product in the production of biodiesel from oil seeds. Beer (2003) assumed canola grain meal is priced at $140 a tonne providing a revenue credit of 36c/L of biodiesel produced. Based on these figures the net revenue required to cover costs is estimated to be 76c/L. In the case where the raw feedstock is canola oil rather than whole seeds the costs of production are even higher ($1.19 per litre) reflecting both the higher cost of the feedstock and the lack of a grain meal co-product.

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[11] http://www.canola-council.org/canolaprices.html

5   CANOLA

5.1   Background

Canola is a member of the *Brassica* genus, which includes broccoli, cabbage, cauliflower, mustard, radish, and turnip. It is a variant of the crop rapeseed, with less erucic acid and glucosinolates than rapeseed. It is grown for its seed, which is crushed for the oil contained within. After the oil is extracted, the by-product is a protein rich meal used by the intensive livestock industry.

Canola is a good rotational crop, acting as a break crop for cereal root diseases. However for disease-related reasons, a rotation period of 3-5 years is required for canola crops.

5.2   Production

Current canola oil production is about 12% of Australian diesel oil consumption. Gross canola yield for 2007/08 is expected to be about 1.5 t/ha of canola seeds but it varies substantially by State as shown in Table 5.1, as well as from year to year (due to drought, yields in recent years have been about 1.2 t/ha). Oil yield from the seed is around 40%. If this were processed into biodiesel, with losses through refining of approximately 2.5%, the potential Australian biodiesel production per hectare is 0.62t, or 0.71kL (based on a density of 0.88 kg/L), up from 0.56kL per hectare in recent years.

Figure 5-1 shows the distribution of oilseed production in Australia in average hectares planted per farm. It reveals intensive activity in the inland area of the south-western part of Western Australia. While Western Australia has the largest area under cultivation for canola, its yields tend to be much lower than the other States that traditionally receive more rain.

Table 5.1: Estimated Yields by State for Canola in 2007/08. Source: Australian Oilseeds Federation Crop Report[12]

Production	Planted (Hectares)	Production (Tonnes)	Yield (Tonne/Hectare)
NSW	206,000	288,000	1.40
VIC	238,000	518,000	2.18
SA	160,000	240,000	1.50
WA	420,000	504,000	1.20
Total	1,024,000	1,550,000	1.51

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[12] http://www.australianoilseeds.com/__data/assets/pdf_file/2778/AOF_Crop_Report_May_07.pdf
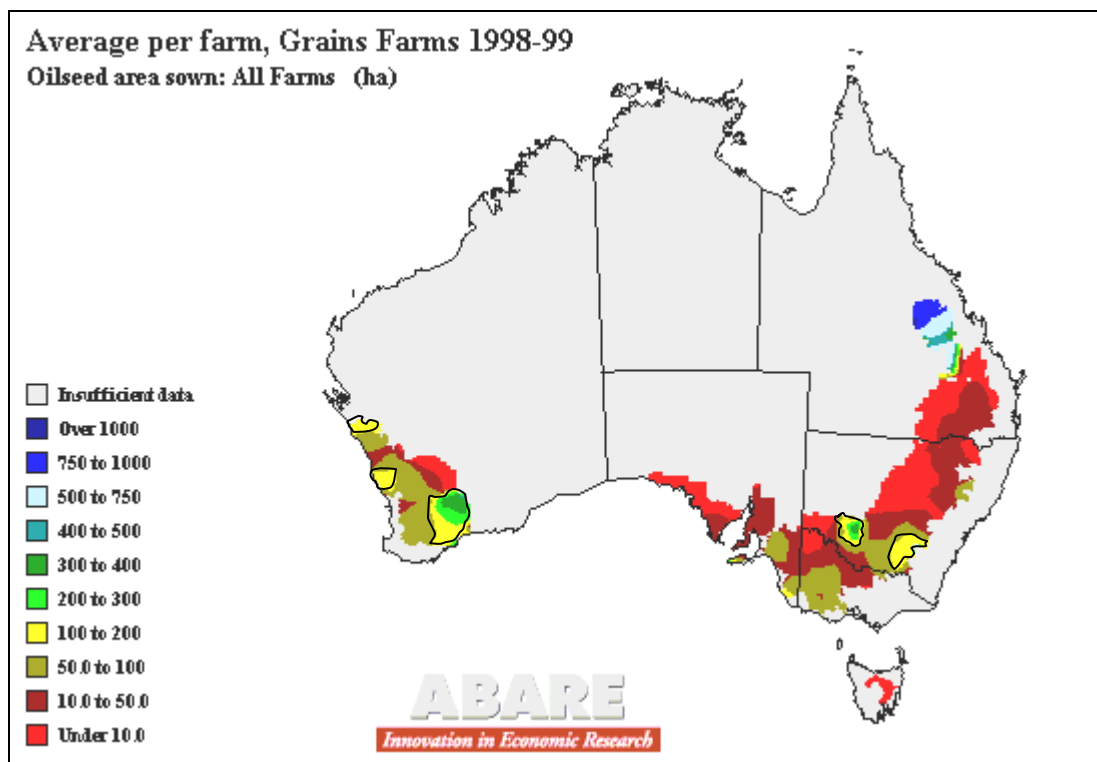
Figure 5-1: Location of Oil Seed production across Australia

5.3 Life Cycle Inventory Data

The life cycle data used for canola production is based on average canola production across Australia. Following are descriptions of data sources and adaptions of data use in the LCA model for production of refined canola oil. The impacts of the transesterification of canola oil are dealt with in a separate section as it is common to all feedstocks.

5.3.1 Fertiliser

Canola is a nutrient hungry crop compared to other winter crops, cereals, and grain legumes. The major nutrients required for Australian canola are nitrogen, sulfur, phosphorous, and zinc.

Available data regarding fertiliser input to canola farming has been collected from various sources, and is shown in Table 5.2. The second from the right column shows the nutrient removal (as grain) per hectare of canola crop. Theoretically this is the amount needed to be replenished for canola agriculture to be sustainable. Recommendations for nutrient addition from the fertiliser producers are shown in the second column but vary widely according to soil conditions and expected yield. The third column is recommendations from the Victorian Department of Natural Resources and Environment (NRE) in regards to the application rates of nitrogen for canola after cereal and pasture crops. The fourth column is estimated from figures on nitrogen and phosphorous usage data in oilseed growing areas from ABARE – AgAccess database (Australian Bureau of

Agricultural Research Economics, 2000). (See Figure 5-3 and Figure 5-4, which overlay the oilseed growing area over the nitrogen and phosphorous usage maps.).

Figure 5-2 shows how fertiliser application is linked to yield outcomes, so the most important factor is to choose fertiliser input values that match the types of yields being modelled. We seek an average value that is appropriate to all of Australia. Figure 5-2 suggests that a gross canola yield of 1.29 t/ha is based on low nitrogen inputs. Note the gross yield would include some land set aside from cropping so the real yield per ha plant would be higher. If 20% of land is assumed to be set aside the real yield per ha would be more like 1.7 t per ha, which corresponds to a nitrogen application rate of 50 kg/ha. Phosphorous inputs are less variable; a value of 15 kg/ha is assumed.

Table 5.2: Information sources regarding fertiliser use when farming canola in kg/ha

Canola	Hi-Fert Re-commendation[1]	Nitrogen application[3] kg/ha	Grain Access Data average fertiliser application in oilseed growing areas[2]	Nutrient removal[1] kg/ha	Data estimate used in this study
Nitrogen	0-100	A=100, B=60-80	20 to >30	82	50
Phosphorous	15-25		10 to 20	14	15
Sulfur	0-30			20	Supplied in other fertiliser
Zinc	0-3			0.080	0

A=after cereal crop   **B=after pasture crop**

[1] WMC Fertilizers Pty Ltd, 2000.
[2] ABARE, 2000.
[3] NRE, 2000.
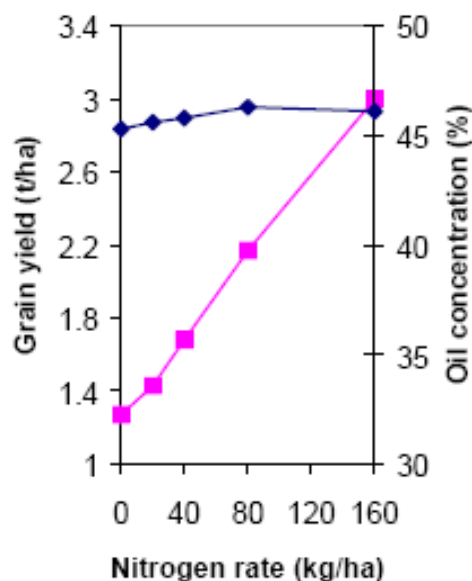
Figure 5-2: Relationship of nitrogen input to crop returns (Hocking, 1999).
The left hand scale refers to the squares and the right hand scale to the diamonds.

The only other data are from cost estimates for growing canola provided by NRE for 1995/96 (see Table 5.4), which has the cost of fertilisers at $65 per hectare for the Mallee in Victoria. Assuming nitrogen costs of around $1.50 per kilogram (currently around $2 per kilogram elemental N after five years of inflation and GST) and phosphorous at around $6 per kilogram (currently around $8-10 per kilogram of elemental P after five years of inflation and GST), 20 kg of N and 10 kg of P would cost around $90, which provides an estimate of the range associated with these costs. Due to a lack of supporting data, sulfur and zinc were assumed to be supplied in existing fertiliser production.

The addition of fertiliser and cropping can lead to soil acidification. Data from the Land and Water Research Development Corporation (Australian Bureau of Statistics 1996) has liming costs for canola in South Australia at around $9 per ha per year in 1996 (averaged over a 15 year period). Using a price of 10c per kilogram from lime in 1996, a lime usage of 90 kg ha^{-1} a^{-1} was arrived at for use in the study.

The process of cultivation and application of fertiliser also has an impact on emissions of nitrous oxide (N_2O). According to NGGIC's AGEIS system there is 21.23 Gg of N_2O emissions per year from indirect sources, and 1.10 Gg from other sources, for 22.33 Gg of N2O emissions from soil disturbance in total across Australia. According to SoEC (2006) there is currently 40.31 MHa of land being used for dryland crops and pastures, and 2.17 MHa for irrigated crops and pastures, for a total of 42.48 Mha. This results in an average of 0.526 kg N_2O ha^{-1} a^{-1} due to soil disturbance. For fertiliser application the accepted emission factor is 0.3 % of nitrogen applied ending up as N_2O emissions. This results in a total N_2O emission per hectare of 0.236 kg as is shown in Table 5.3.

Table 5.3: Nitrous Oxide Emissions from Fertiliser and Soil Disturbance

Nitrogen Source	Annual fertiliser applied (kg/ha)	Emission Factor % of N applied[1]	kg N ha^{-1} a^{-1}	Conversion Factor (N - N$_2$0)[1]	kg N$_2$O ha^{-1} a^{-1}
Soil disturbance			0.335	1.57	0.526[2]
Fertiliser application	50	0.3%	0.15	1.57	0.236
Total					0.76

[1] NGGIC 2007 – Agriculture Methodology

[2] Calculated from values in NGGIC 2007 - AGEIS and SoEC 2006
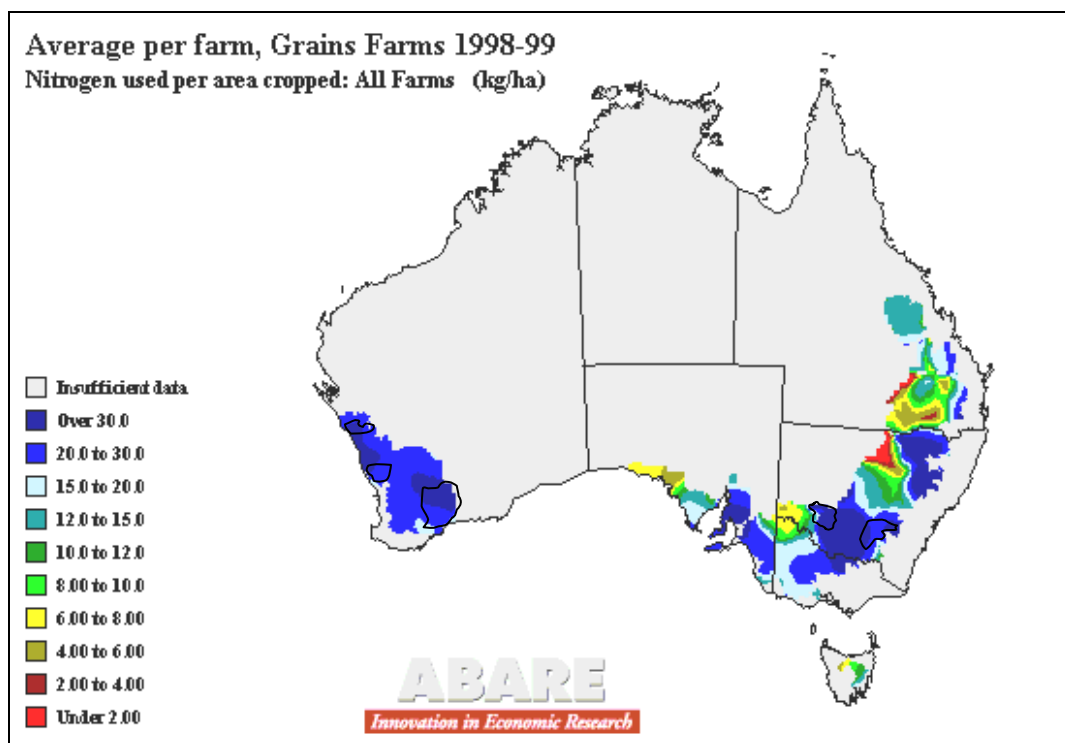
Figure 5-3: Elemental Nitrogen use per ha across Australian Farms with major oilseed production areas outlined
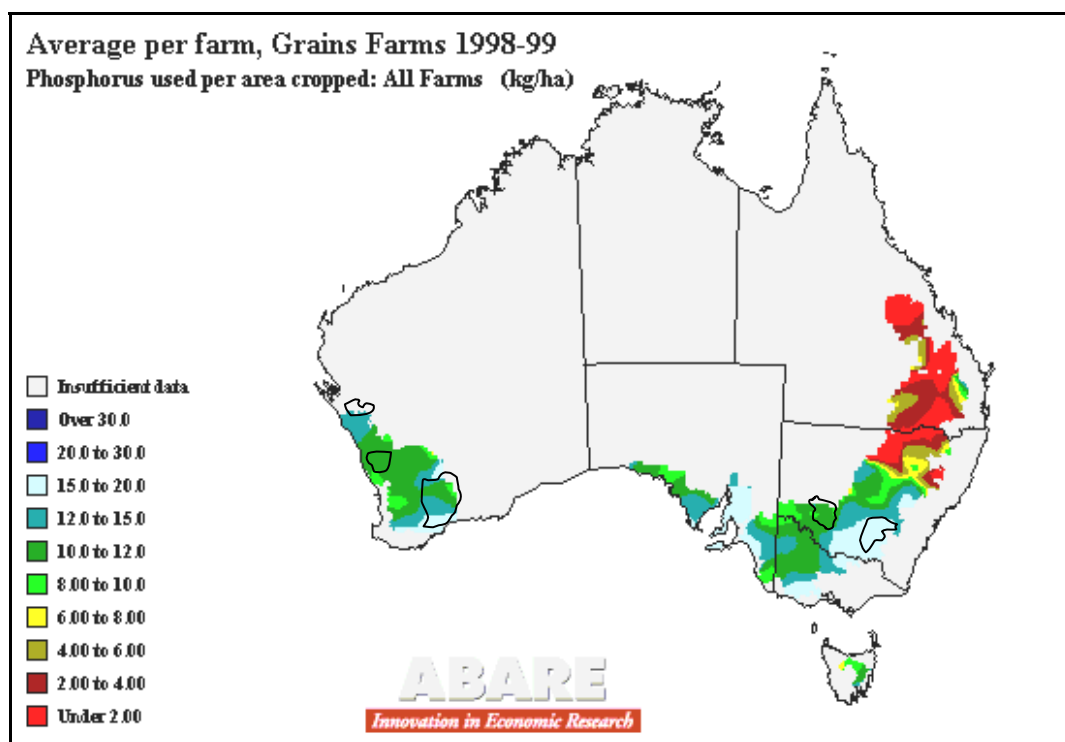
Figure 5-4: Elemental Phosphorous use per ha across Australian Farms with major oilseed production areas outlined

Table 5.4: Variable costs for canola grower in the Wimmera, 1995/96 (NRE, 2000)

Item	$/ha
seed	13
Fertiliser	65
herbicides and insecticides	36
tractor costs	20
harvesting	31
other	10
total variable costs	175

5.3.2 Water Requirements

Canola as a crop does not have a high demand for water. Although high temperatures and low water content limits oil yield, the cost of irrigating canola crops does not warrant such practices. Moreover industry experts believe that yield is affected more by disease than by climate, but at this stage are unsure about the exact nature of the disease and how it affects oil content. (Gammie, 2001). This has not stopped growers from experimenting

with irrigation, especially in drought conditions, but for the purpose of this study it is assumed that the majority of canola production does not use irrigation. If this situation changed other alterations would be required; for example, the amount of N_2O emissions from fertiliser conversion tends to be higher on irrigated land.

5.3.3 Fuel Use

Overseas data from rapeseed production (Table 5.5) indicates a total diesel usage of 70 litres per ha. The Australian data suggests a range of 33-44 litres per ha for Western Australia, and 66-100 litres per ha in New South Wales. With one third of the production being based in Western Australia at an average of 38 litres and two thirds in New South Wales, Victoria and South Australia at an average of 83 litres, a final estimate of 68 litres per hectare was incorporated into the SimaPro life-cycle database.

Table 5.5: Fuel use data from rapeseed production in European RME LCA

Fuel	L/ha
Ploughing	20.3
Harrowing	8.3
Seed bed preparation	12
Sowing	4.9
Fertilizer application	7.6
Harvesting	17
Total	70.1

Source: (Ceuterick and Spirinckx, 1997)

5.4   Other Issues

5.4.1 Chemical Crop Protection

Early weed control needs to be effective to ensure that the canola crop is successfully established. Both broadleaves and grasses need to be controlled to ensure healthy crop development. One of the more common herbicides used in the agricultural industry is *Roundup*. As a dry formula the application rate is 265 g-660 g/ha and costs $120 per 11 kg container. In its liquid state the application rate is 400 ml-1.2 L/ha and costs $90 per 20 L container. (Prices based on bulk purchasing prices-E.E. Muir & Sons.)

Disease control is required to prevent fungal, bacterial, and viral pathogens. The impact of disease on canola crops is dependent upon region, climate, land management, as well as the previous crop harvested. Consequently application rates vary depending on the factors listed above. Table 5.6 gives the application rates incorporated into the SimaPro life-cycle database.

Figure 5-5 shows a map of spray usage per ha for Australian farms with the canola growing areas overlaid. It indicates that spraying costs in 1998-99 were around $40-$45 per ha in the oilseed growing areas.

The energy involved in the fertiliser and pesticide production and application, and the upstream emissions as a result of the production and application have been included in the calculation of upstream emissions.
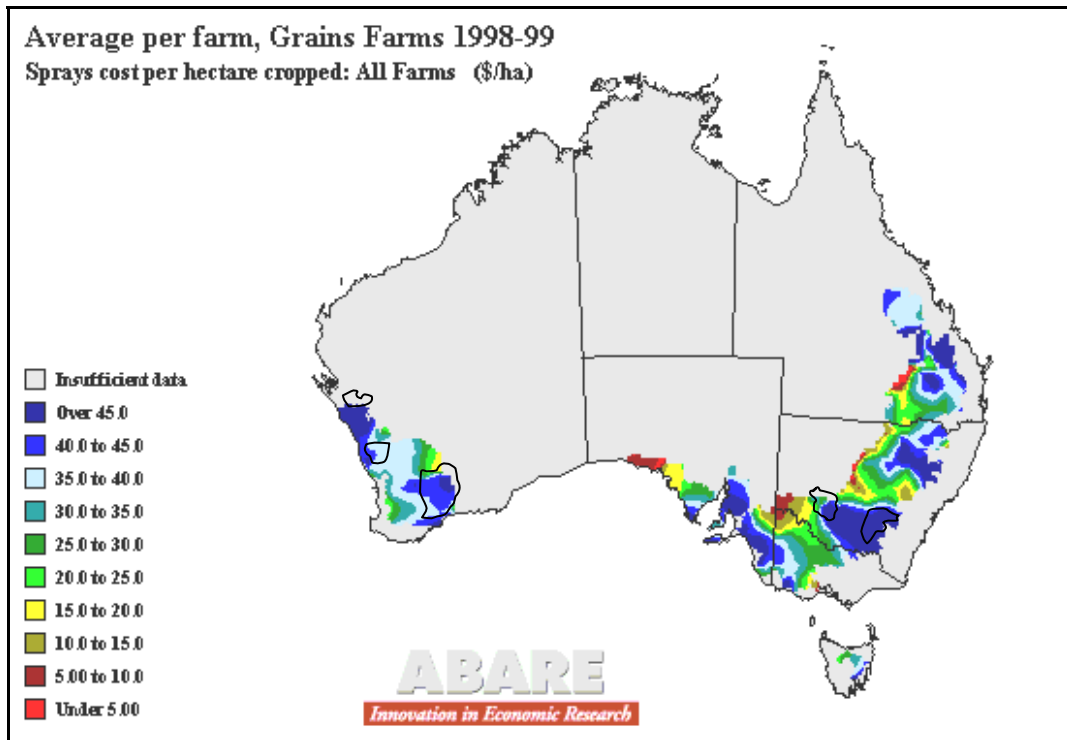
Figure 5-5: Spray cost per ha farm across Australian Farms with major oilseed production areas outlined

Table 5.6: Suggested crop protection application rates for canola (Coombs, 1994)

Herbicide kg/ha	Pesticide kg/ha	Fungicide kg/ha
1.9	0.7	1.4

5.5   Summary for Canola production

Table 5.7: Summary of inputs and outputs for canola production

Inputs	Unit	Value	Comments
Occupation, arable, non-irrigated	land	1	1 hectare used for 1 year
Fertiliser, NPKS 32 10, at regional store	kg	150	48 kg Nitrogen and 15kg of Phosphorous
Urea, at regional store	kg	4.35	2kg additional Nitrogen
Lime, Calcined	kg	90	Estimated from ABS 1996 figure of $9/ha Liming cost for SA canola growers
Active pesticide	kg	2	
Tractor, low population area, per MJ fuel input	MJ	2625	Total of 68L per ha or 2625MJ
Outputs			
Canola seed, at farm	ton	1.7	Canola yields vary but this amount is set relative to fertliser inputs
Dinitrogen monoxide volatilisation from Nitrogen fertiliser application	kg	0.236	From NGGIC 2007 - 0.3% of nitrogen fertilizer applied (non-irrigated crop average)
Dinitrogen monoxide emissions from soil disturbance	kg	0.526	From NGGIC 2007 and SoEC 2006

5.5.1   Co-products for Canola Seed Production

Canola seed is produced as part of the canola crop and represents a small part of the total crop biomass. Though the seed is clearly the primary product from canola, the other parts of the plant, the straw and stump and root material, also provide economic benefits. The straw may be used for feed, or as an energy source in the production of biodiesel. The straw and the root material may also be returned to the soil to replace nutrient material.

In the Flemish LCA of biodiesel (Ceuterick and Spirinckx, 1999) from rapeseed, the rape straw was assumed to be used for some economic purpose and was treated as product of equal value, per unit of dry mass. In a UK study (EcoTec Research and Consulting Ltd, 1999) straw was included as a fuel for biodiesel production, therefore eliminating the need to estimate the relative value of straw and the seed. In Australia the current practice is to leave the straw and stubble in the field as its quality does not warrant production into straw for feed, and the quantity is not sufficient for field burning (Gammie, 2001). For this reason no allocation in required to deal with canola straw in this LCA.

5.5.2 Drying, Storage and Handling

European data on rapeseed processing considers the seed to require drying to reduce the moisture content from 15% to below 9% for storage purposes (Ceuterick and Spirinckx, 1999). In Australia, the canola seed requires no drying as it contains approximately 6-10% moisture (Norton, 2000) thus drying was not incorporated into the upstream activities. Transport of canola from the farm to oil-processing is assumed to be relatively short. A value of 150 km by road is assumed in this study.

5.5.3 Oil Extraction and Refining

Data on canola oil extraction and refining in Australia is not available. However the canola refining process described by the Canadian Canola Council (Canola Council of Canada, 2001) is very similar to that used for rapeseed as described in the Flemish rapeseed biodiesel LCA (Ceuterick and Spirinckx, 1999), for which process data is available. The data and processes are described below.

Cleaning of the incoming seed removes plant material and other debris. The seeds are then de-hulled, comminuted and heat-treated. The seeds are then pressed to produce oil (first press oil) and seed cake with an oil content of around 14 to 18%. This occurs at a temperature of between 72-84°C. The seed cake is then treated to a solvent extraction process (hexane), to decrease the oil content of the cake to between 3 and 5%. The hexane solvent is recycled through the process with a net loss of 1.5 kg per tonne of seeds handled. This is assumed to be lost as an emission to air. The seed cake is then toasted to remove the solvent before being sold as a protein source for feedstock. The oil-hexane-water mixture is then heated to remove water and recover the hexane, leaving the crude oil. Process data for these steps are shown in Table 5.8.

Table 5.8: Process input and outputs for oil extraction of canola

Inputs	Unit	Value
Oils seeds	kg	1000
Electricity[1]	kWh	45
Steam (natural gas fired)[2]	kg	310
Hexane[1]	kg	1.5
Outputs		
Crude Oil[3]	kg	399
Seed Cake[3]	kg	598
Solid Waste[1]	kg	3
Hexane to Air[1]	kg	1.5

Notes
[1] Taken from rapeseed data (Ceuterick and Spirinckx, 1999)
[2] Taken from rapeseed data (Ceuterick and Spirinckx, 1999) based on energy input of 3.64 MJ/kg steam
[3] Based on expected canola oil yield of 40% less solid waste produced

Canola meal (seed cake) is as a high protein stock feed. Following the system boundary expansion approach, canola is provided with a credit equivalent to the most likely alternative option for producing (or not producing) stock feed. In other words as canola production increases, what activities no longer need to be undertaken at the margins because of the supply of this additional canola meal in the market place? The most likely crop for meal production is taken to be lupins or similar crops. Being a nitrogen fixing crop, little fertiliser is required for lupins. Basic data from NSW Department of Agriculture are shown in Table 5.9.

Table 5.9: Inputs and output from 1 ha of lupins production in Australia

Inputs	Unit	Value	Comment
Occupation, arable, non-irrigated	Land	1	1 hectare used for 1 year
Triple superphosphate at regional store	kg	9	48% P
Lime, Calcined	kg	30	Estimated from ABS 1996 figure of $2/ha Liming cost for SA canola growers
Active pesticide	kg	2	
Tractor, low population area, per MJ fuel input	MJ	2123	Total of 55L per ha taken from soybeans
Outputs			
Dinitrogen monoxide	kg	0.526	From NGGIC 2007 and SoEC 2006 for soil disturbance
Lupins	ton	1.46	

5.5.3.1 Crude Canola Oil Refining

The crude canola oil from the extraction process contains phosphatides, gums and other colloidal compounds, which can cause problems through settling during storage. A steam refining process, during which 2.5% of the oil is lost as a solid waste, removes them. Process data is shown in Table 5.10.

Table 5.10: Process input and outputs for oil extraction of canola

Inputs	Unit	Value
Crude Oil	kg	1000
Electricity[1]	kWh	10
Steam (natural gas fired)[2]	kg	80
Outputs		
Refined Oil[1]	kg	975
Solid Waste[1]	Kg	25

Notes: [1] From rapeseed data (Ceuterick and Spirinckx, 1999) [2] From rapeseed data (Ceuterick and Spirinckx, 1999) based on 2.5% of energy input as steam with an energy density of 3.64 MJ/kg
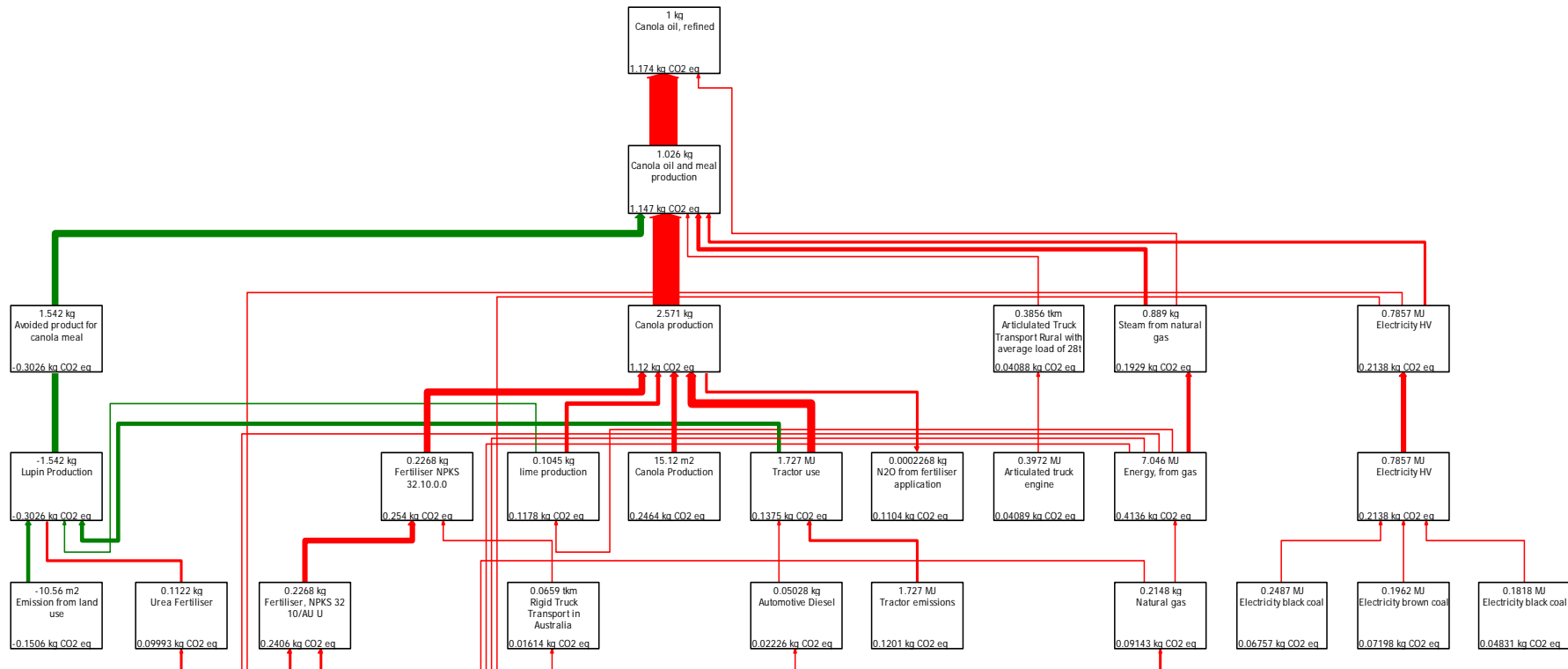
Figure 5-6: Process network showing greenhouse gas emissions in refined canola oil production. Upper values show total flow, lower values show cumulative greenhouse gas emissions. Only processes with above 1% contribution to cumulative greenhouse gas emissions are shown on tree**.**

6   TALLOW

Meat rendering is the processing of carcass waste from the meat industry. The process involves crushing the raw material, followed by the indirect application of heat. This evaporates the moisture and enables the fat, known as 'tallow', to be separated from the high-protein solids, known as 'greaves'. Pure tallow is a creamy-white substance. The greaves are pressed, centrifuged or subjected to a process of solvent extraction to remove more tallow, before being ground into (MBM) meat and bone meal (Matravers 2000).

According to the UK report of Matravers (2000), most rendering plants were 'dry rendering' (atmospheric) batch processors up until the 1960s. From the 1970s onwards, a variety of continuous rendering systems became available. They all use heating, separation and cooling on a continuous flow basis - essentially, raw material was fed in one end of the cooker and the finished product ejected out the other. Solvent extraction appears to have fallen out of favour in most countries due to the cost and hazards.

6.1   Life Cycle Inventory Data

6.1.1   Allocation Issues for Biodiesel from Tallow

The main products from the meat industry are hides, offal, meat and bone meal and tallow. Of the value of slaughtered animals, 89% comes from the meat, with the remaining 11% from co-products. Of this, skins and hides make up 6%, offal 4% and other rendered products, including bone meal and tallow, the remaining 1% (MLA 2007). These co-products deliver a return of around $1.7 billion per annum (MLA 2007). This is for all livestock; the majority of tallow comes from rendered beef. As such about 3.6% of the value of slaughtered cattle is from rendered products, with a full 20% from all co-products.

Tallow is used directly in animal and bird feed, as well as in cooking (generally as "lard"). It is also used to produce oleochemicals, which are then used to make (or assist in the production of) products as diverse as soaps, rubber, textiles, cosmetics, plastics, racket strings and lubricants. Due to health concerns over issues such as BSE (bovine spongiform encephalopathy, commonly known as "mad cow disease") and cholesterol, the amount of tallow used in food and animal feed has dropped over the last decade, with a corresponding rise in its use in derivatives.

There are two possible approaches to determining the impacts from increasing the use of tallow for biodiesel. One is to assume that increased demand for tallow will marginally increase the demand and consequent production of beef products in general. This is not very likely as beef demand is the main determining factor in beef cattle production (assuming this increase is linked to the economic value of the co-products, this is referred to as an economic allocation of co-products).

The second approach is to assume that tallow will be taken from other current users of tallow to meet the demand for tallow in biodiesel. These other uses include soap and cosmetic applications and use in animal feedstocks. Many vegetable oils can be used in place of tallow for the soap and for cosmetic purposes, and are assumed to be the most likely replacement for displaced tallow. Akaike (1985) suggests that tallow is the most competitive fat to palm oil in industrial applications.

The impact of diverting tallow to biodiesel is therefore modelled as the production of palm oil to replace tallow displaced into biodiesel as shown in Figure 6-1. The LCA Standards (International Standards Organisation, 1997) refer to this type of modelling as system boundary expansion, which avoids allocation between the different beef co-products.
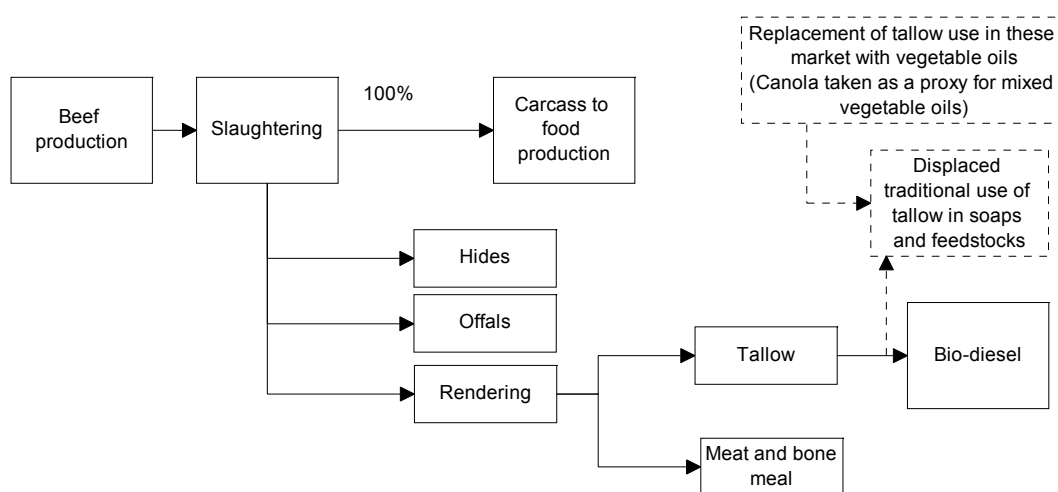
Figure 6-1: Allocation of beef impact with system boundary expansion to include implications of using tallow in biodiesel production

The alternative approach, mentioned above, is the economic allocation of emissions between the different co-products. Table 6.1 outlines estimates of the prices per head of beef for different products and co-products with the yield of production and the allocation percentage used in the study.

Table 6.1 details the value and allocation percentage for rendering products showing that tallow represents 45% of the economic value of rendering products, which equates to 1.6% of total beef value. This leads to an allocation of beef production impacts to tallow as shown in Table 6.2.

The modelling of beef production has been simplified in the study. From a greenhouse perspective the beef industry is responsible for a significant proportion of the greenhouse emissions due to methane from enteric fermentation, and N_2O from faecal matter and urine. Due to its importance, these emissions are included in the beef (and therefore, in part, in the tallow) production inventory.

Table 6.1: Allocation of beef products and co-products

	Average yield per kg of beef cattle	Average value of product per head of cattle (A$)	Allocation %
Beef Product	0.55^3	800^1	80.2%
Hides	0.060	90^2	9.1%
Render Products	0.292^2	36^2	3.6%
Offals	0.098^2	71^2	7.1%

[1] At an estimated US$400 per head
[2] Averaged across for Australian beef types (Prime Steer, US Cows, Japan Grass Fed Steer, Japan Grain Fed Steer) from MLA (2000)
[3] Estimated meat yield of 55%

Table 6.2: Allocation of rendering products based on economic value

	Average yield (kg per kg rendered feedstock)	Average price per head of cattle (A$)	Allocation %
Tallow	0.54	16.23^1	0.45
Meat and Bone Meal	0.46	19.76^1	0.55

[2] Averaged across for Australian beef types (Prime Steer, US Cows, Japan Grass Fed Steer, Japan Grain Fed Steer)
Source: Adapted from MLA (2000)
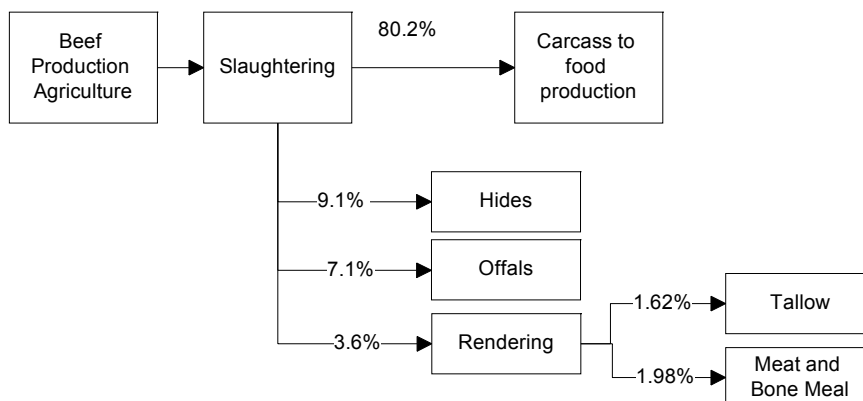
Figure 6-2: Summary of tallow production allocation from beef cattle agriculture

Although numerous animal products other than beef contribute to total tallow production, for reasons of simplicity this study will assume all tallow is derived primarily from beef products (the beef industry is estimated to provide 60% of the input to meat rendering).
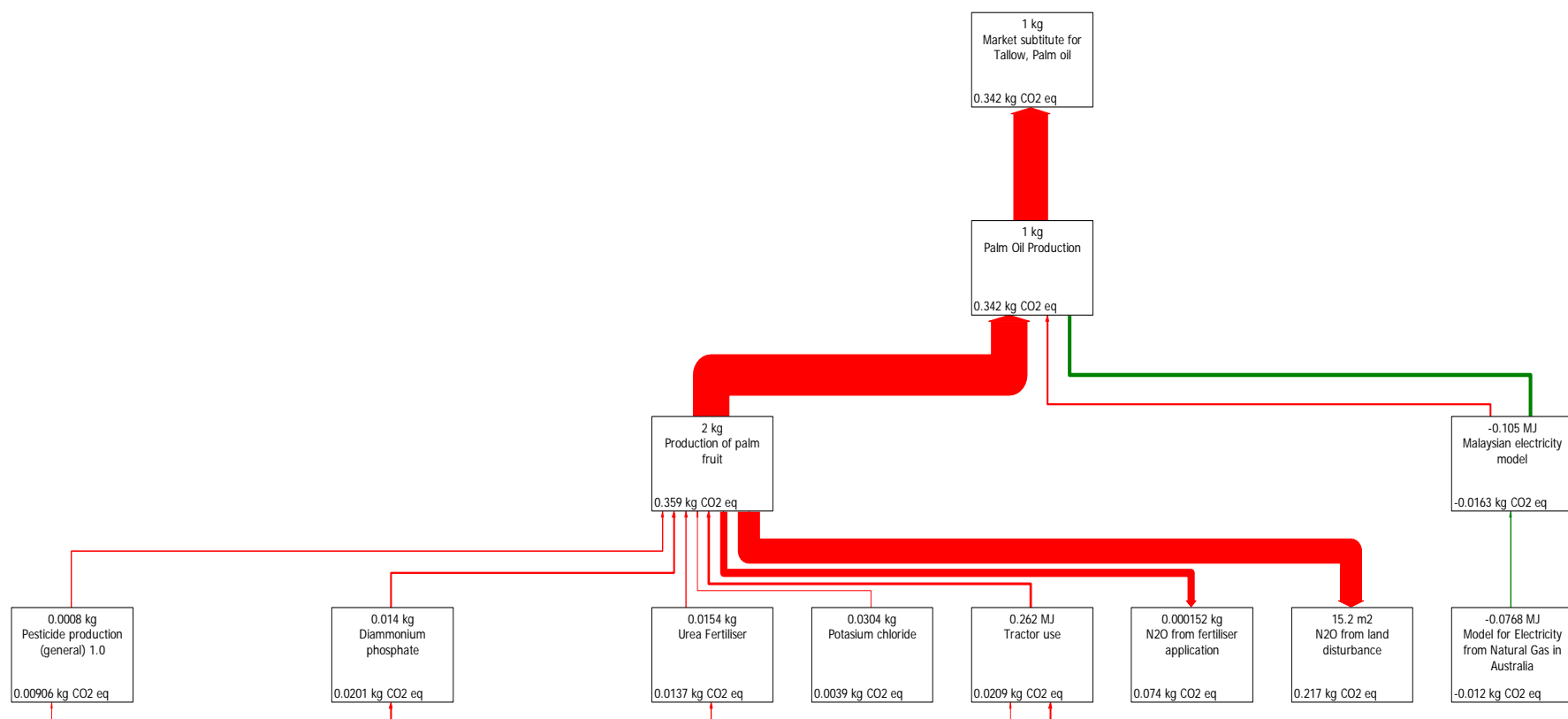
Figure 6-3: Process network showing greenhouse gas emissions in tallow feedstook life cycle with market substitution approach. Upper values show total flow, lower values show cumulative greenhouse gas emissions. Only processes with above 1% contribution to cumulative greenhouse gas emissions are shown on the tree.

6.1.2 Summary of Inventory for Tallow

The expanded system boundary approach is used in preference to the economic allocation, however with palm oil as the substitute for tallow, the uncertainty of palm oil production emissions is brought into the tallow biodiesel. For simplicity, only the palm oil from existing plantations is used, which assumes that this type of palm oil is used as the most likely substitute for palm oil. These values for palm oil from existing plantations are justifiable because they are also representative of a range of possible marginal oil suppliers (which could include other oil crops). All results for tallow should be viewed in the context of the possible risks and emissions from land clearing for palm oil production.

7   USED COOKING OIL

Cooking oils used for frying food have a limited life in food production due to contamination of the oil by food material. The disposal of used cooking oil into landfill is generally prohibited in Australia[13], so that at the present time cooking oil needs to be collected from the food industry for recycling or treatment for use in stockfeed. Possibilities for the processing of used cooking oils include:

- treatment and use in stockfeed in Australia

- use of oil for stationary energy production

- export to Asia for soap or stockfeed production

- use for production of biodiesel.

Information on used cooking oil collection indicates that large providers of oil are paid for their oil while small producers may have to pay to have their oil collected (Anthony, 2001).

There are a number of proposed or existing biodiesel plants that intend to make biodiesel from used cooking oil. They all appear to be small scale. In Victoria, Vilo Assets Management acquired from the Victor Smorgon group their used cooking oil business and a plant in Laverton North with a present capacity of 10 ML/a. According to Kenworth Trucks[14] the Biodiesel Industries of Australia operation at Rutherford near Newcastle produces 9 ML/a of vegetable oil-based biodiesel. Nevertheless, it would appear that used cooking oil is in the process of transformation from a waste product to a product with a commercial value so that it will no longer be treated as the former in life-cycle calculations.

7.1   Life Cycle Inventory Data

The difficulty in modelling the life cycle of used cooking oil is to identify how the use of used cooking oil leads to market substitution of other products (oils or stockfeeds) as the biodiesel industry has been responsible for increasing demand for used cooking oil, which has lead to increases in collection and capture of this oil. The allocation approach for "real" waste products which were previously not being utilised is to receive the waste with no prior envioronmental burden taken into account and then to add any processing of the waste for utilisation to the beneficial use of the waste, that is, to the biodiesel life-cycle. With no specific data on used cooking oil production, the processing impacts for refining crude canola oil have been used. These are shown in the canola section in Table 5.10 and illustrated in Figure 7-1.

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[13] For Victoria - Environment Protection (Prescribed Waste) Regulations 1998 S.R. No. 95/1998, Part B Prescribed Industrial Wastes Waste cooking oils unfit for their original intended use.
[14] http://www.kenworth.com.au/kenworth/kenworth_newsview.asp?id=77
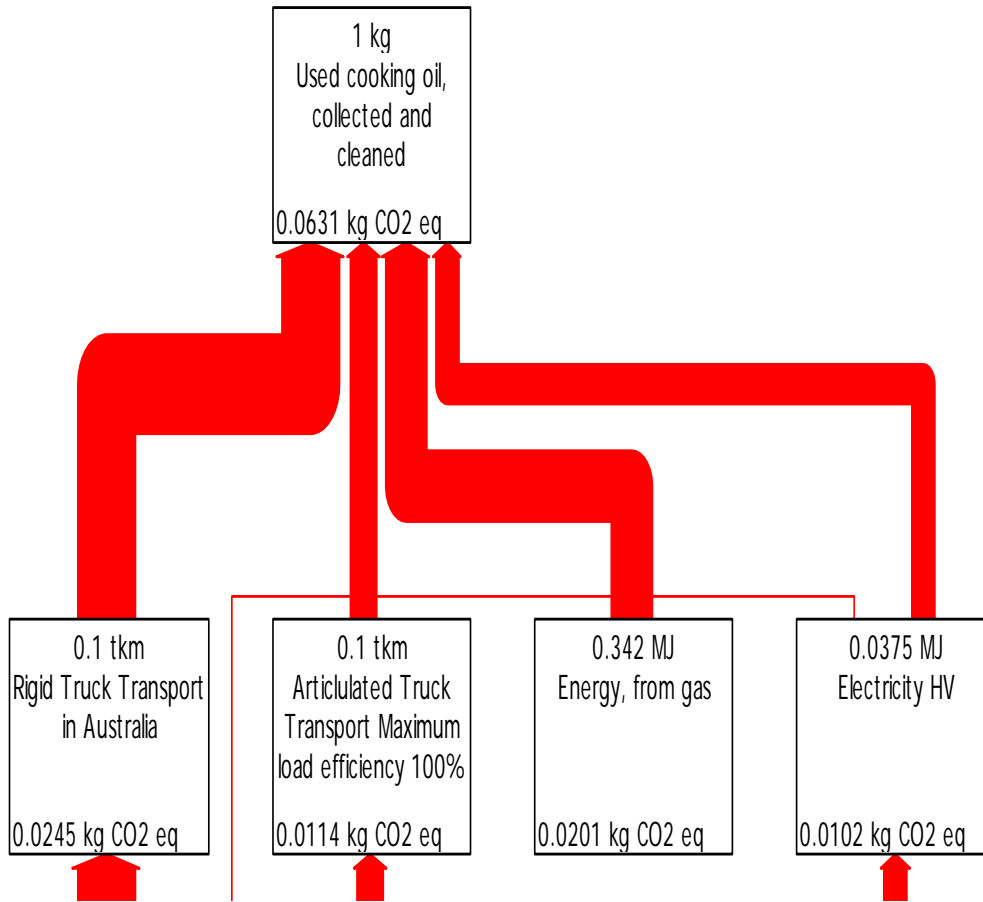
Figure 7-1: Process network showing greenhouse gas emission for used cooking oil feedstock
Upper values shows total flow, lower values show cumulative greenhouse emissions. Only
processes with above 1% contribution to cumulative greenhouse gas emissions are shown on the
tree.

8   PALM OIL

Unlike the other feedstocks discussed so far, palm oil is not produced in Australia. It is readily available from Indonesia and Malaysia, and it has been suggested that in the event of Australia not being able to provide sufficient local feedstock to meet biofuel requirements (especially if a high percentage biodiesel mandate was introduced) that imported palm oil would be the most likely feedstock to make up the difference. As such in this section we examine current and near-future plans for palm oil biodiesel in Australia, as well as issues involved with its production overseas.

8.1   Australian Palm Oil Use

On the basis of Table 4.1 the largest planned biodiesel producer in Australia is Natural Fuels Australia (http://www.naturalfuels.com.au/). Babcock & Brown Environmental Investments Limited has a 50% interest in Natural Fuels Australia. In July 2005 the company began construction of their biodiesel plant in the Northern Territory, near Darwin. The company has announced that they intend to use imported Malaysian palm oil.

Axiom Energy is a company based in Victoria that is following a strategy of locating facilities close-to-port rather than close-to-growing area. The company has an initial project involving a 150 ML biodiesel refinery located at the port of Geelong. Their biodiesel is to be produced initially from locally sourced tallow and imported palm oil, whose supply is contracted to two multinational commodity trading firms, Gardner Smith and Cargill Australia (Cargill will supply imported palm oil, while Gardner Smith will supply tallow sourced from Victoria). The plant will be constructed under a fixed price contract by Safer Energy LLC (Safer), who is supplying the technology for the biodiesel plant. Safer technology comes as a small modular expandable design. The company has an option over a site at Botany Bay in Sydney for a second plant. Axiom has entered alliances with diesel fleet operators Visy Industrial Packaging and Linfox to trial its biodiesel blend in their fleets[15].

(South) Australian Farmers Fuel (SAFF) is the largest retailer of biodiesel (as well as selling ethanol blends, and wholesaling) in Australia, with dozens of outlets across South Australia (and a few in NSW, Victoria and Western Australia) selling BD20 and BD100 biodiesel. As well as producing their own stock they also on-sell biodiesel from Australian Renewable Fuels in Adelaide. Their biodiesel is currently made mainly from tallow with some used cooking oil as well as virgin canola oil blended in to improve the cloud point. SAFF have a relationship with the Malaysian company Carotino[16], who own and manage 100,000 acres of oil palm plantations in Malaysia. SAFF currently are not using palm oil and do not intend to do so in the foreseeable future due to purely economic reasons; by the time palm oil makes its way into Australia it is currently more expensive than the locally available feedstock. However, SAFF have expressed the opinion that if the demand for biodiesel increases substantially the lack of local feedstock could force them to import palm oil in the future.

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[15] http://www.axiomenergyltd.com.au/news/
[16] http://www.carotino.com/

8.2   Palm Oil Overseas

Palm oil has traditionally been used as oil for cooking and salads, in addition to being a base and natural colourant for many foods, health foods and skin care products. It is also incorporated into animal feed, as are some of the by-products. It is only in the last few years with the explosion of interest in biofuels that palm oil has been considered as a feedstock for biodiesel.

The establishment and running of oil palm plantations in Malaysia and Indonesia has been shrouded with controversy for several decades now, as discussed at length in the references below, as well as in Gellert (2005).

Although there are many oil palm plantations that have been established on existing croplands, the ever-increasing demand for palm oil has led to 'slash and burn' techniques being used in lowland tropical rainforests. When this occurs a section of tropical rainforest (or peat swamp forest) is initially logged for useful timber. Then the remains are cleared by fire (Glastra 2002). An oil palm plantation is established (often after some time), which is economically productive for 20-25 years; at this time harvesting becomes uneconomic due to reduced production and increased tree height, and decreased soil fertility if expensive fertilisers are not employed (Härdter, 1997). However, many companies find it more profitable at this point to repeat the process, abandoning the existing plantation (Webster 2004) and making additional money by logging a new section of forest. Some companies do not even establish the plantation (Okamato 1999, Curran 2004); according to Potter (2005) by 2002 in East Kalimantan although 2 million hectares of land had been reserved for oil palm development, 3.1 million hectares of forest had been cleared ostensibly for plantation development, and only 303 thousand hectares had actually been planted.

The practises mentioned above have led to widespread deforestation across Indonesia and Malaysia. It has been estimated that in Malaysia nearly half of all new oil palm plantations involve deforestation, with 87% of deforestation between 1985 and 2000 due to oil palm expansion (Wakker, 2005).

This deforestation has, according to many sources, also led to a substantial reduction in biodiversity, with an 80-100% loss of species of mammal, reptiles and birds in an area of tropical rainforest converted to oil palm plantations (Webster 2004). Indonesia, despite occupying only 1.3% of the planet's land surface, is home to an estimated 11% share of the world's plant species, 10% of the mammal species and 16% of the bird species, the majority of which live in the tropical rainforests (Glastra 2002). This means that Indonesia now has the world's longest list of species threatened with extinction, including the orang-utan.

There are also concerns in relation to the treatment of the local inhabitants. An area may be assigned to a company for logging by the national government without any consultation with the people living there, who are then removed (occasionally forcefully). Recent reports to the UN suggest that 5 million people in Indonesia could be displaced due to biofuel production (Tauli-Corpuz 2007), whilst many others may end up working for subsidence wages on the plantation (Webster 2004, Wakker 2005). This can also occur when existing plantations are replanted, possibly with different crops; there are

reports of workers (especially women) who had established a comfortable standard of living, having built up a substantial degree of expertise harvesting rubber trees, whom were then forced into subsidence wages when the trees were replaced by oil palms. There are also reports that such workers are expected to apply dangerous pesticides without adequate safety precautions (Sangaralingam 2005).

It was for these reasons that the Roundtable on Sustainable Palm Oil (RSPO, http://www.rspo.org/) was established in 2002 with the support of the World Wildlife Fund (WWF), in order to ensure that palm oil was produced in a responsible manner.

Despite the advent of the RSPO, there is a belief that palm oil (or a substantial amount of it) is being produced in a manner that at the very least counteracts some of the major reasons for creating biofuels in the first place, i.e. sustainable production without sizeable non-renewable inputs (such as fossil-fuel based fertilizers and pesticides), and lowered emissions, especially of climate-affecting greenhouse gases including carbon dioxide.

Various reports tend to support this view. Tropical rainforests contain a substantial amount of carbon locked away in trees and soil. On average, conversion of tropical rainforest into an oil palm plantation will see a loss of 252 t C ha^{-1}, on the basis of the difference in above-ground vegetation mass (Palm 1999, IPCC 2000). If that is all converted into CO_2 it would lead to an additional 924 t CO_2 ha^{-1} being released into the atmosphere. This is 18.5 t a^{-1} when amortized over 50 years. These emissions more than balance the reduced emissions from using palm oil biodiesel rather than petroleum diesel as a fuel (Biofuelwatch 2007, Roland 2007).

A sizeable amount can also be lost from the soil in the form of carbon dioxide (and methane). This is especially the case for oil palm plantations based on former peat swamp forests, which are responsible for approximately 27% of all oil palm production in Indonesia, with a similar amount estimated for Malaysia (Hooijer 2006, Silvius 2007). Peat, an early stage in the formation of coal, contains a very high level of carbon. As such, it has been (and still is) used as a fuel for heating. When peat dries out and is exposed to air (as occurs when peat swamp forest is replaced by crops), it releases huge amounts of CO_2. The amount released is highly dependent upon what is done with the peat; values can be as 'low' as 15 t CO_2 ha^{-1} a^{-1} for peat covered by grassland and shrubs, but the worse-case scenario is for peat covered with large plantations including oil palms, where in the order of 70-100 t CO_2 ha^{-1} a^{-1} over the course of decades is emitted (Hooijer 2006, Ali 2006, Kasimir-Klemedtsson 1997).

In addition to this, clearing by fire has led to substantial fires burning uncontrollably in peat swamp forests; in 1997 it was estimated that peat and forest fires in Indonesia released between 0.81 and 2.57 Gt of carbon, equivalent to 13-40% of the amount released annually across the entire planet by burning fossil fuels (Pearce 2004). Some reports suggest that if CO_2 released due to drying peat swamp forests was taken into account, even ignoring that produced by fires, Indonesia would leap from its current position of 19th largest producer of carbon dioxide in the world[17] to 3rd largest, behind only China and the USA, with nearly a tenfold increase in emissions (Hooijer 2006, Silvius 2007, Sari 2007).

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[17] Millenium Development Goals Indicators from the United Nations at
http://millenniumindicators.un.org/unsd/mdg/SeriesDetail.aspx?srid=749

The increasing amount of emissions from biomass decay, especially that of peat, has recently (May 2007) been acknowledged by the IPCC. As Figure 8-1 shows, although greenhouse gas emissions into the atmosphere from deforestation have remained fairly steady over the last few decades, the amount from the decay of peat and other biomass has increased noticeably.
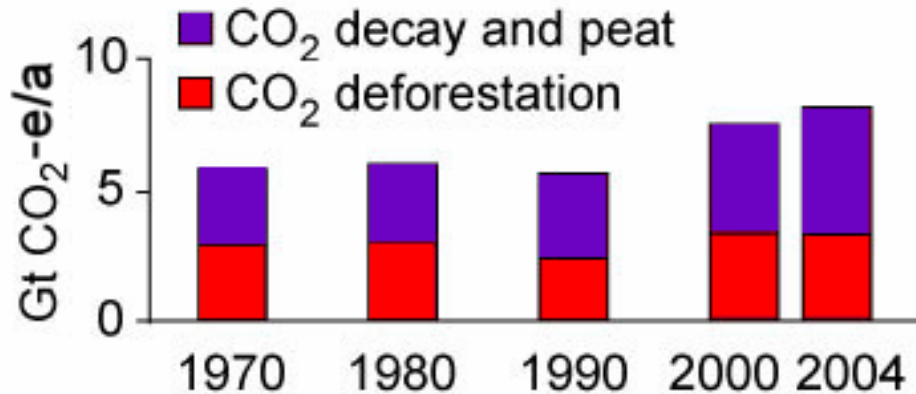
Figure 8-1: Global CO_2 emissions due to deforestation and biomass decay (including peat)[18]

Due to the importance of tropical peatlands as a carbon store and their potential impact on climate change the European Commission has set up an international project called CARBOPEAT to investigate these peatlands and reduce global carbon emissions over the next couple of years [19,20].

For the various reasons given above many EU member states and companies are reluctant to import palm oil from Malaysia and Indonesia for use as a biodiesel feedstock, regardless of whether it comes from a member of the RSPO. However, with growing demand for biodiesel, especially in Europe, with increasingly large suggested as well as mandatory targets, it has been observed that it is unlikely production will be able to meet future demand without the use of palm oil as a feedstock.

8.3   Life Cycle Inventory Data

In this document we have listed values for palm oil generated from three different types of plantations. In the case of "palm oil, existing plantations" we assume that the land was cleared a long time ago for crop use, and the palm oil plantation has possibly replaced an existing crop or plantation (e.g. rubber trees). In this case there has been no assignment of emissions due to land clearing. Several examples of plantations of this variety can be found in Thailand. As such the emissions associated with land clearing and with soil disturbance are not counted as greenhouse gas emissions under present methods of carbon accounting. For "palm oil from cleared rainforest" we assume that until recently the land was tropical rainforest, and that the trees were logged and removed before the plantation was established. We do not take into account clearing by fire, which in the past has been

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[18] IPCC Working Group III Mitigation of Climate Change, Fourth Assessment Report. Climate Change 2007: Mitigation of Climate Change available from http://www.mnp.nl/ipcc/
[19] A typical announcement of the formation of CARBOPEAT can be seen at http://www.feast.org/?articles&ID=547
[20] The home page for CARBOPEAT is at http://www.geog.le.ac.uk/carbopeat/wg/wg1home.html

the main method of clearing tropical rainforest. If this was taken into account there would be a larger amount of methane and NO_x generated, leading to a higher level of CO_2-equivalent emissions per unit of travel on biodiesel created from this type of palm oil. We also consider a worse-case scenario, which is "palm oil from cleared peat swamp forest". This assumes that the land being used for the palm oil plantation was recently a peat swamp forest and has just been cleared and dried out suitably. Once again we do not take into account clearing by fire. As noted above, in this case the normally high levels of emissions due to land clearing are relatively minor in comparison to the levels of emissions caused by the peat drying. It is estimated that 27% of palm oil produced in Indonesia comes from cleared peat swamp forests.

For modelling purposes an expected life of palm oil plantations derived from cleared forest needs to be assumed. Figure 8-2 shows the effects of different assumptions concerning the plantation life on the final greenhouse gas emissions per kg of biodiesel produced from palm oil. It also shows the chosen value of 50 years, which was selected as a conservative estimate. Note that these values are just for initial land clearing; they do not include emissions due to clearing by fire (which in this report we ignore), nor the emissions due to peat oxidation (which are given later on in the report).
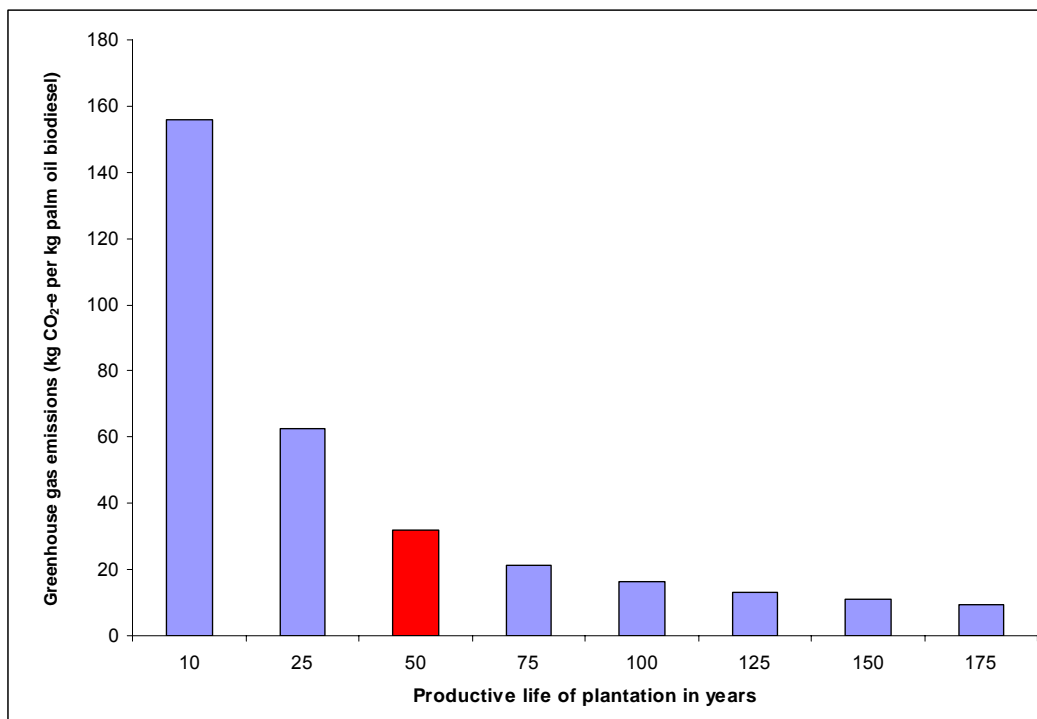
Figure 8-2: Change in greenhouse impacts of palm oil from rainforest clearing with change in assumed life of plantation (incorporating land use change only with no fire use)

8.3.1 Summary of input and output for palm oil production scenarios

Table 8.2 shows the input and output for palm fruit production under three different scenarios used in the LCA:

- on existing plantation cropland
- on cleared rainforest areas
- on cleared peat swamp forest areas.

The main differences between the scenarios are the CO_2 emission from land use change and peat emissions. The extraction of oil from palm fruit is common to all scenarios and its inputs and outputs are summarised in Table 8.1.

The resulting process diagrams for each palm oil production scenario are shown in Figure 8-3 to Figure 8-5.

Table 8.1: Input and outputs to palm oil production from palm fruit

Inputs	Flow	Unit
Palm fruit	5000	Kg
Electricity	320	MJ
Outputs		
Palm Kernal, cleared peat swamp forest	330	kg
Palm Oil, cleared peat swamp forest	2500	kg
Electricity	590	MJ
Emissions to air		
Carbon monoxide	5.64	kg
Nitrogen oxides	0.64	kg
Sulfur dioxide	0.02	kg

Table 8.2: Input and outputs to palm fruit production scenarios

Production scenario	Unit	Palm fruit (Malaysian Cropland)	Palm fruit (Malaysian Rainforest)	Palm fruit (Indonesia-peat swamp forest)
Inputs				
Occupation, arable, non-irrigated	m^2a	3.8	3.8	3.8
Active pesticide	kg	2	2	2
Diammonium phosphate, at regional store	kg	35	35	35
Urea, at regional store	kg	38.47	38.47	38.47
Potasium chloride, AU, at regional store	kg	76	76	76
Tractor, low population area, per MJ fuel input	MJ	656.2	656.2	656.2
Electricity	kWh	2	2	2
Outputs				
Product				
Palm fruit	tonne	5000	5000	5000
Emission to air				
Carbon dioxide, land use change[1]	tonne	0	67.7	67.7
Carbon dioxide, peat emissions	tonne	0		86
Nitrogen dioxide	kg	0.5	0.5	0.5
Sulfur dioxide	kg	0.2	0.2	0.2
Pesticides, unspecified	kg	0.1	0.1	0.1
Nitrogen volatilisation from fertiliser application	kg	0.38	0.38	0.38
Nitrogen volatilisation from land disturbance	ha	3.8	3.8	3.8
Emissions to water				
Pesticides, unspecified	kg	0.4	0.4	0.4
Phosphorus pentoxide	kg	2	2	2
Nitrogen, total	kg	5	5	5

1 Based on land use change difference with 50 years of production from palm oil plantation
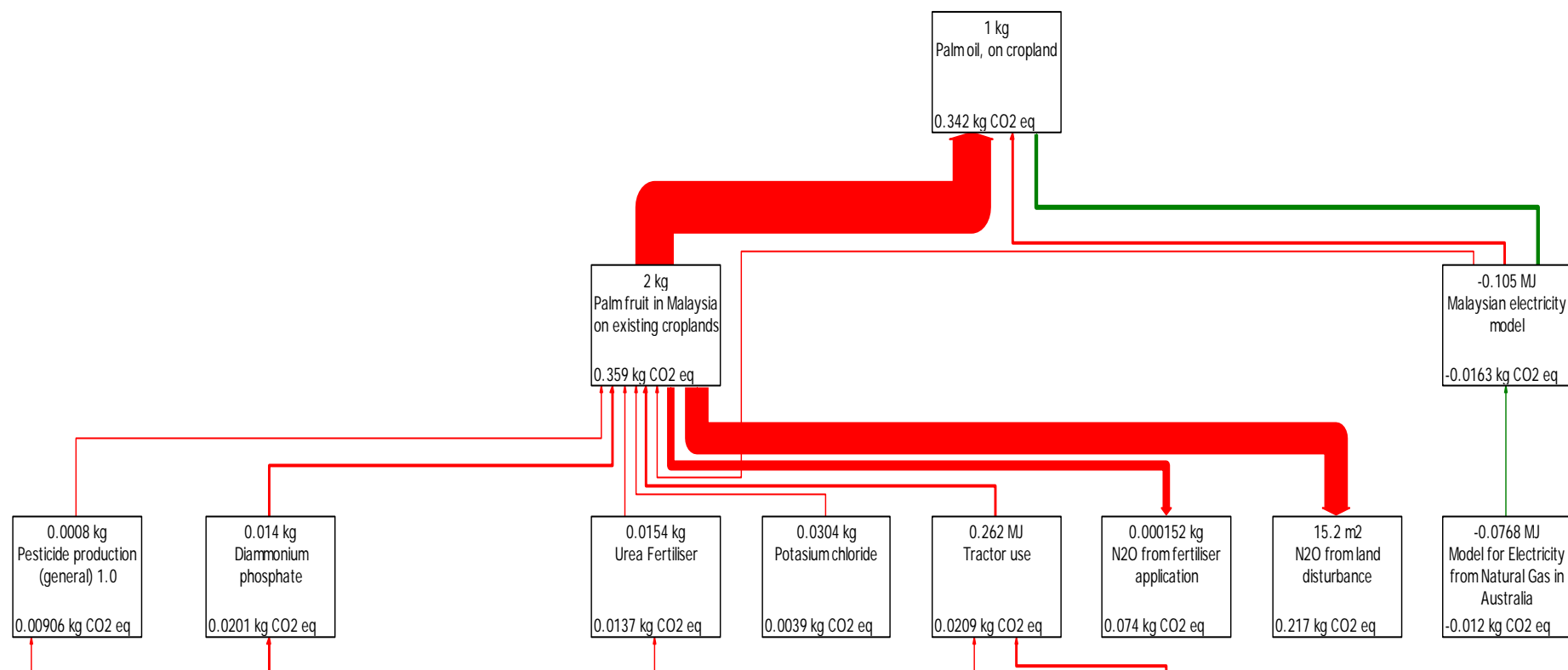
Figure 8-3: Process network showing greenhouse gas emissions for palm oil production on existing cropland. Upper values show total flow, lower values show cumulative greenhouse gas emissions. Only processes with above 0.5% contribution to cumulative greenhouse gas emissions are shown on the tree.
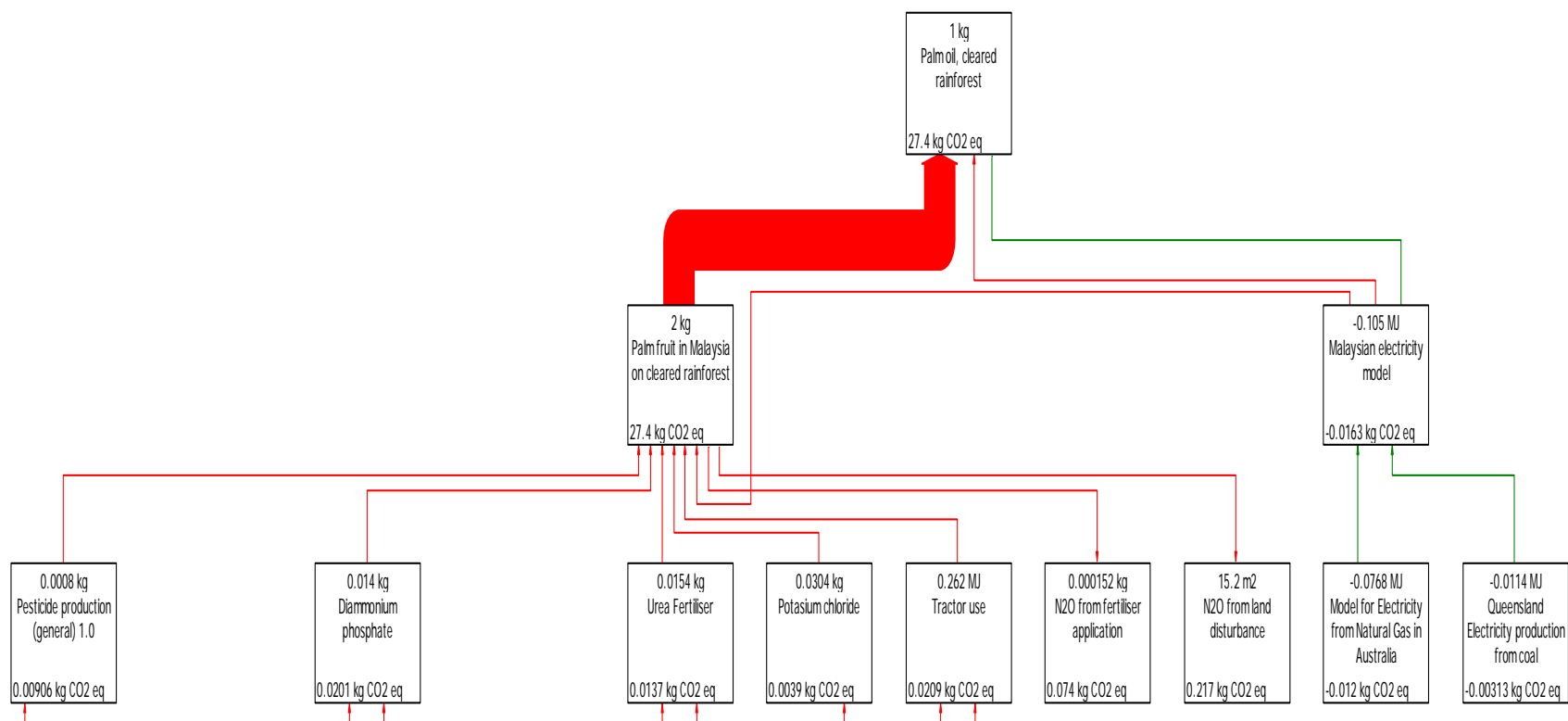
Figure 8-4: Process network showing greenhouse gas emissions for palm oil production on cleared rainforest land. Upper values show total flow, lower values show cumulative greenhouse gas emissions. Only processes with above 0.005% contribution to cumulative greenhouse gas emissions are shown on the tree.
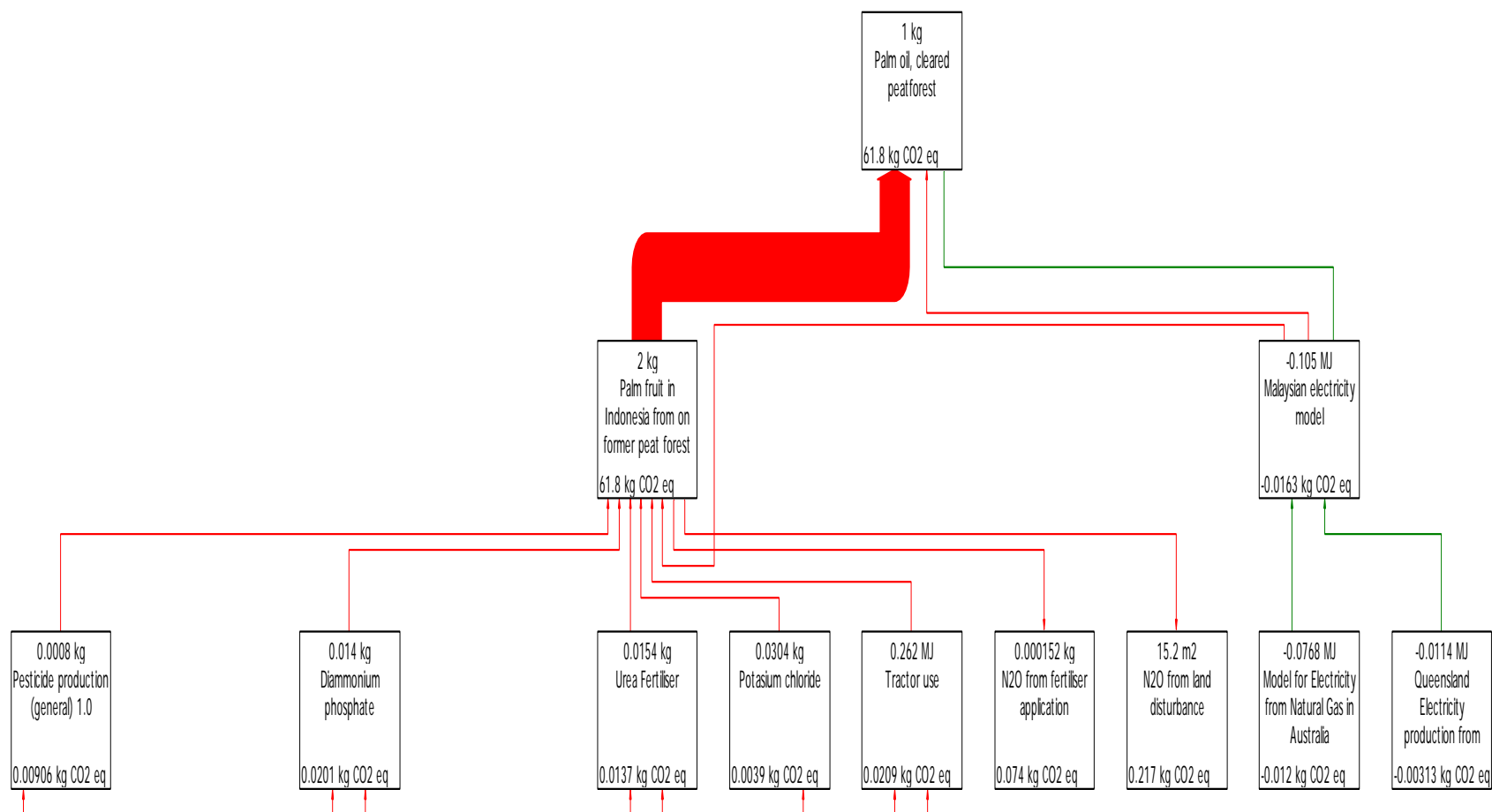
Figure 8-5: Process network showing greenhouse gas emissions for palm oil production on cleared peat swamp forest. Upper values show total flow, lower values show cumulative greenhouse gas emissions. Only processes with above 0.005% contribution to cumulative greenhouse emissions are shown on the tree.

9   DIESEL

Two types of diesel are modelled in this study:

- Ultra low sulfur (ULS) diesel, nominally at 50 ppm sulfur, based on average Australian diesel production data, but assumed to be transported from Caltex's Kurnell refinery.

- Extra low sulfur (XLS) diesel, nominally at 10 ppm sulfur, based on production at Caltex's Lytton refinery.

9.1   Life Cycle Inventory Data

The ULS diesel is modelled from a variety of public data sources as follows:

- Production data on fuel mixes produced in Australian refineries is from ABARE (ABARE 2006).

- Direct fuel use in refineries and oil and gas production, associated emissions and fugitive emissions are taken from the National Greenhouse Gas Inventory (ABARE 2006, DEW Australian Greenhouse Office 2006).

- Electricity use in refineries is taken from the ABARE energy accounts (Australian Bureau of Agricultural Research Economics 2005).

- Additional refinery processing to produce ULSD instead of conventional or low sulfur diesel is taken from the Comparison of Transport Fuels (Australian Bureau of Agricultural Research Economics 2005, Beer 2001) which in turn was from industry information of expected processing requirements. This may still be needed as the assessed year for the diesel inventory is 2003-04, and most diesels at that time are assumed to be low sulfur diesel only.

- Shipping of domestic fuel is estimated from the National Greenhouse Gas Inventory and trucking is estimated based on typical distance from ports and refineries to the customers.

The resulting greenhouse impacts per 1000 litres of ULS diesel produced are shown in Figure 9-1. The main greenhouse impacts occur at the refineries, followed by oil and gas production and the shipping of crude oil.

For XLSD the refinery impacts have all been taken from the Caltex Lytton refinery, however crude oil and distribution data are the same as used for ULS diesel. The greenhouse impacts of XLS diesel are shown in Figure 9-2.
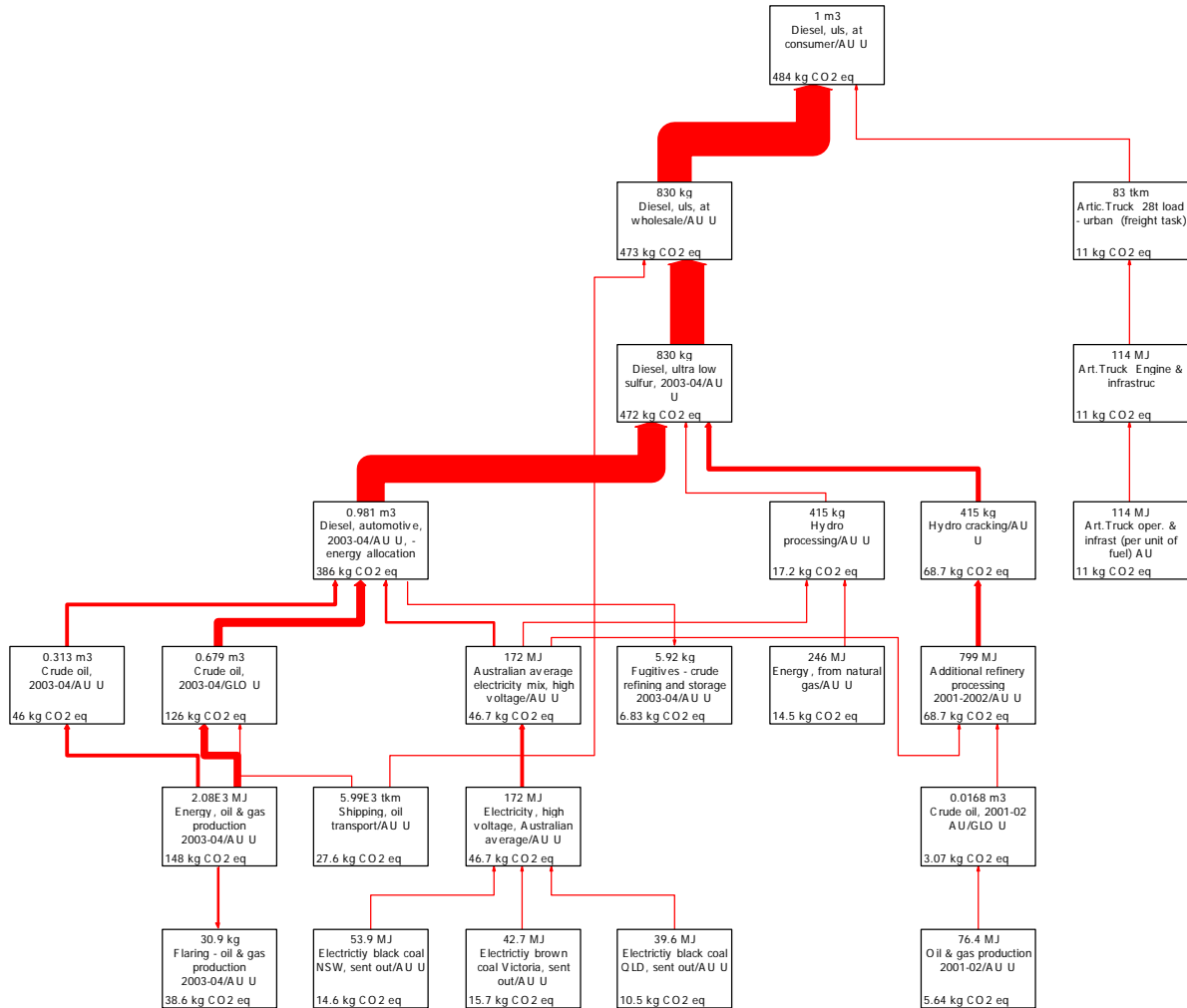
Figure 9-1: Process network showing main materials and energy flows and cumulative greenhouse gas impacts for 1000 litres of ULS diesel. Processes with greenhouse contributions less than 2% are not shown.
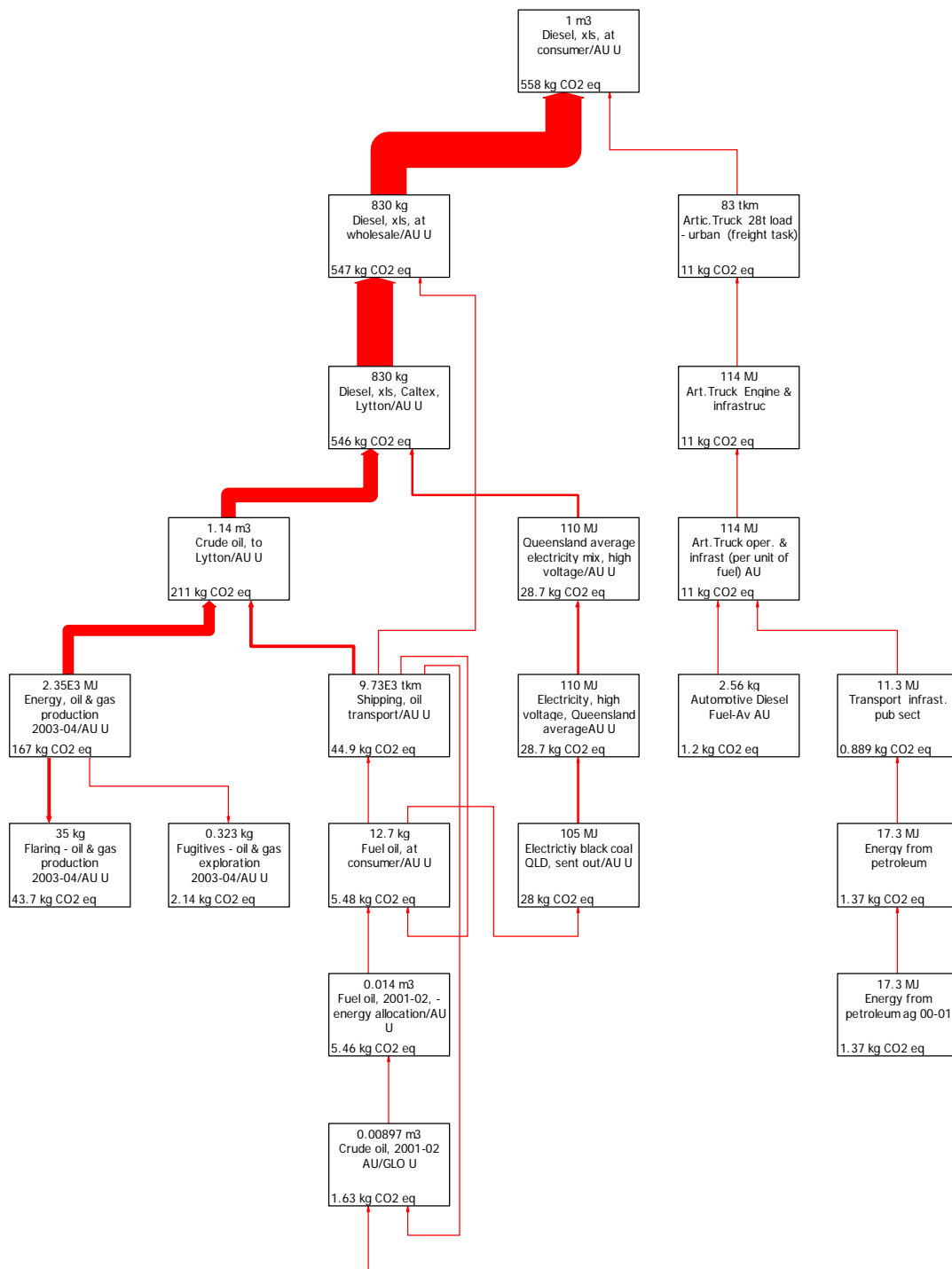
Figure 9-2: Process network showing main materials and energy flows and cumulative greenhouse gas impacts for 1000 litres of XLS diesel. Processes with greenhouse contributions less than 1% are not shown.

10 TAILPIPE EMISSIONS FROM BIODIESEL BLENDS

10.1 BD2 Studies

As noted in Section 2 this study was originally intended to analyse only 2% biodiesel blends (BD2). As part of this study we undertook a literature search to discover whether any experimental studies exist that have examined the emissions performance of BD2. The results are given in Appendix B – Literature Search on Biodiesel Emissions, but on more detailed examination there were only two studies that examined BD2 – as opposed to interpolating BD2 based on other results. As discussed below, neither study was particularly encompassing, nor was the second very rigourous.

Correa and Arbilla (2006) is a study of BD2, BD5 & BD20 that reports testing for emissions of mono- and poly-cyclic aromatic hydrocarbons (MAH and PAH) at a steady state engine speed of 25 Hz (1500 rpm). They only tested on 6-cylinder heavy diesel engines, which are basically the ones used for Brazilian buses. They measured a 2.7% reduction in PAHs for BD2 (6.3% for BD5, 17.2% for BD20), and a 4.2% reduction in MAHs for BD2 (8.2% for BD5, 21.1% for BD20). These results match the HC curve from US EPA (2002) report, in that the HC curves in US EPA (2002) deviate noticeably from a linear interpolation at low percentages.

Schumacher (2005) used a single vehicle (1996 Dodge pickup). They showed that BD2 provided suitable lubrication (when compared to sulfur diesel), but measured exhaust emissions showed no change in CO, HC or NO_x, although their test results showed considerable variability: two tests on CO were widely different (2nd test up to 40% lower readings than first), probably due to using two different instruments for testing. HC was also up & down depending upon the measurement.

They state that "black exhaust smoke was reduced", which would indicate PM reduction, but this is based on opacity rather than on measurement. They used an opacity meter on the soot, and it failed in one test. They noticed consistently less with biodiesel, but highly variable reductions (15-46%). So, their conclusions are that with BD2 lubrication is fine, PM is down, HC and NO_x are too close to call, and CO may be down slightly (although it is unclear whether this claim can be substantiated given the variability).

10.2 Tailpipe Emissions Studies

The use of BD1 and BD2 is recommended for lubricity; the sulfur in most diesels acts as a lubricant, so that LSD, ULSD and XLSD causes more wear on an engine. Many studies[21] indicate that adding even 1% biodiesel to diesel makes a dramatic difference, even improving the lubricity of diesel by up to 65%.

The results of the US EPA Biodiesel Emissions Analysis Program may be found at http://www.epa.gov/otaq/models/biodsl.htm. There is a bibliography of biodiesel studies, a biodiesel emissions database (that does not contain any information on BD2 or BD5

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[21] For example, http://www.eere.energy.gov/cleancities/blends/pdfs/37136.pdf

emissions, although it does contain data on BD10, BD20 and BD100 emissions) and a comprehensive report that summarised the results of biodiesel studies conducted up to 2002. This report (US EPA, 2002[22]) consists of a compilation of 39 different studies (extracted from 80 studies of which only 39 were considered to be credible); the majority were on BD20 and BD100, but there was also a fair number of BD50, BD40, BD30 and BD10 tests with a small number on BD70, BD80, BD60 and BD90. These results were collated and curves produced to indicate the variation in tailpipe emissions as the biodiesel content of the blend varies. Because of the paucity of BD2 data, the results of this study were used to determine the tailpipe emissions for all biodiesel blends.

10.3 The NO$_x$ Effect

The US EPA study (2002) notes that when BD100 is used in heavy vehicle engines, there is an overall decrease in particulate matter (PM) emissions and an *increase* in NO$_x$ emissions. Szybist (2005) note that the NO$_x$ effect is real and is due to an inadvertent advance of fuel injection timing as a result of the higher bulk modulus of compressibility of biodiesel blends. It is possible to retard the timing and thus reduce the NO$_x$, but then the PM goes up. This may explain why there are occasional studies that find that PM emissions increase when biodiesel is used.

Szybist (2005) ascribe the NO$_x$ increase to biodiesel made from soy – and claim that by using methyl oleate (i.e. biodiesel made from tallow or canola) the NO$_x$ increase could be eliminated. McCormick (2006) studied the effects of biodiesel blends on vehicle emissions and found NO$_x$ emissions from a variety of different engines to be extremely variable. They conclude that although some models produce a slight increase, others produce a slight decrease, and their results yielded an average *reduction* of 0.6% (+/- 2.0% for a 95% confidence interval) for BD20. This would result in an average reduction of about 3% for BD100.

As a result of these uncertainties, we have again used the NO$_x$ emission increases in the US EPA study (2002), although it may be more accurate to assume no overall changes in tailpipe NO$_x$ result from using biodiesel rather than normal diesel.

10.4 Tailpipe Emissions Analysis

The most comprehensive data set was the US EPA (2002) correlations based on over 100 sets of fuels emission data across a large range of biodiesel blends. This report developed correlations between percentage of biodiesel blended with diesel, and the percentage change in air quality emissions. These are described in Appendix A - Correlations described in EPA 2002, however the results of the correlation of biodiesel emissions are shown in Table 10.1 and Table 10.2 for oil- and animal-based biodiesel respectively.

The fuel usage comparison, expressed as brake-specific fuel consumption (BSFC) in US imperial units[23], between biodiesel and conventional diesel is provided by a regression formulae in the US EPA report as shown in Equation 10-1. The result is the mass of fuel

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[22] http://www.epa.gov/otaq/models/analysis/biodsl/p02001.pdf
[23] Conversion to metric units is 1 lb/(hp-hr) = 0.608 kg/ (kW-hr) = 0.1689 kg/MJ

in pounds used per brake horsepower hour which is converted to energy input per energy output.

$$\text{BSFC, lb/hp-hr} = \exp[0.0008189 \times (\text{vol\% biodiesel}) - 0.855578]$$

Equation 10-1: Brake-Specific Fuel Consumption

Emissions for canola are shown in Table 10.1.

Table 10.1: Tailpipe emissions (per MJ) for canola biodiesel blends with ULS diesel

Emission	Unit	ULSD	BD2 canola	BD5 canola	BD10 canola	BD20 canola	BD100 canola
Carbon dioxide, fossil	g CO_2	69.17	67.91	66.02	62.85	56.41	0.00
Carbon dioxide, biogenic	g CO_2	0.00	1.25	3.14	6.32	12.76	69.17
Nitrous oxide	g N_2O	0.00	0.00	0.00	0.00	0.00	0.00
Carbon monoxide	g CO	0.28	0.28	0.27	0.27	0.25	0.16
Methane	g CH_4	0.001	0.001	0.001	0.001	0.001	0.001
NMVOC	g HC	0.072	0.072	0.072	0.072	0.072	0.072
Oxides of nitrogen	g NOx	0.84	0.84	0.85	0.85	0.87	1.00
Particulate matter <10μm	mg PM10	28.29	27.77	27.01	25.79	23.52	11.25

The US EPA study (2002) did not include palm oil in their analysis. We were unable to find specific studies on emissions of biodiesel made from palm oil, so it is assumed in this study that the tailpipe emissions are the same as those of biodiesel made from canola oil.

The analysis in Table 10.1 was actually based on a fuel that the US EPA refers to as "clean diesel", which refers to diesel that has cetane number greater than 52, and total aromatics content less than 25% by volume, with a specific gravity of under 0.84. We equate this fuel to ULS diesel.

Emissions for tallow-based and used cooking oil-based biodiesel are shown in Table 10.2. Note US EPA (2002) assumes the same emissions from biodiesel generated from both these feedstocks.

Table 10.2: Tailpipe emissions (per MJ) for tallow and used cooking oil based biodiesel blends with ULS diesel

Emission	Unit	ULSD	BD2 tallow/UCO	BD5 tallow/UCO	BD10 tallow/UCO	BD20 tallow/UCO	BD100 tallow/UCO
Carbon dioxide	g CO_2	69.17	67.91	66.02	62.85	56.41	0.00
Carbon dioxide, biogenic	g CO_2	0.00	1.25	3.14	6.32	12.76	69.17
Nitrous oxide	g N_2O	0.00	0.00	0.00	0.00	0.00	0.00
Carbon monoxide	g CO	0.28	0.28	0.28	0.27	0.26	0.19
Methane	g CH_4	0.001	0.001	0.001	0.001	0.001	0.001
NMVOC	g HC	0.072	0.072	0.072	0.072	0.072	0.072
Oxides of nitrogen	g NOx	0.84	0.84	0.85	0.86	0.87	1.02
Particulate matter <10μm	mg PM10	28.29	27.82	27.14	26.04	23.98	12.39

The results of fuel usage calculations (based on Equation 10-1) combined with engine efficiency and brake efficiency calculations show in Table 10.3 that biodiesel is more efficient in combustion than diesel.

Table 10.3: Engine conversion efficiency of bio-diesel blends from US EPA correlations

	Blend %	lbs per (hp-hr)[1]	kg per MJ ([2])	Energy content of fuel[3] MJ/kg	MJ fuel used per MJ brake	Engine efficiency	Difference
Bio-diesel	100	0.461	0.078	36.65	2.857	35.00%	93.7%
Bio-diesel	20	0.432	0.073	41.30	3.015	33.17%	98.9%
Bio-diesel	5	0.427	0.072	42.17	3.041	32.88%	99.7%
Bio-diesel	2	0.426	0.072	42.35	3.046	32.83%	99.9%
Conventional diesel	0	0.425	0.072	42.46	3.050	32.79%	

[1] Calculated from Equation 10-1   [2] MJ/(hp-hr) = 2.68452, kg/lb = 0.453592
[3] Energy densities are lower heating value (LHV) and are taken from US EPA (2002).

11 LIFE CYCLE RESULTS

11.1 Ultra Low Sulfur Diesel

The life cycle results, combining the upstream emissions that are described in Sections 5 to 9, and the tailpipe emissions described in Section 10 are calculated in this Section for a vehicle representative of a truck undergoing the CUEDC drive cycle specified in the Diesel NEPM. Such a vehicle uses 10 MJ/km of fuel energy. The results, for biodiesel blended with ULSD, are presented for different biofuel sources and blends. Each of the major pollutant splits is also shown. The results for canola are given in tabular form in Table 11.1, and in diagrammatic form in Figure 11-1 to Figure 11-5. Palm oil results are given in Table 11.2 and Figure 11-6 to Figure 11-10 (from existing plantations), Table 11.3 and Figure 11-11 to Figure 11-15 (from recently cleared rainforest) and in Table 11.4 and Figure 11-16 to Figure 11-20 (from recently cleared peat swamp forest). Tallow results are given in Table 11.5 and Figure 11-21 to Figure 11-25. Used cooking oil results are given in Table 11.6 and Figure 11-26 to Figure 11-30. As noted previously none of the palm oil cases take into account land clearing by fire. Figure 11-31 to Figure 11-35 summarise the GHG emissions of BD2, BD5, BD10 and BD20 ULSD blends and BD100 respectively.

11.1.1 Canola biodiesel blends with ULS diesel

Table 11.1: Upstream and tailpipe emissions (per km)[1] for ULSD canola biodiesel blends

Impact category	Unit	ULSD	BD2	BD5	BD10	BD20	BD100
CO_2 (Upstream)	g CO_2	132	137	143	154	176	357
Methane (Upstream)	g CH_4	0.19	0.19	0.20	0.22	0.25	0.49
N_2O (Upstream)	g N_2O	0.001	0.005	0.011	0.020	0.040	0.197
Sequestration	g CO_2	0.000	0.000	0.000	0.000	0.000	0.000
Other	g CO_2-e	0.000	0.001	0.002	0.004	0.007	0.038
CO_2 (Tailpipe)	g CO_2	692	679	659	626	560	0
Methane (Tailpipe)	g CH_4	0.01	0.01	0.01	0.01	0.01	0.01
N_2O (Tailpipe)	g N_2O	0.016	0.016	0.016	0.016	0.016	0.015
CO (Upstream)	g CO	2.98	2.97	2.95	2.91	2.84	2.48
CO (Tailpipe)	g CO	2.81	2.78	2.75	2.69	2.57	1.79
NO_x (Upstream)	g NO_x	8.68	8.74	8.84	8.99	9.30	11.90
NO_x (Tailpipe)	g NO_x	8.40	8.43	8.47	8.53	8.67	9.84
NMVOC (Upstream)	g NMVOC	1.64	1.63	1.60	1.57	1.50	0.94
NMVOC (Tailpipe)	g NMVOC	0.72	0.71	0.71	0.71	0.71	0.69
Particles (Upstream)	mg PM10	290	296	306	321	355	684
Particles (non-urban)	mg PM10	0	1	1	2	3	13
Particles (Tailpipe)	mg PM10	283	278	271	260	238	119
Greenhouse equivalents total	g CO_2-e	834	827	815	797	759	433

[1] Per kilometre of rigid truck as used in the diesel NEPM tests
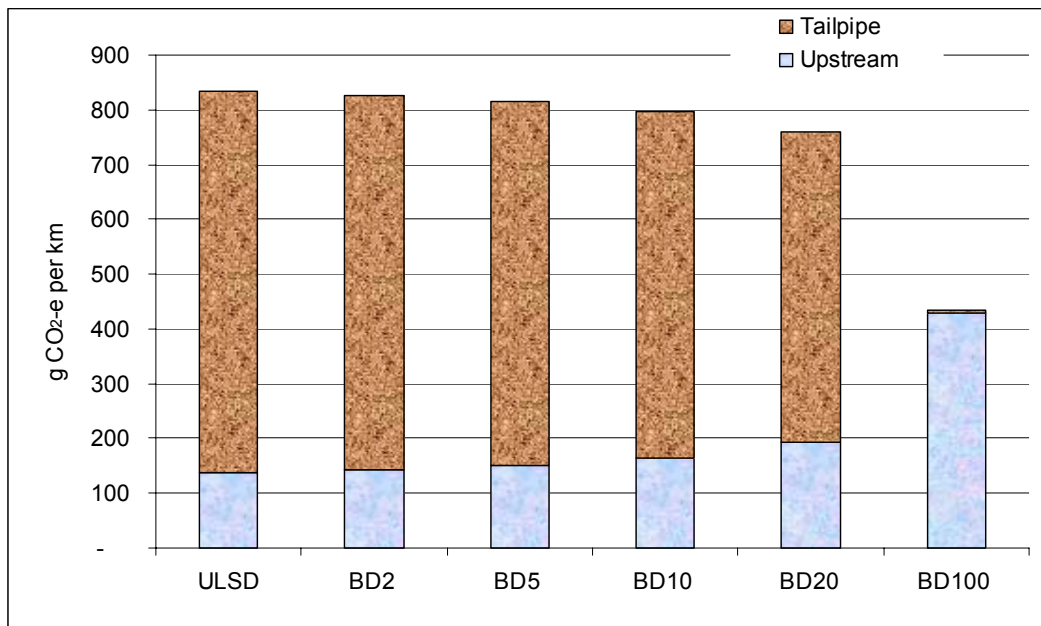
Figure 11-1: Canola ULSD biodiesel blends greenhouse gas emissions in g/km for a truck
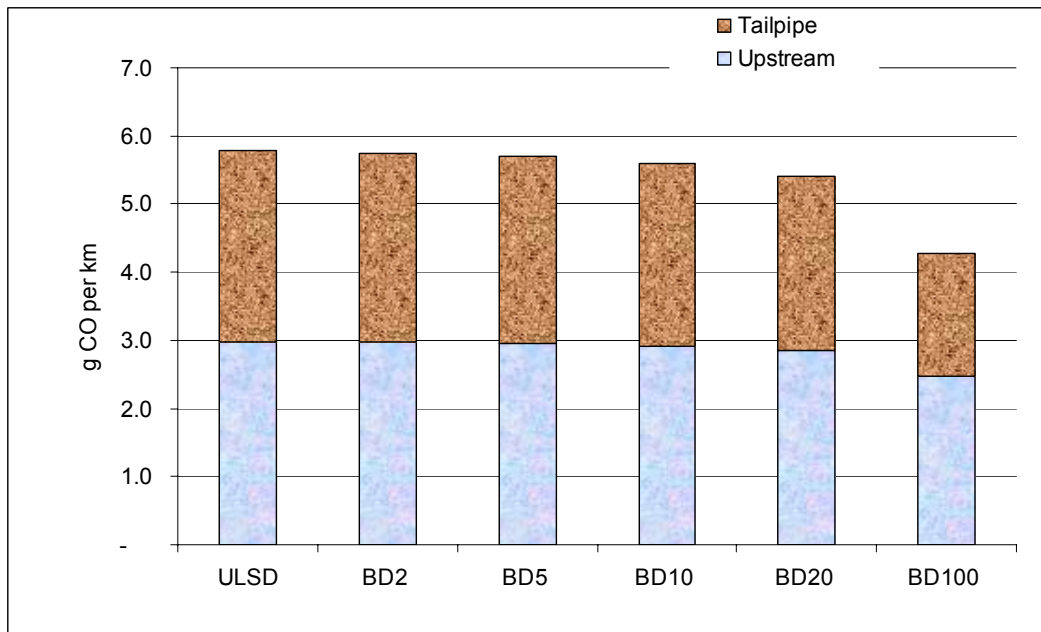
Figure 11-2: Canola ULSD biodiesel blends carbon monoxide emissions in g/km for a truck
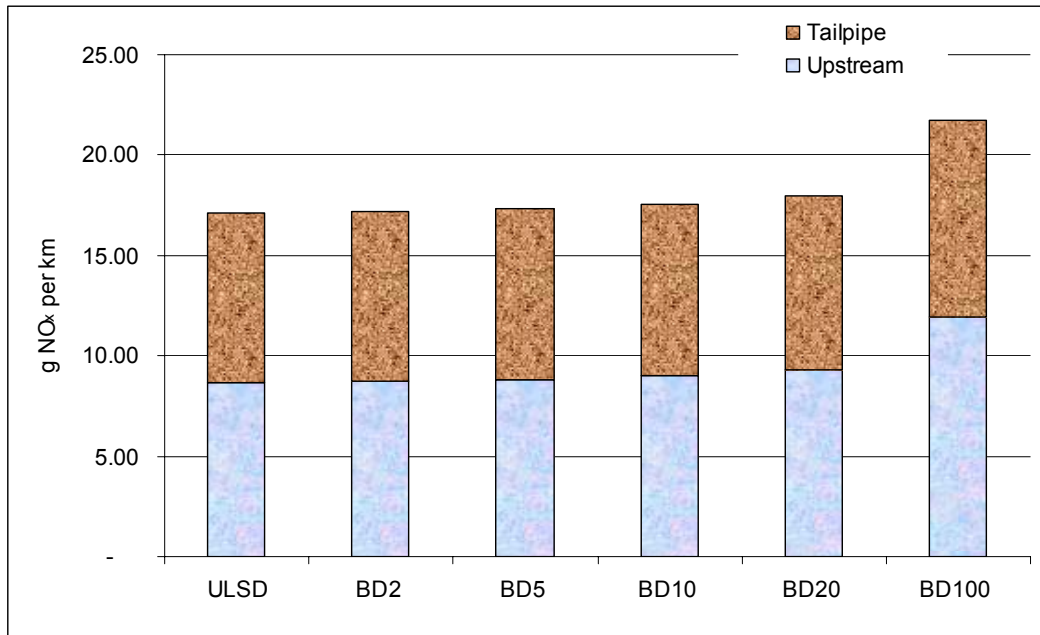
Figure 11-3: Canola ULSD biodiesel blends emissions of oxides of nitrogen in g/km for a truck
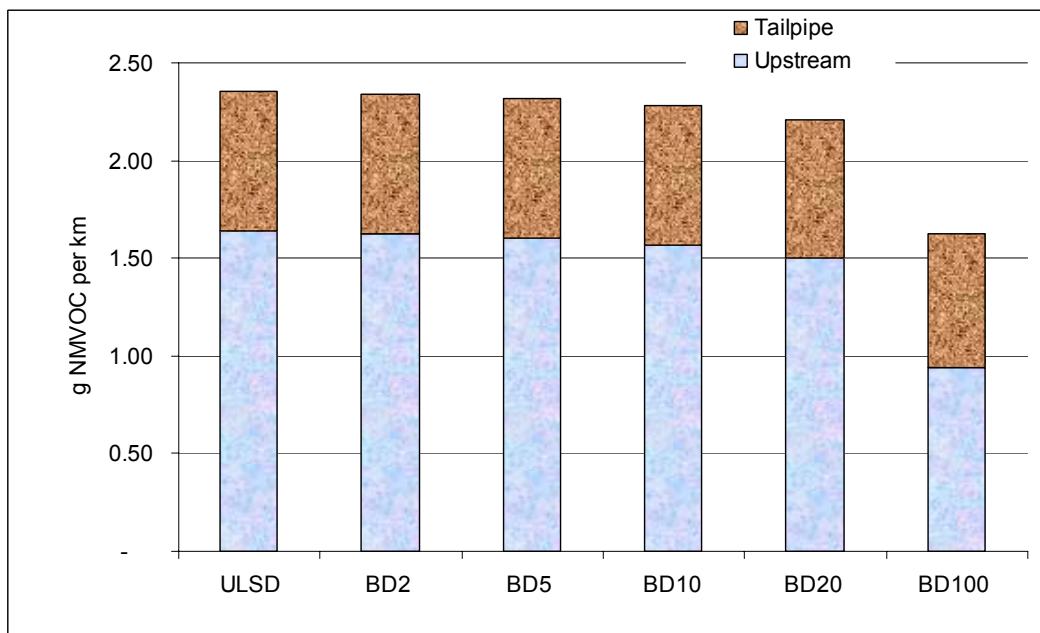
Figure 11-4: Canola ULSD biodiesel blends total non-methanic hydrocarbon emissions in g/km for a truck
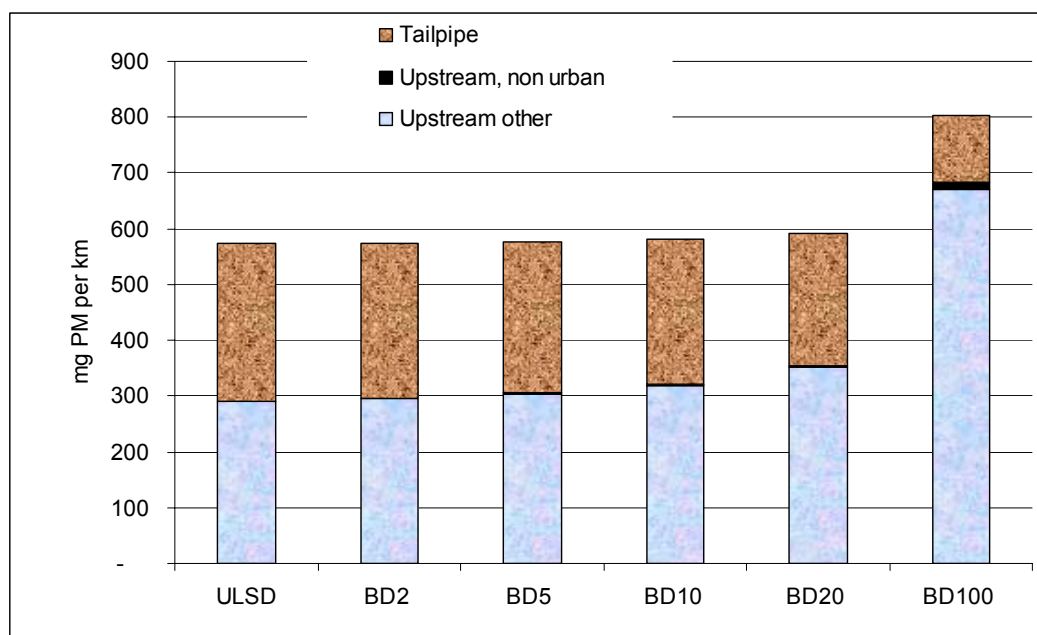
Figure 11-5: Canola ULSD biodiesel blends particulate matter (PM10) emissions in mg/km for a truck

11.1.2 Palm oil (existing plantations) biodiesel blends with ULS diesel

Table 11.2: Upstream and tailpipe emissions (per km) for ULSD biodiesel blends using palm oil from existing plantations

Impact category	Unit	ULSD	BD2	BD5	BD10	BD20	BD100
CO_2 (Upstream)	g CO_2	132	131	130	127	122	81
Methane (Upstream)	g CH_4	0.19	0.19	0.18	0.18	0.18	0.15
N_2O (Upstream)	g N_2O	0.001	0.007	0.015	0.028	0.055	0.275
Sequestration	g CO_2	0.000	0.000	0.000	0.000	0.000	0.000
Other	g CO_2-e	0.000	0.001	0.001	0.003	0.005	0.027
CO_2 (Tailpipe)	g CO_2	692	679	659	626	560	0
Methane (Tailpipe)	g CH_4	0.01	0.01	0.01	0.01	0.01	0.01
N_2O (Tailpipe)	g N_2O	0.016	0.016	0.016	0.016	0.016	0.015
CO (Upstream)	g CO	2.98	2.97	2.96	2.94	2.90	2.75
CO (Tailpipe)	g CO	2.81	2.78	2.75	2.69	2.57	1.79
NO_x (Upstream)	g NO_x	8.68	8.71	8.76	8.84	8.99	10.33
NO_x (Tailpipe)	g NO_x	8.40	8.43	8.47	8.53	8.67	9.84
NMVOC (Upstream)	g NMVOC	1.64	1.62	1.60	1.55	1.46	0.74
NMVOC (Tailpipe)	g NMVOC	0.72	0.71	0.71	0.71	0.71	0.69
Particles (Upstream)	mg PM10	290	287	282	275	261	208
Particles (non-urban)	mg PM10	0	0	1	1	2	7
Particles (Tailpipe)	mg PM10	283	278	271	260	238	119
Greenhouse equivalents total	g CO_2-e	834	822	803	771	708	175
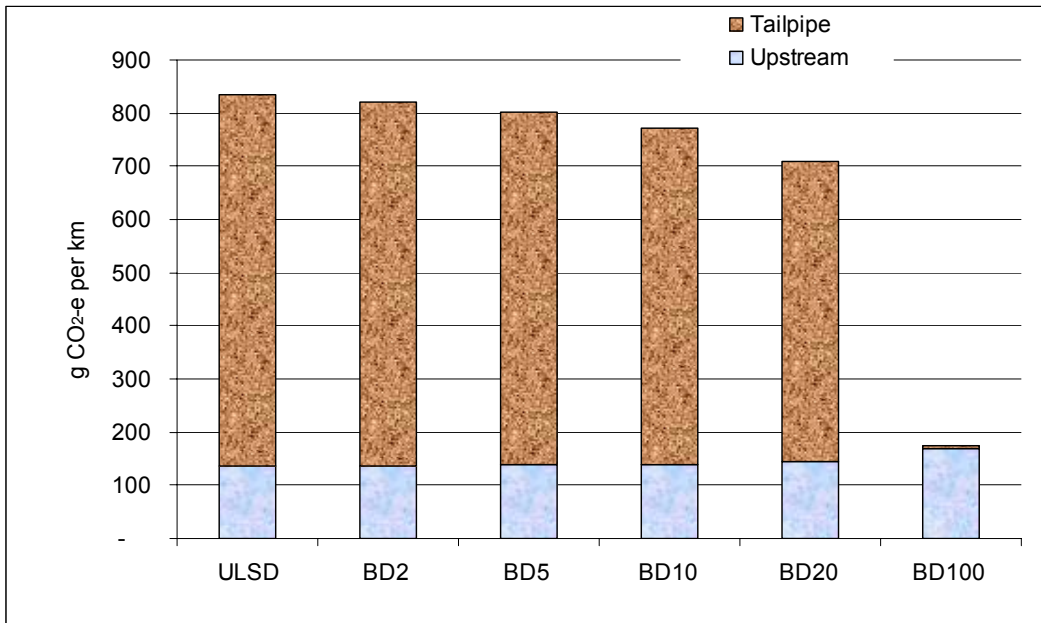
Figure 11-6: Palm oil (existing plantations) ULSD biodiesel blends greenhouse gas emissions in g/km for a truck
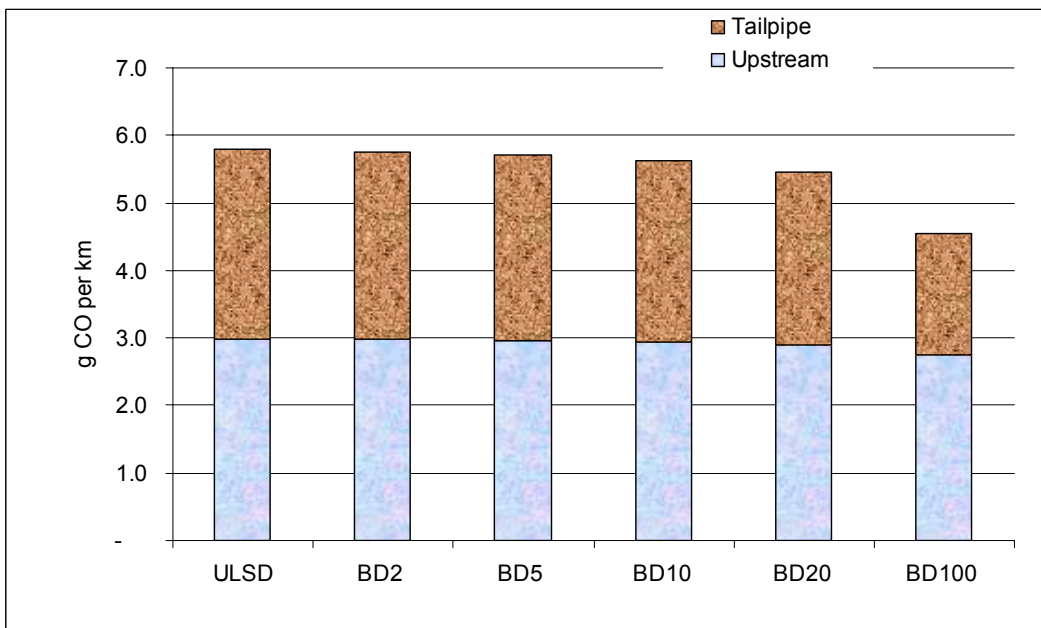
Figure 11-7: Palm oil (existing plantations) ULSD biodiesel blends carbon monoxide emissions in g/km for a truck

Figure 11-8: Palm oil (existing plantations) ULSD biodiesel blends emissions of oxides of nitrogen in g/km for a truck

Figure 11-9: Palm oil (existing plantations) ULSD biodiesel blends total non-methanic hydrocarbon emissions in g/km for a truck
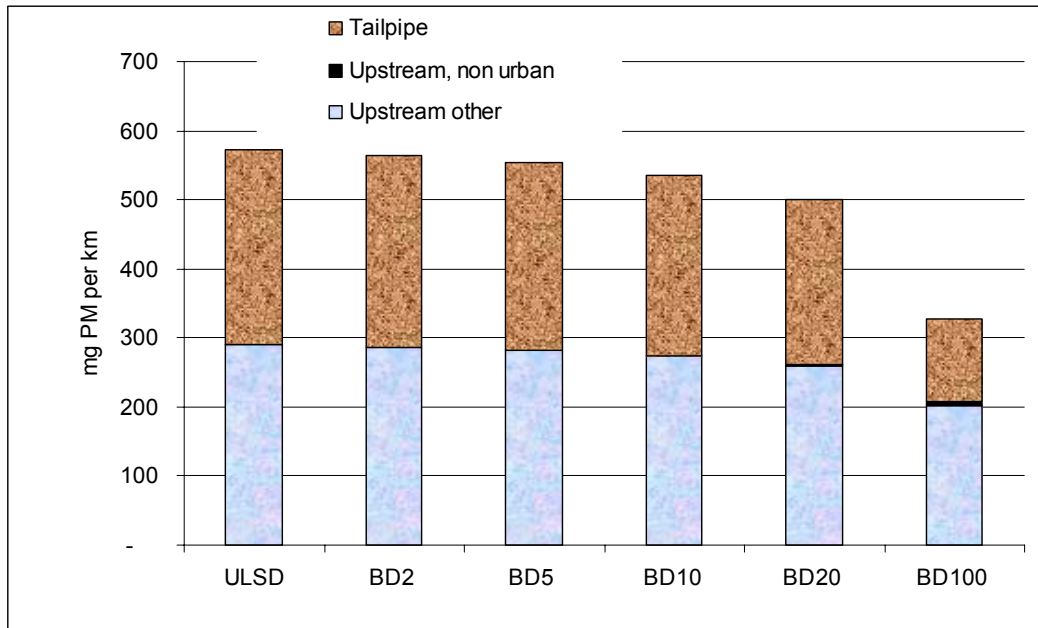
Figure 11-10: Palm oil (existing plantations) ULSD biodiesel blends particulate matter (PM10) emissions in mg/km for a truck

11.1.3 Palm oil (cleared rainforest) biodiesel blends with ULS diesel

Table 11.3: Upstream and tailpipe emissions (per km) for ULSD biodiesel blends using palm oil from cleared rainforest.

Impact category	Unit	ULS	BD2	BD5	BD10	BD20	BD100
CO_2 (Upstream)	g CO_2	132	286	516	901	1673	7981
Methane (Upstream)	g CH_4	0.19	0.19	0.18	0.18	0.18	0.15
N_2O (Upstream)	g N_2O	0.001	0.007	0.015	0.028	0.055	0.275
Sequestration	g CO_2	0.000	0.000	0.000	0.000	0.000	0.000
Other	g CO_2-e	0.000	0.001	0.001	0.003	0.005	0.027
CO_2 (Tailpipe)	g CO_2	692	679	659	626	560	0
Methane (Tailpipe)	g CH_4	0.01	0.01	0.01	0.01	0.01	0.01
N_2O (Tailpipe)	g N_2O	0.016	0.016	0.016	0.016	0.016	0.015
CO (Upstream)	g CO	2.98	2.97	2.96	2.94	2.90	2.75
CO (Tailpipe)	g CO	2.81	2.78	2.75	2.69	2.57	1.79
NO_x (Upstream)	g NO_x	8.68	8.71	8.76	8.84	8.99	10.33
NO_x (Tailpipe)	g NO_x	8.40	8.43	8.47	8.53	8.67	9.84
NMVOC (Upstream)	g NMVOC	1.64	1.62	1.60	1.55	1.46	0.74
NMVOC (Tailpipe)	g NMVOC	0.72	0.71	0.71	0.71	0.71	0.69
Particles (Upstream)	mg PM10	290	287	282	275	261	208
Particles (non-urban)	mg PM10	0	0	1	1	2	7
Particles (Tailpipe)	mg PM10	283	278	271	260	238	119
Greenhouse equivalents total	g CO_2-e	834	976	1189	1545	2259	8075
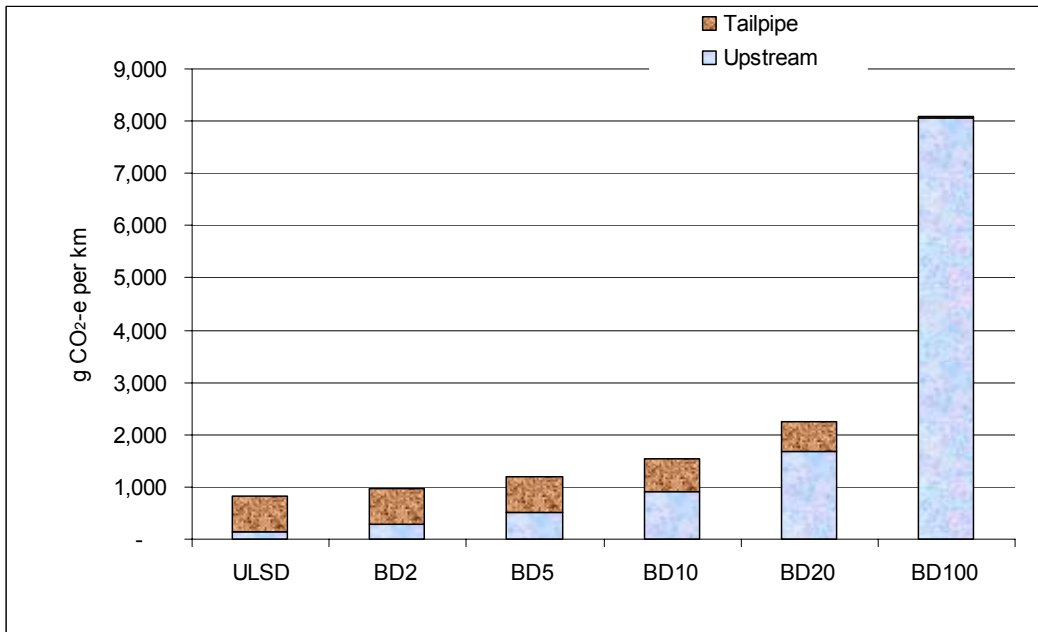
Figure 11-11: Palm oil (cleared rainforest) ULSD biodiesel blends greenhouse gas emissions in g/km for a truck
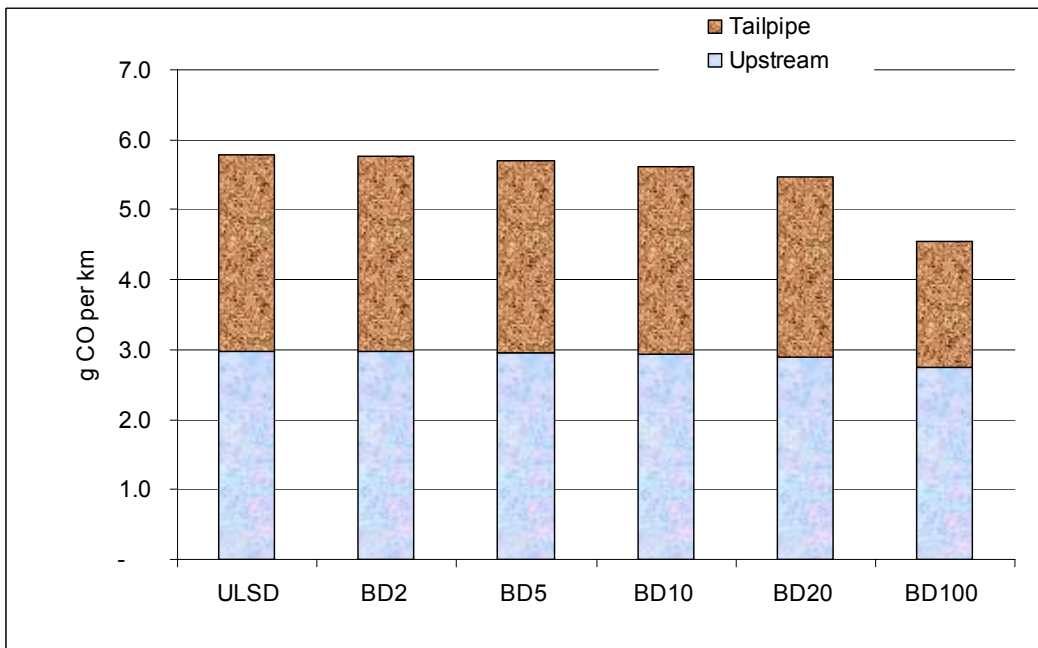
Figure 11-12: Palm oil (cleared rainforest) ULSD biodiesel blends carbon monoxide emissions in g/km for a truck

Figure 11-13: Palm oil (cleared rainforest) ULSD biodiesel blends emissions of oxides of nitrogen in g/km for a truck

Figure 11-14: Palm oil (cleared rainforest) ULSD biodiesel blends total non-methanic hydrocarbon emissions in g/km for a truck

Figure 11-15: Palm oil (cleared rainforest)-biodiesel blends particulate matter (PM10) emissions in mg/km for a truck

11.1.4 Palm oil (cleared peat swamp forest) biodiesel blends with ULS diesel

Table 11.4: Upstream and tailpipe emissions (per km) for ULSD biodiesel blends using palm oil from cleared peat swamp forest

Impact category	Unit	ULS	BD2	BD5	BD10	BD20	BD100
CO_2 (Upstream)	g CO_2	132	482	1007	1884	3642	18014
Methane (Upstream)	g CH_4	0.19	0.19	0.18	0.18	0.18	0.15
N_2O (Upstream)	g N_2O	0.001	0.007	0.015	0.028	0.055	0.275
Sequestration	g CO_2	0.000	0.000	0.000	0.000	0.000	0.000
Other	g CO_2-e	0.000	0.001	0.001	0.003	0.005	0.027
CO_2 (Tailpipe)	g CO_2	692	679	659	626	560	0
Methane (Tailpipe)	g CH_4	0.01	0.01	0.01	0.01	0.01	0.01
N_2O (Tailpipe)	g N_2O	0.016	0.016	0.016	0.016	0.016	0.015
CO (Upstream)	g CO	2.98	2.97	2.96	2.94	2.90	2.75
CO (Tailpipe)	g CO	2.81	2.78	2.75	2.69	2.57	1.79
NO_x (Upstream)	g NO_x	8.68	8.71	8.76	8.84	8.99	10.33
NO_x (Tailpipe)	g NO_x	8.40	8.43	8.47	8.53	8.67	9.84
NMVOC (Upstream)	g NMVOC	1.64	1.62	1.60	1.55	1.46	0.74
NMVOC (Tailpipe)	g NMVOC	0.72	0.71	0.71	0.71	0.71	0.69
Particles (Upstream)	mg PM10	290	287	282	275	261	208
Particles (non-urban)	mg PM10	0	0	1	1	2	7
Particles (Tailpipe)	mg PM10	283	278	271	260	238	119
Greenhouse equivalents total	g CO_2-e	834	1172	1680	2527	4228	18108
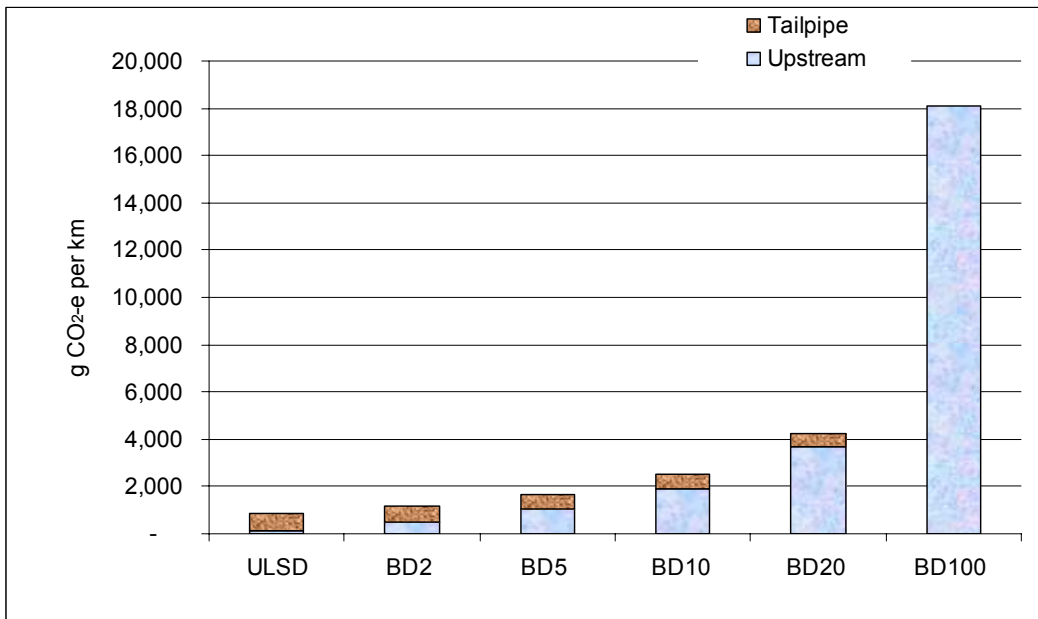
Figure 11-16: Palm oil (cleared peat swamp forest) ULSD biodiesel blends greenhouse gas emissions in g/km for a truck
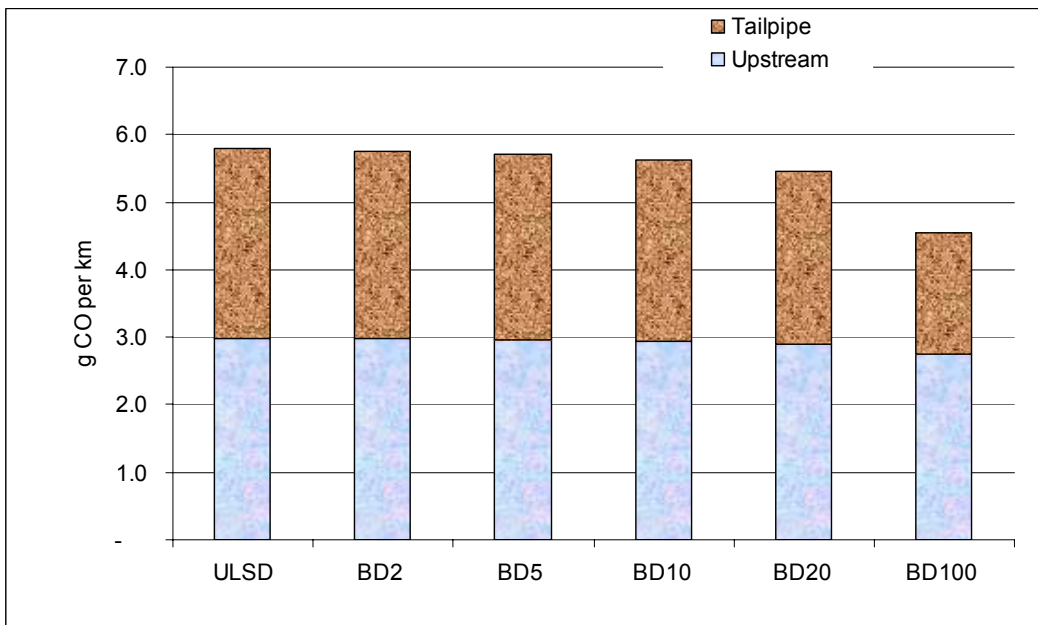
Figure 11-17: Palm oil (cleared peat swamp forest) ULSD biodiesel blends carbon monoxide emissions in g/km for a truck
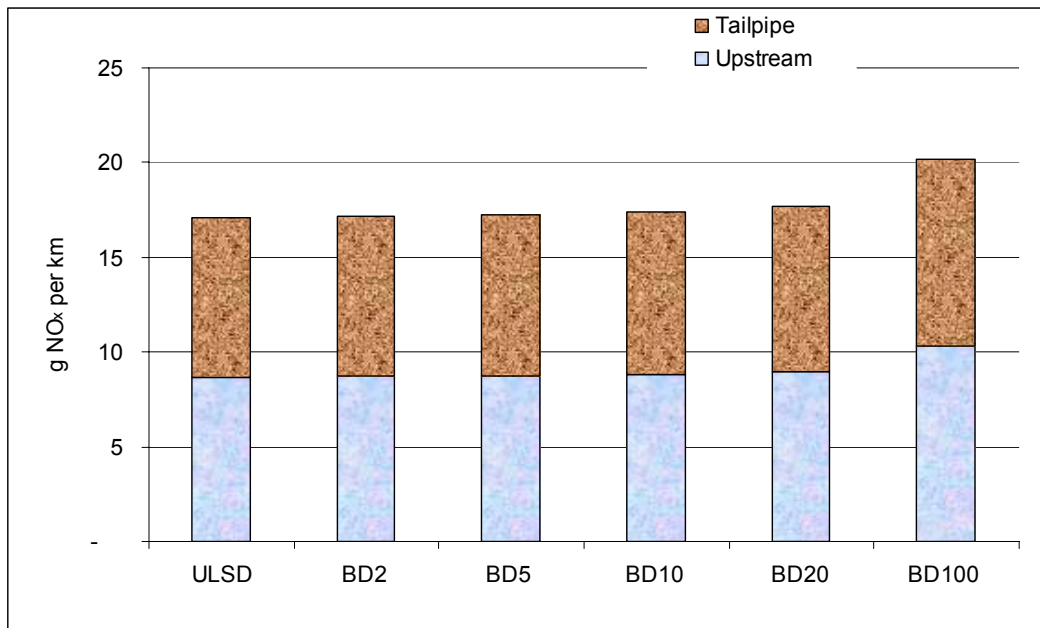
Figure 11-18: Palm oil (cleared peat swamp forest) ULSD biodiesel blends emissions of oxides of nitrogen in g/km for a truck

Figure 11-19: Palm oil (cleared peat swamp forest) ULSD biodiesel blends total non-methanic hydrocarbon emissions in g/km for a truck
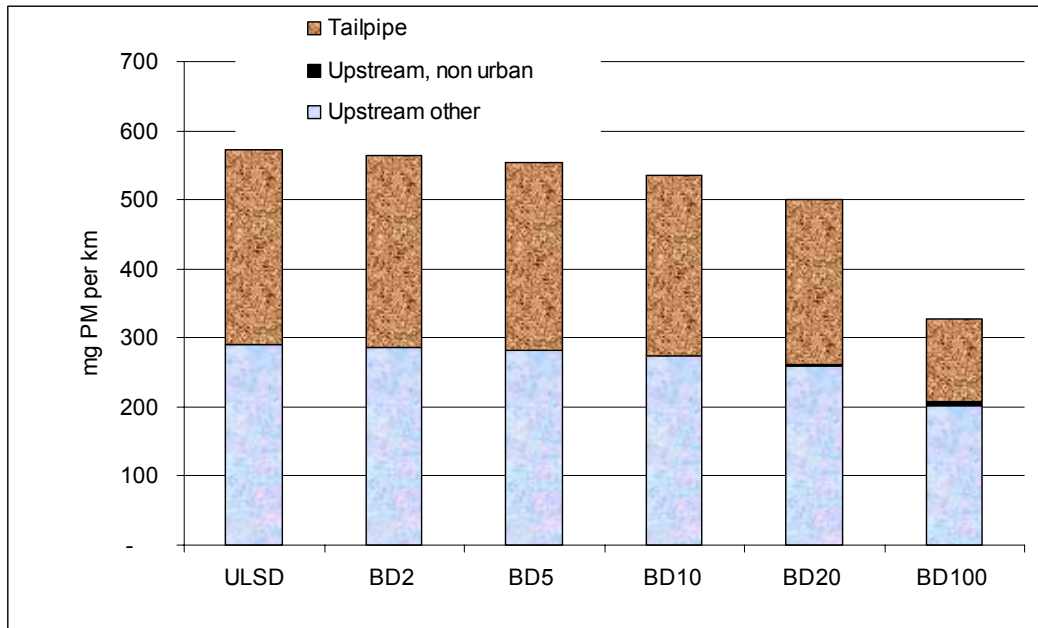
Figure 11-20: Palm oil (cleared peat swamp forest) ULSD biodiesel blends particulate matter (PM10) emissions in mg/km for a truck

11.1.5 Tallow biodiesel blends with ULS diesel

Table 11.5: Upstream and tailpipe emissions (per km) for ULSD biodiesel blends using tallow

Impact category	Unit	ULS	BD2	BD5	BD10	BD20	BD100
CO_2 (Upstream)	g CO_2	132	132	131	130	127	104
Methane (Upstream)	g CH_4	0.19	0.19	0.19	0.18	0.18	0.16
N_2O (Upstream)	g N_2O	0.001	0.007	0.016	0.032	0.062	0.312
Sequestration	g CO_2	0.000	0.000	0.000	0.000	0.000	0.000
Other	g CO_2-e	0.000	0.000	0.000	0.000	0.000	0.001
CO_2 (Tailpipe)	g CO_2	692	679	658	624	557	0
Methane (Tailpipe)	g CH_4	0.01	0.01	0.01	0.01	0.01	0.01
N_2O (Tailpipe)	g N_2O	0.016	0.016	0.016	0.016	0.016	0.015
CO (Upstream)	g CO	2.98	2.97	2.96	2.94	2.91	2.83
CO (Tailpipe)	g CO	2.81	2.78	2.74	2.68	2.55	1.74
NO_x (Upstream)	g NO_x	8.68	8.71	8.75	8.81	8.95	10.06
NO_x (Tailpipe)	g NO_x	8.40	8.42	8.46	8.51	8.62	9.55
NMVOC (Upstream)	g NMVOC	1.64	1.62	1.60	1.55	1.46	0.74
NMVOC (Tailpipe)	g NMVOC	0.72	0.71	0.71	0.71	0.71	0.67
Particles (Upstream)	mg PM10	290	287	282	274	260	203
Particles (non-urban)	mg PM10	0	0	0	0	1	1
Particles (Tailpipe)	mg PM10	283	278	271	259	237	115
Greenhouse equivalents total	g CO_2-e	834	822	804	773	712	209

Figure 11-21: Tallow ULSD biodiesel blends greenhouse gas emissions in g/km for a truck

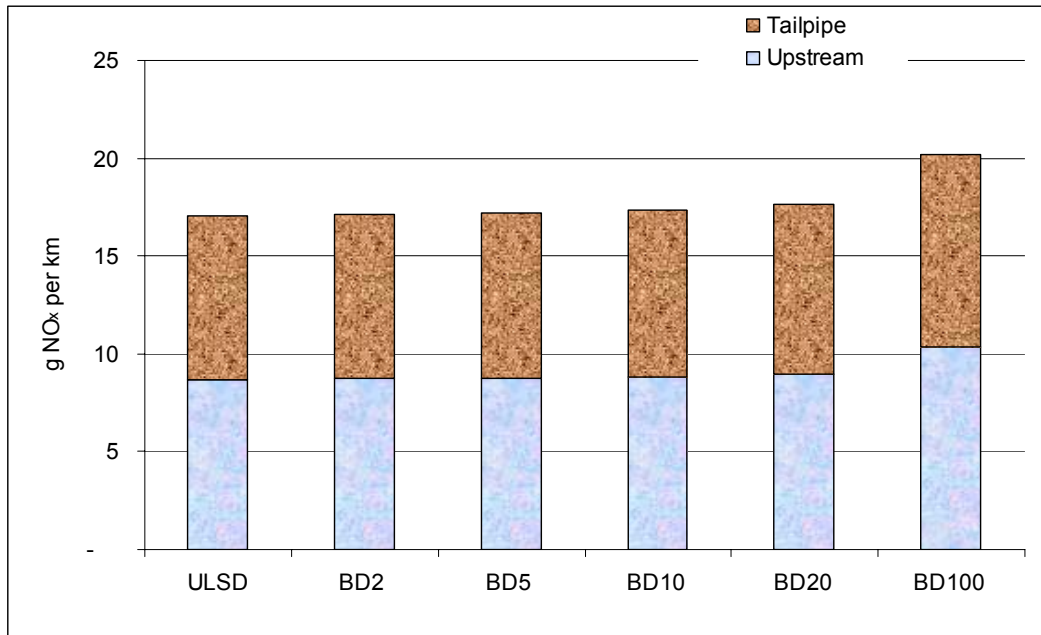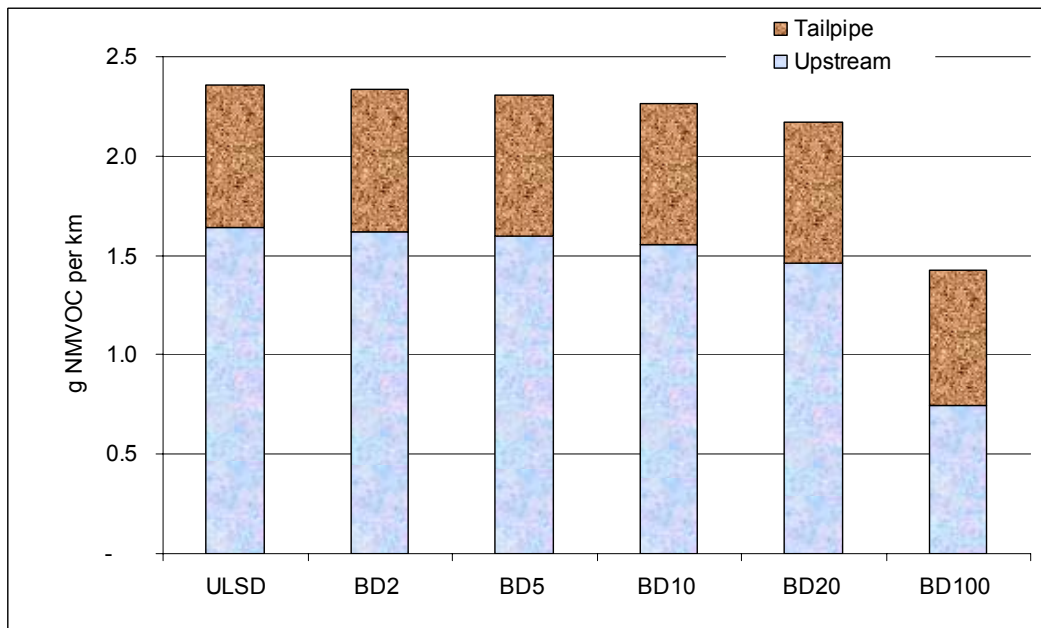Figure 11-22: Tallow ULSD biodiesel blends carbon monoxide emissions in g/km for a truck

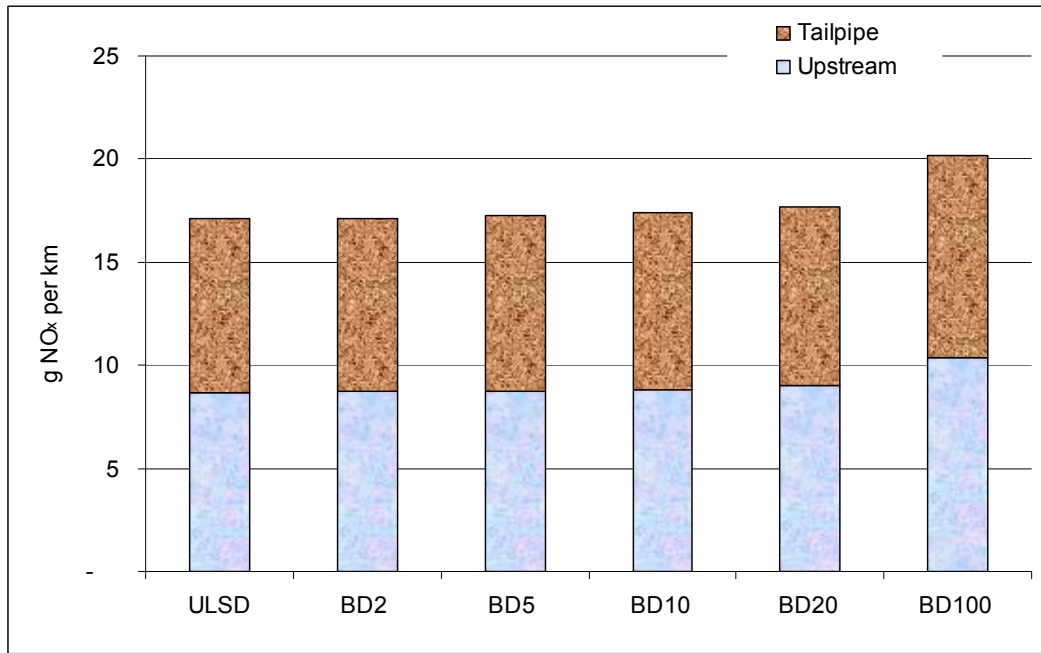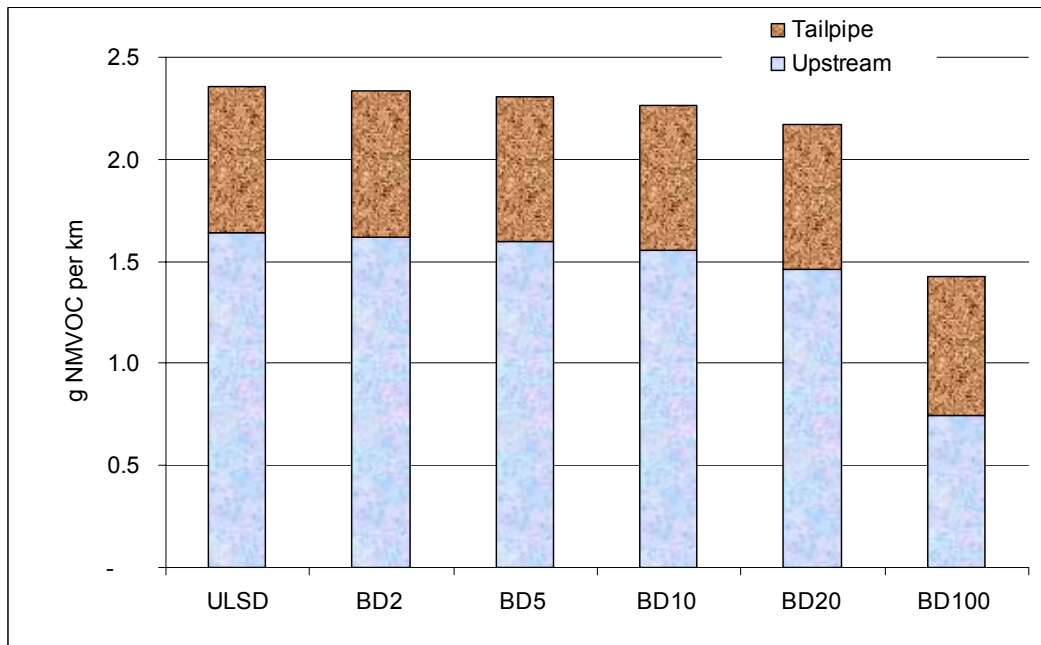Figure 11-23: Tallow ULSD biodiesel blends emissions of oxides of nitrogen in g/km for a truck

Figure 11-24: Tallow ULSD biodiesel blends total non-methanic hydrocarbon emissions in g/km for a truck
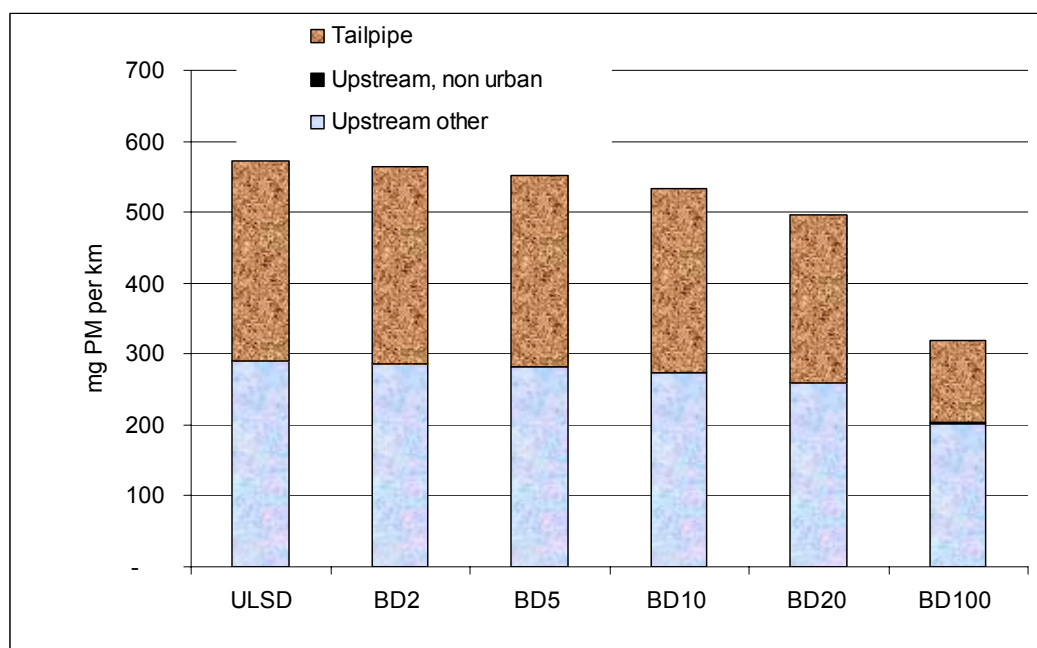
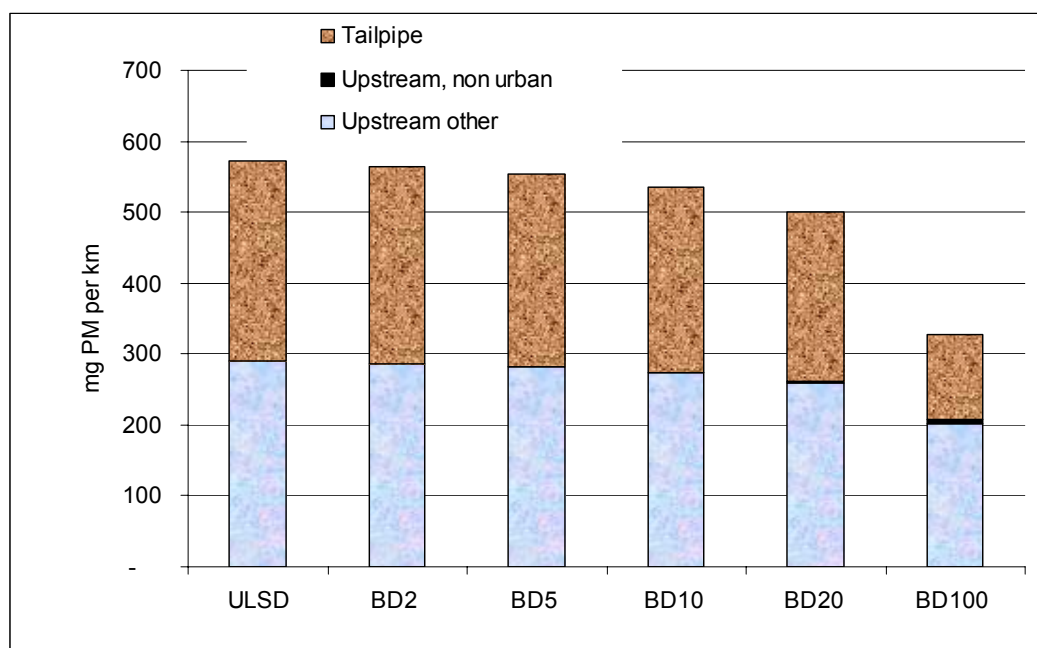Figure 11-25: Tallow ULSD biodiesel blends particulate matter (PM10) emissions in mg/km for a truck

11.1.6 Used cooking oil biodiesel blends with ULS diesel

Table 11.6: Upstream and tailpipe emissions (per km) for ULSD biodiesel blends using used cooking oil

Impact category	Unit	ULS	BD2	BD5	BD10	BD20	BD100
CO_2 (Upstream)	g CO_2	132	132	131	129	126	101
Methane (Upstream)	g CH_4	0.19	0.19	0.18	0.18	0.18	0.14
N_2O (Upstream)	g N_2O	0.001	0.001	0.001	0.001	0.001	0.001
Sequestration	g CO_2	0.000	0.000	0.000	0.000	0.000	0.000
Other	g CO_2-e	0.000	0.000	0.001	0.002	0.004	0.019
CO_2 (Tailpipe)	g CO_2	692	679	658	624	557	0
Methane (Tailpipe)	g CH_4	0.01	0.01	0.01	0.01	0.01	0.01
N_2O (Tailpipe)	g N_2O	0.016	0.016	0.016	0.016	0.016	0.015
CO (Upstream)	g CO	2.98	2.96	2.93	2.87	2.76	2.10
CO (Tailpipe)	g CO	2.81	2.78	2.74	2.68	2.55	1.74
NO_x (Upstream)	g NO_x	8.68	8.70	8.74	8.80	8.91	9.87
NO_x (Tailpipe)	g NO_x	8.40	8.42	8.46	8.51	8.62	9.55
NMVOC (Upstream)	g NMVOC	1.64	1.62	1.59	1.55	1.46	0.74
NMVOC (Tailpipe)	g NMVOC	0.72	0.71	0.71	0.71	0.71	0.67
Particles (Upstream)	mg PM10	290	285	278	266	244	125
Particles (non-urban)	mg PM10	0	0	0	0	0	0
Particles (Tailpipe)	mg PM10	283	278	271	259	237	115
Greenhouse equivalents total	g CO_2-e	834	820	799	763	692	109

Figure 11-26: Used cooking oil ULSD biodiesel blends greenhouse gas emissions in g/km for a truck

Figure 11-27: Used cooking oil ULSD biodiesel blends carbon monoxide emissions in g/km for a truck

Figure 11-28: Used cooking oil ULSD biodiesel blends emissions of oxides of nitrogen in g/km for a truck

Figure 11-29: Used cooking oil ULSD biodiesel blends total non-methanic hydrocarbon emissions in g/km for a truck

Figure 11-30: Used cooking oil ULSD biodiesel blends particulate matter (PM10) emissions in mg/km for a truck

Figure 11-31 to Figure 11-35 diagrammatically illustrates the life-cycle greenhouse gas emissions from BD2 to BD100 for different feedstock sources in ULSD.
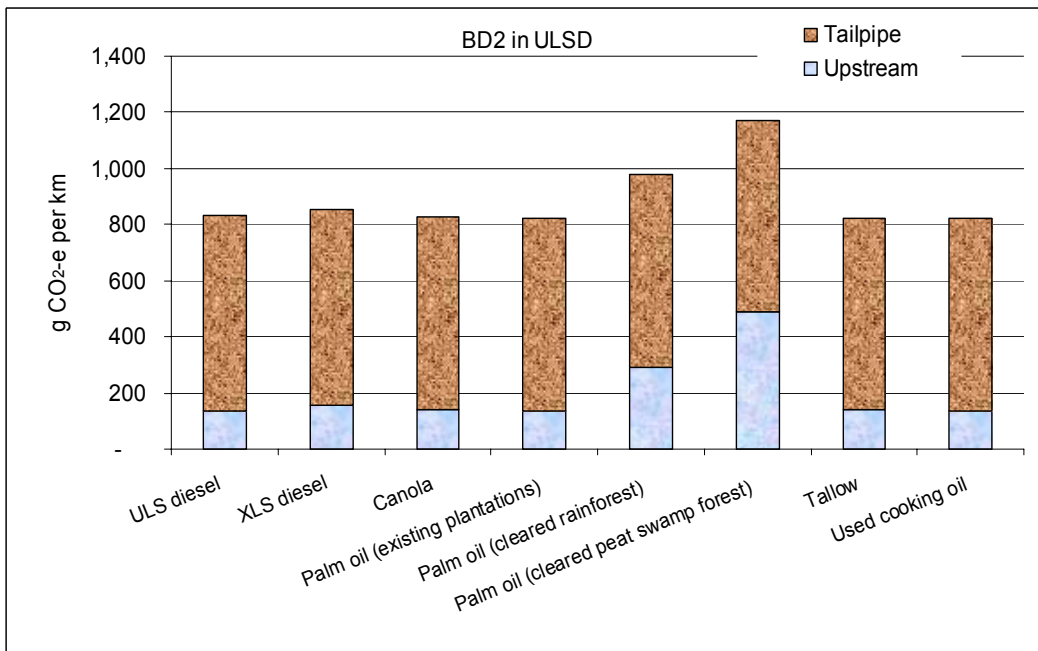
Figure 11-31: Full life-cycle GHG emissions from 2% ULSD biodiesel blends (per km NEPM rigid truck)
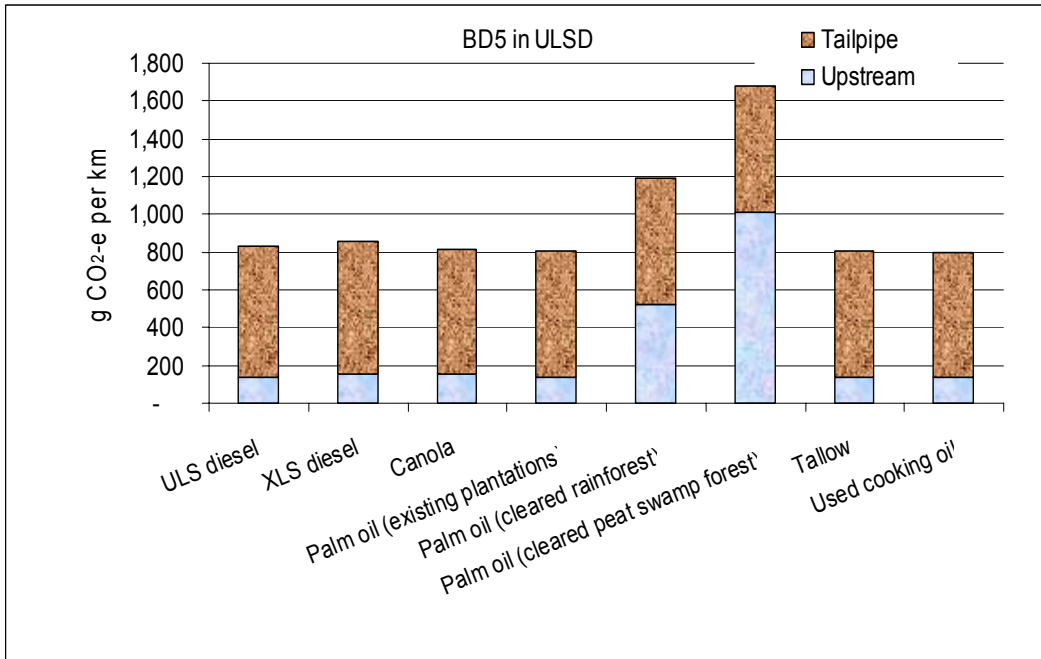
Figure 11-32: Full life-cycle GHG emissions from 5% ULSD biodiesel blends (per km NEPM rigid truck)
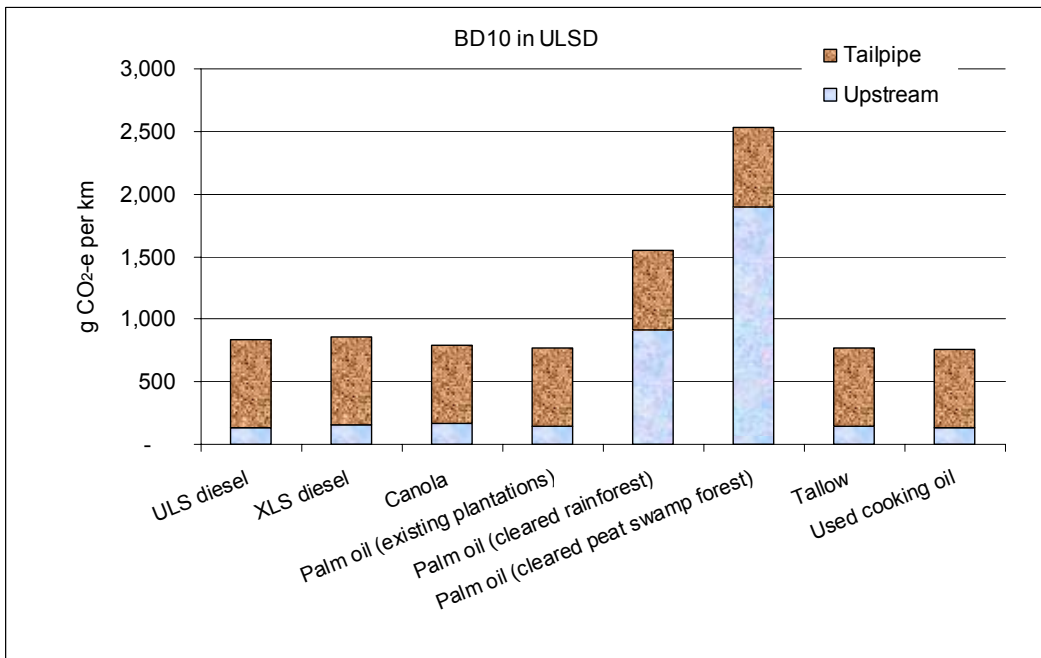
Figure 11-33: Full life-cycle GHG emissions from 10% ULSD biodiesel blends (per km NEPM rigid truck)
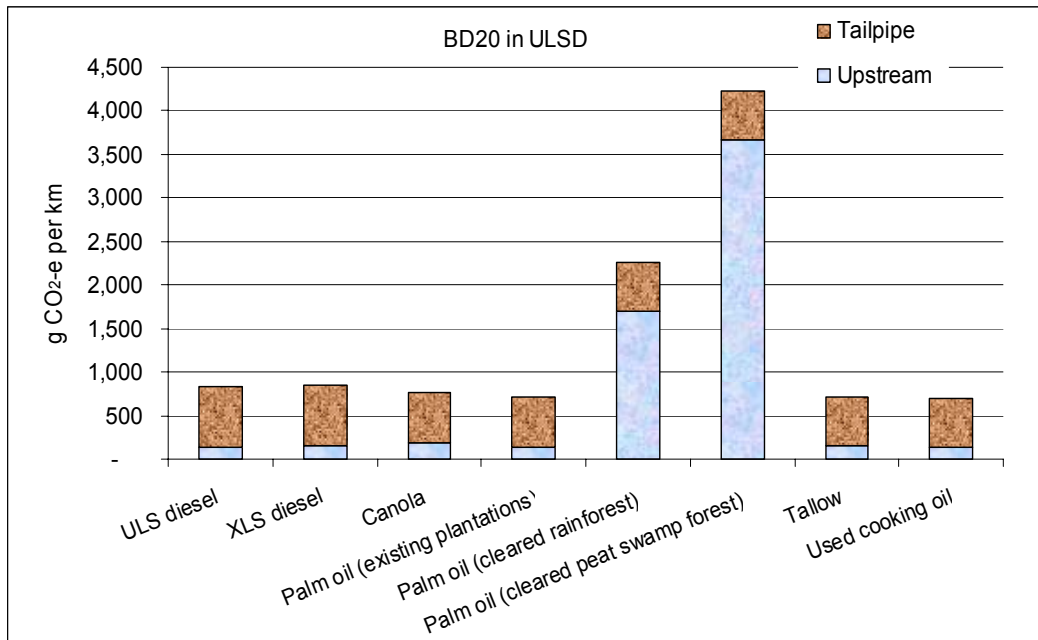
Figure 11-34: Full life-cycle GHG emissions from 20% ULSD biodiesel blends (per km NEPM rigid truck)
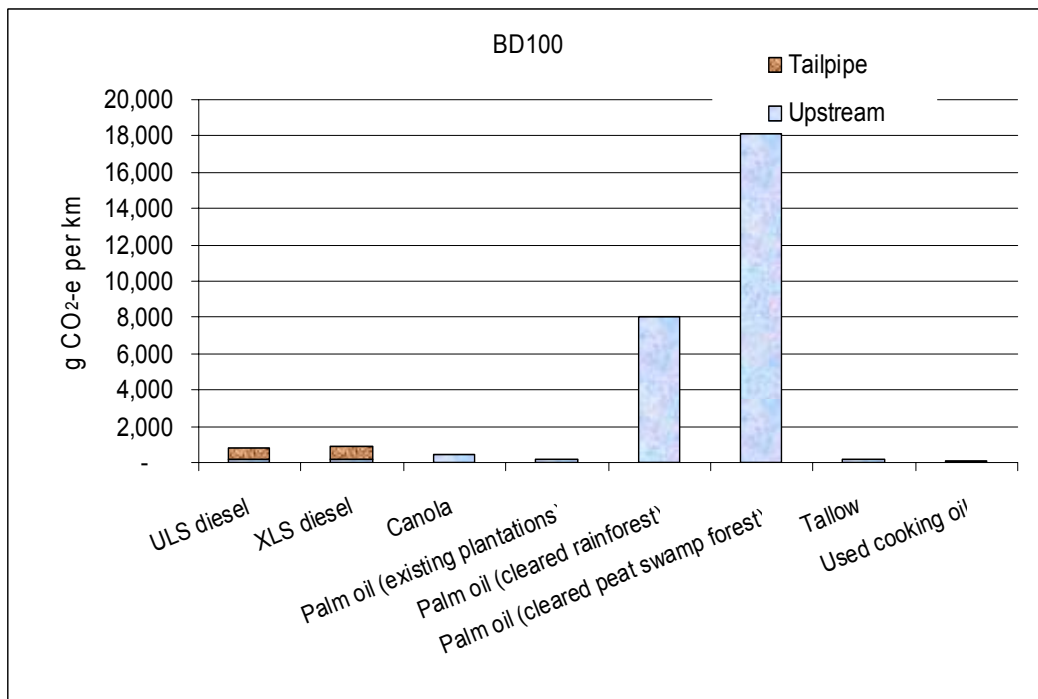
Figure 11-35: Full life-cycle GHG emissions from 100% ULSD biodiesel blends (per km NEPM rigid truck)

11.2 Extra Low Sulfur Diesel (XLSD)

This section provides the same results as section 11.1 except that the various biodiesel blends are blended with XLS diesel and not ULS diesel. This only affects the upstream emissions at this point as we were not able to establish any definitive results on the benefits of XLS over ULS diesel without the implementation of new pollution control technologies. The results, for biodiesel blended with XLSD, are presented for different biofuel sources and blends. Each of the major pollutant splits is also shown. The results for canola are given in tabular form in Table 11.7, and in diagrammatic form in Figure 11-36 to Figure 11-40. Palm oil results are given in Table 11.8 and Figure 11-41 to Figure 11-45 (from existing plantations), Table 11.9 and Figure 11-46 to Figure 11-50 (from cleared rainforest) and in Table 11.10 and Figure 11-51 to Figure 11-55 (from cleared peat swamp forest). Tallow results are given in Table 11.11 and Figure 11-56 to Figure 11-60 and used cooking oil results are given in Table 11.12 and Figure 11-61 to Figure 11-65. Figure 11-66 to Figure 11-70 summarise the GHG emissions of BD2, BD5, BD10 and BD20 XLSD blends and BD100 respectively. Figure 11-71 also shows GHG emissions for BD100, but with the Y-axis truncated so that the non palm oil biodiesels can be more readily compared.

11.2.1 Canola biodiesel blends with XLSD

Table 11.7: Upstream and tailpipe emissions (per km)[1] for XLSD canola biodiesel blends

Impact category	Unit	XLSD	BD2	BD5	BD10	BD20	BD100
CO_2 (Upstream)	g CO_2	129	133	140	151	174	357
Methane (Upstream)	g CH_4	1.35	1.34	1.31	1.27	1.18	0.49
N_2O (Upstream)	g N_2O	0.001	0.005	0.011	0.020	0.039	0.197
Sequestration	g CO_2	0.000	0.000	0.000	0.000	0.000	0.000
Other	g CO_2-e	0.000	0.001	0.002	0.004	0.007	0.038
CO_2 (Tailpipe)	g CO_2	692	679	659	626	560	0
Methane (Tailpipe)	g CH_4	0.01	0.01	0.01	0.01	0.01	0.01
N_2O (Tailpipe)	g N_2O	0.016	0.016	0.016	0.016	0.016	0.015
CO (Upstream)	g CO	3.15	3.13	3.10	3.06	2.98	2.48
CO (Tailpipe)	g CO	2.81	2.78	2.75	2.69	2.57	1.79
NO_x (Upstream)	g NO_x	8.75	8.81	8.90	9.05	9.36	11.90
NO_x (Tailpipe)	g NO_x	8.40	8.43	8.47	8.53	8.67	9.84
NMVOC (Upstream)	g NMVOC	1.63	1.62	1.60	1.57	1.50	0.94
NMVOC (Tailpipe)	g NMVOC	0.72	0.71	0.71	0.71	0.71	0.69
Particles (Upstream)	mg PM10	286	292	301	317	351	684
Particles (non-urban)	mg PM10	0	0	1	1	3	13
Particles (Tailpipe)	mg PM10	283	278	271	260	238	119
Greenhouse equivalents total	g CO_2-e	855	847	835	815	776	433

[1] Per kilometer of rigid truck as used in the diesel NEPM tests
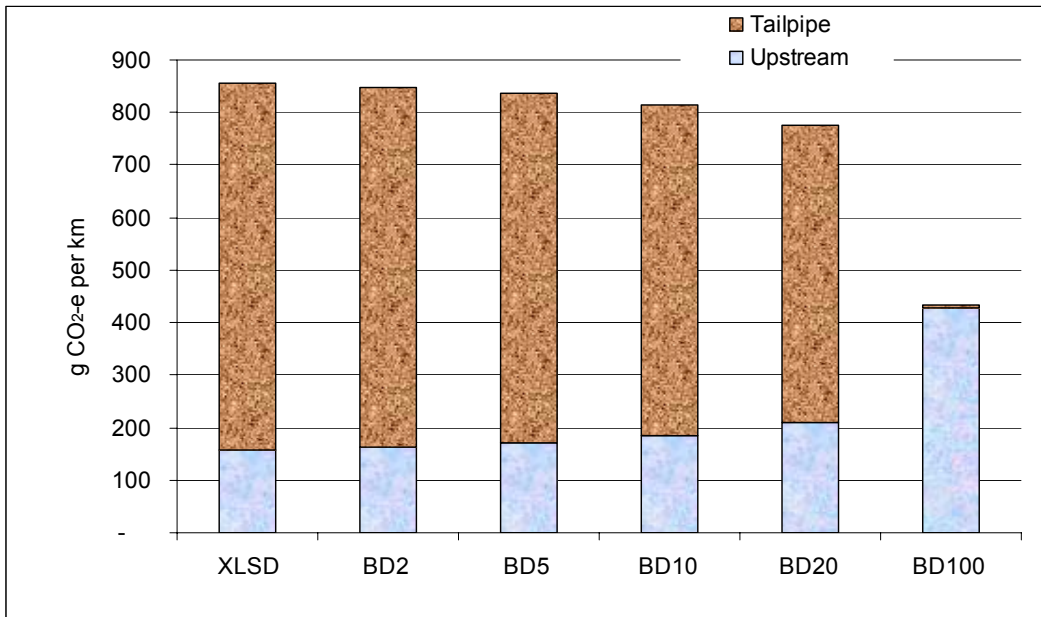
Figure 11-36: Canola XLSD biodiesel blends greenhouse gas emissions in g/km for a truck
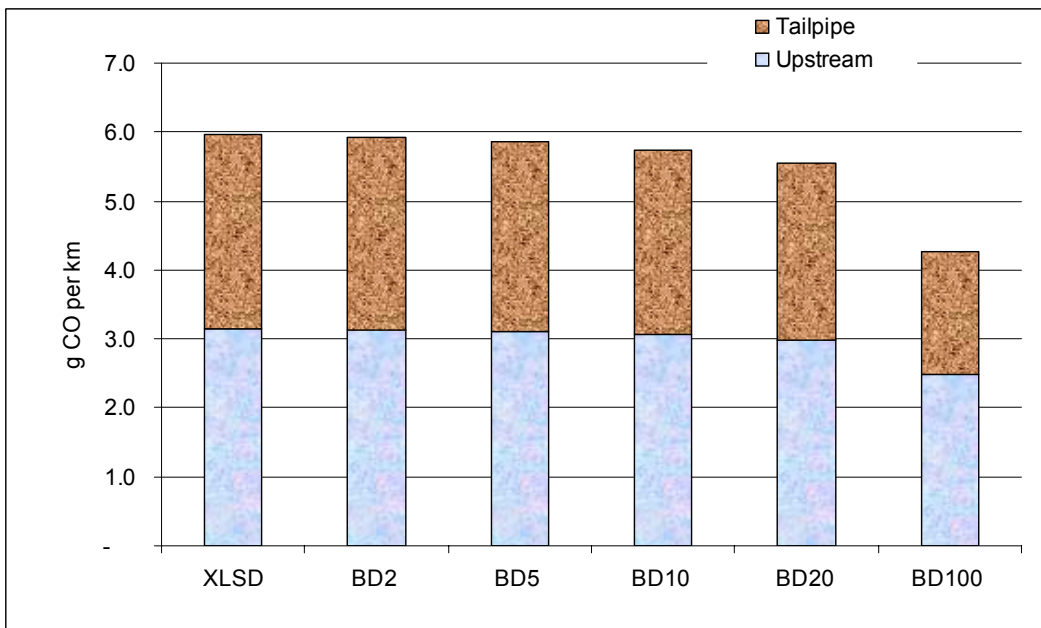
Figure 11-37: Canola XLSD biodiesel blends carbon monoxide emissions in g/km for a truck
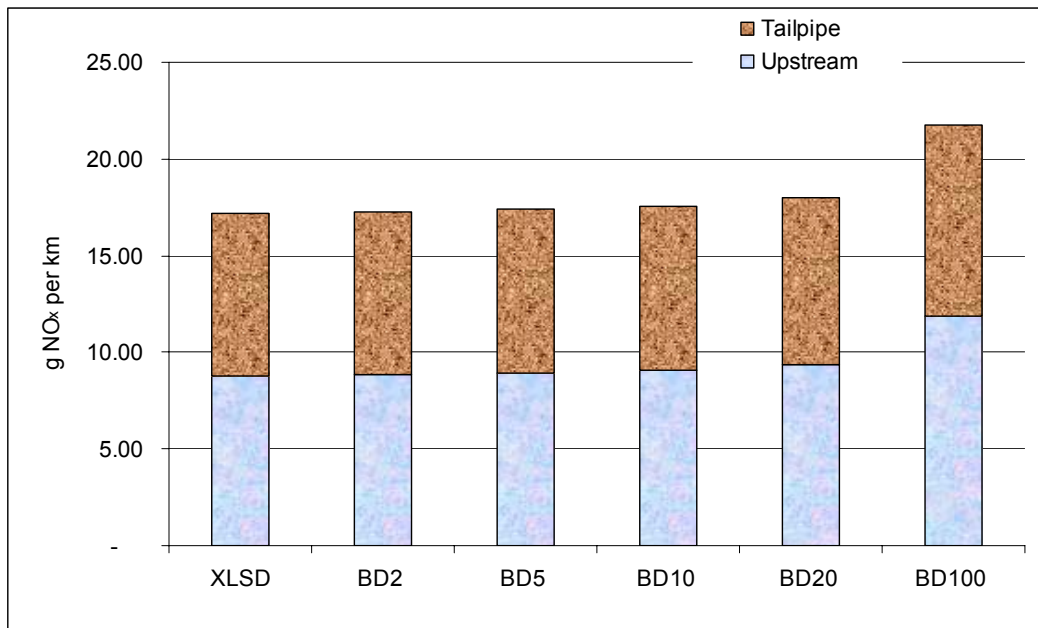
Figure 11-38: Canola XLSD biodiesel blends emissions of oxides of nitrogen in g/km for a truck

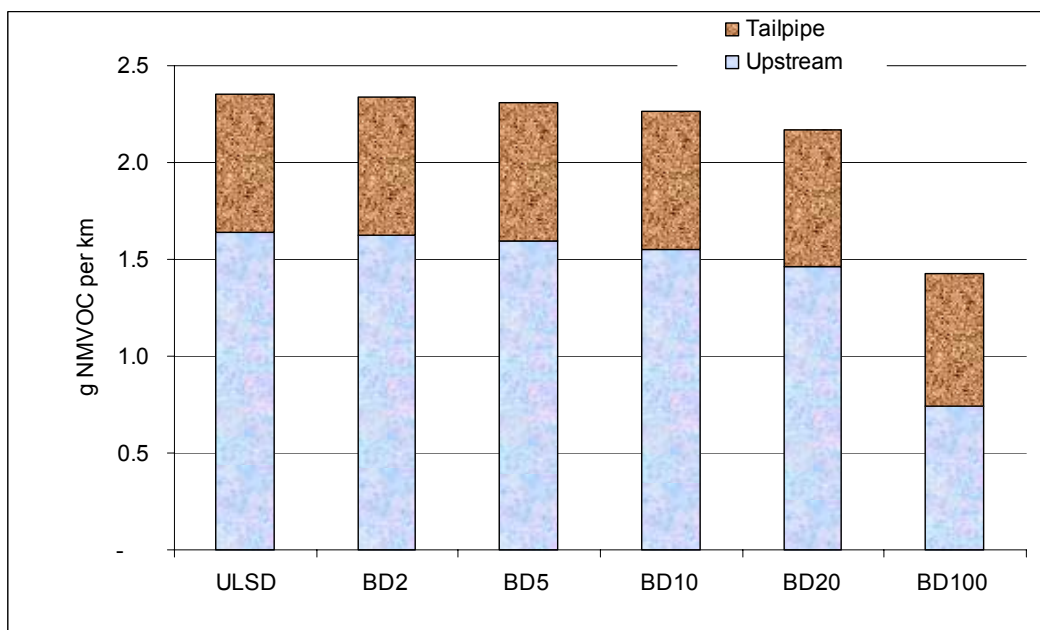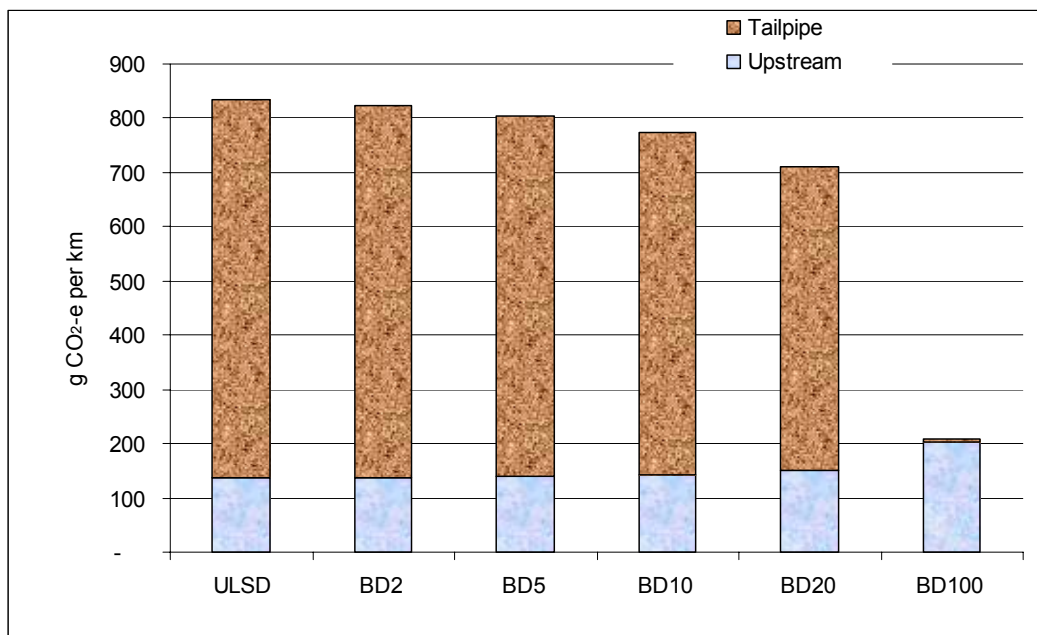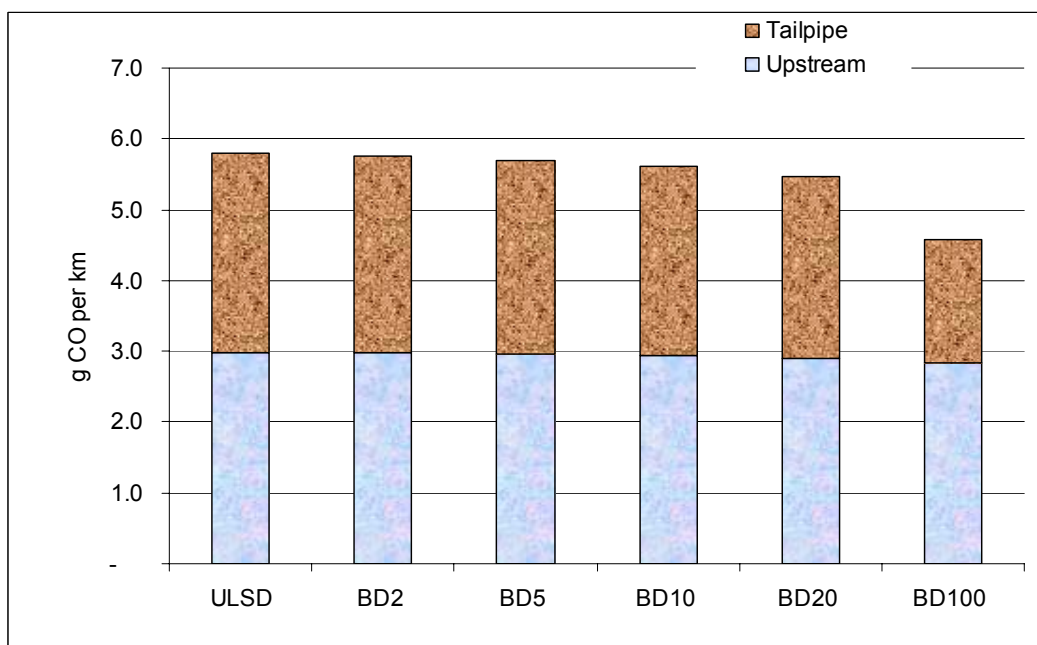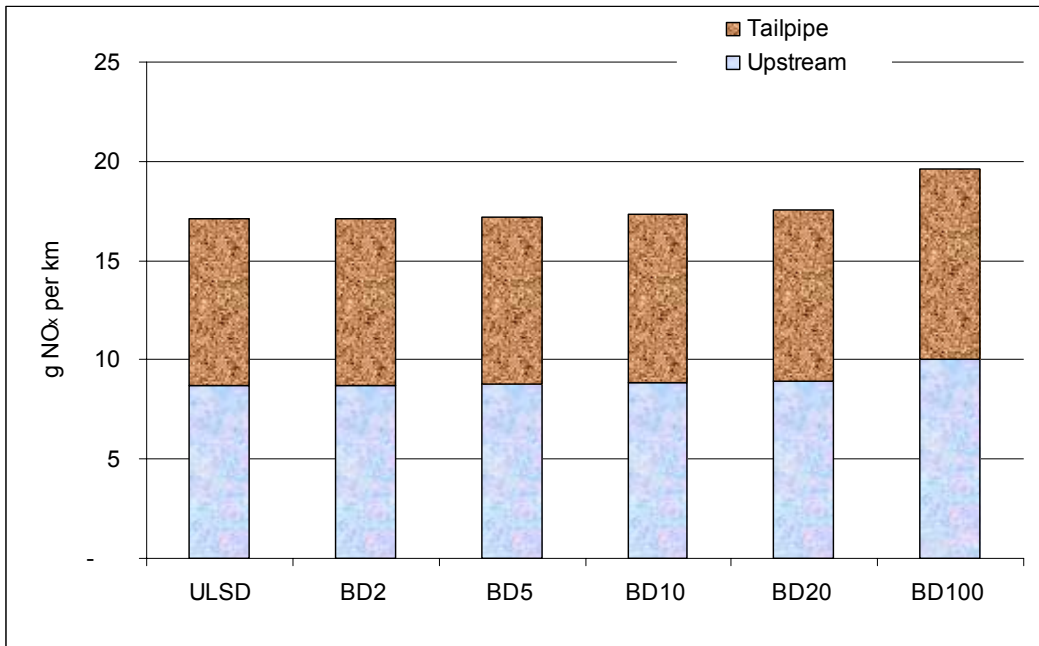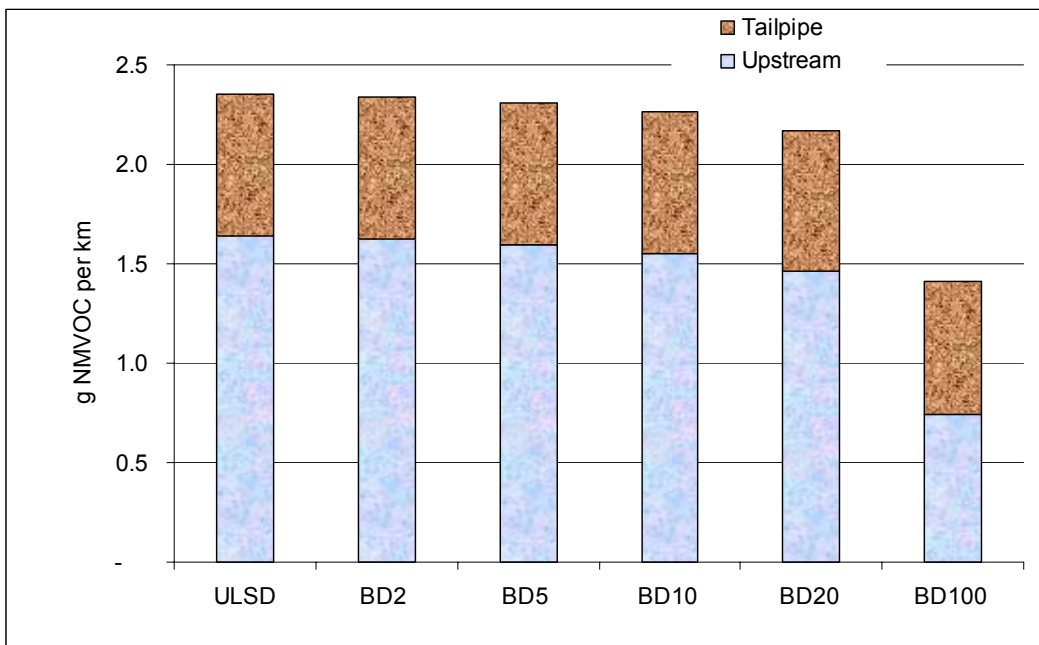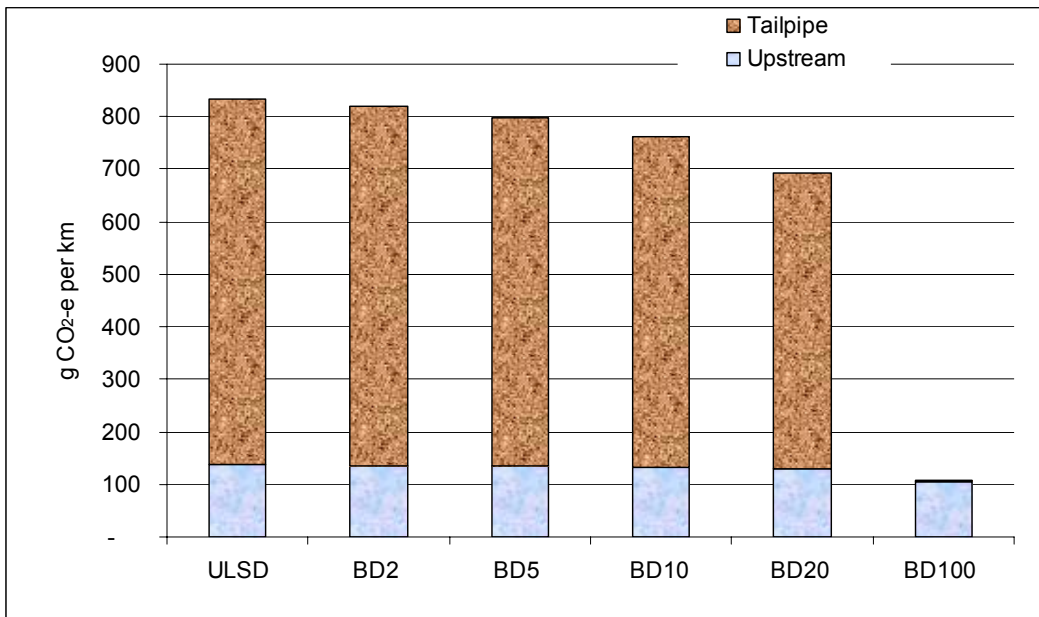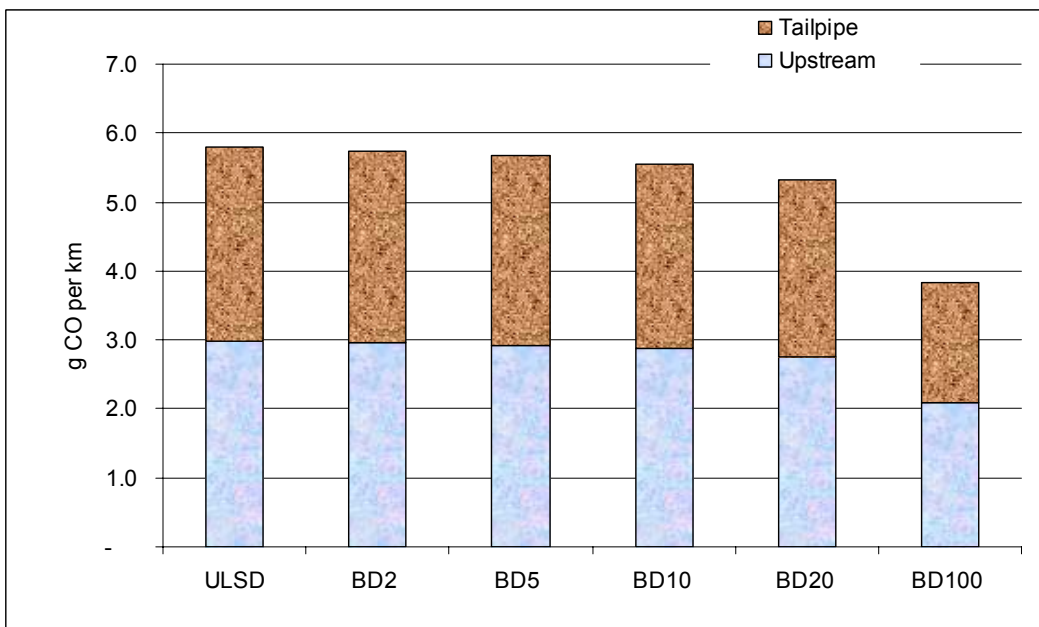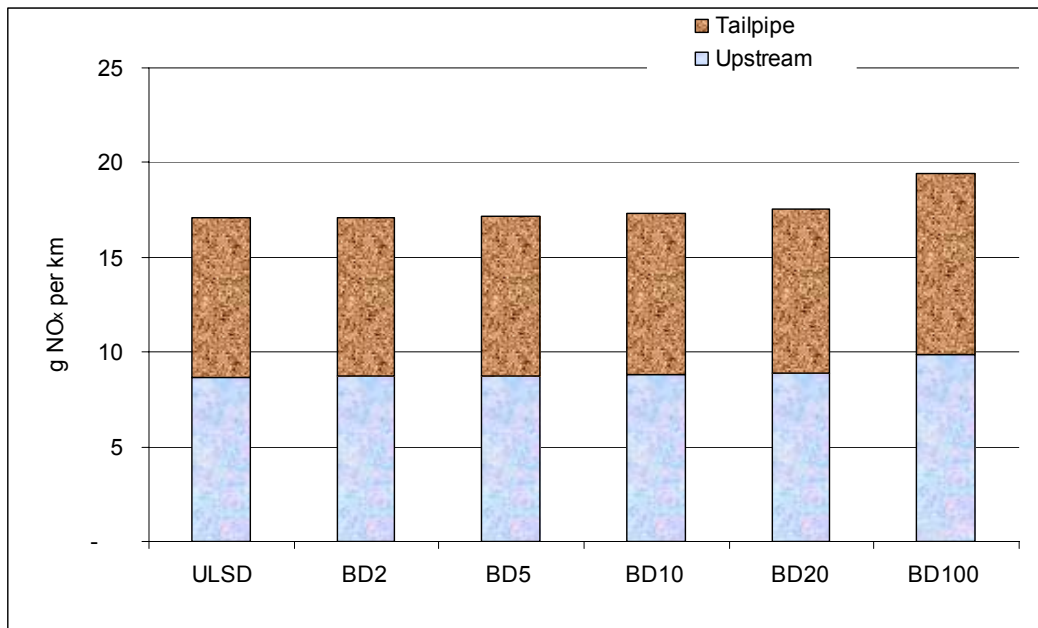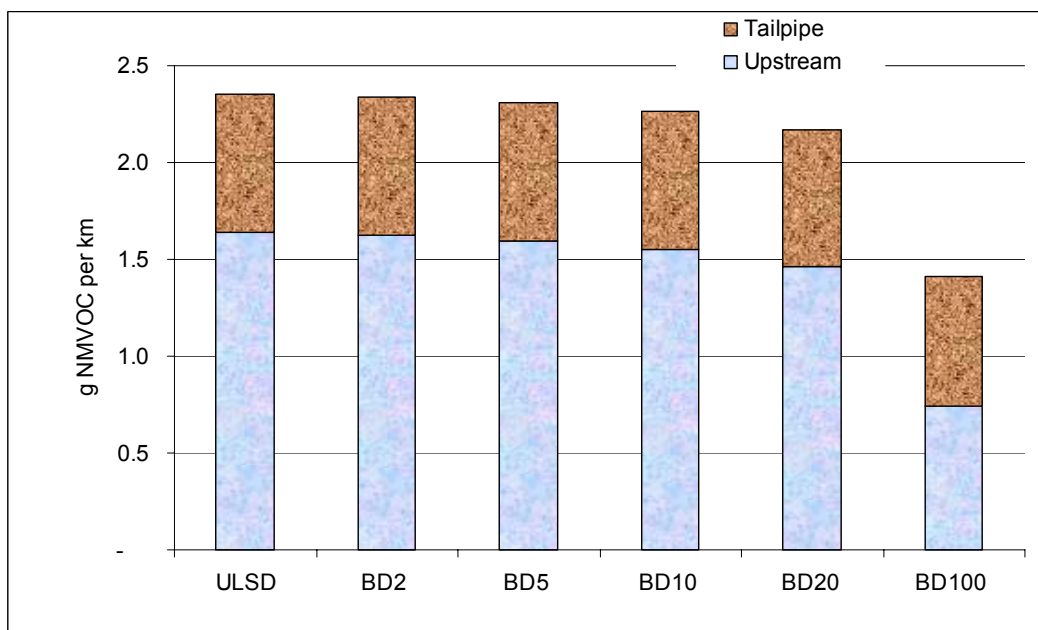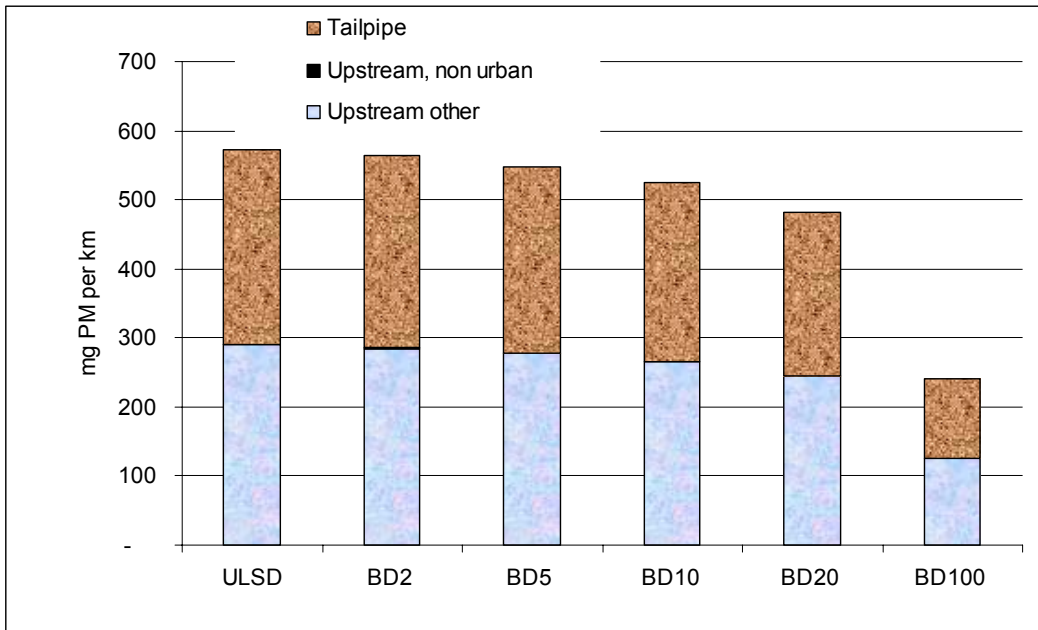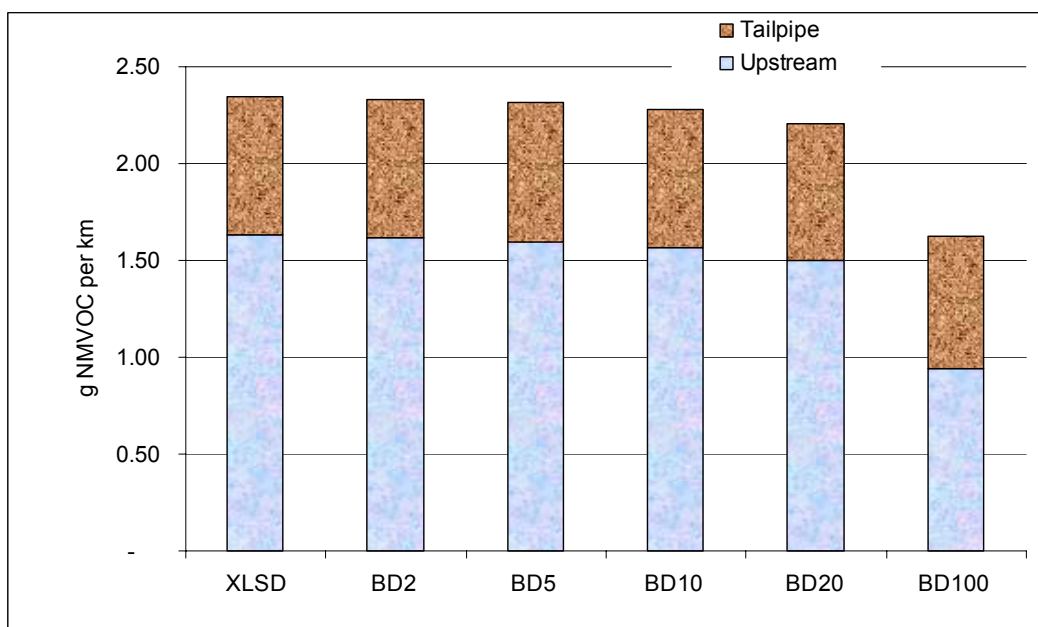Figure 11-39: Canola XLSD biodiesel blends total non-methanic hydrocarbon emissions in g/km for a truck
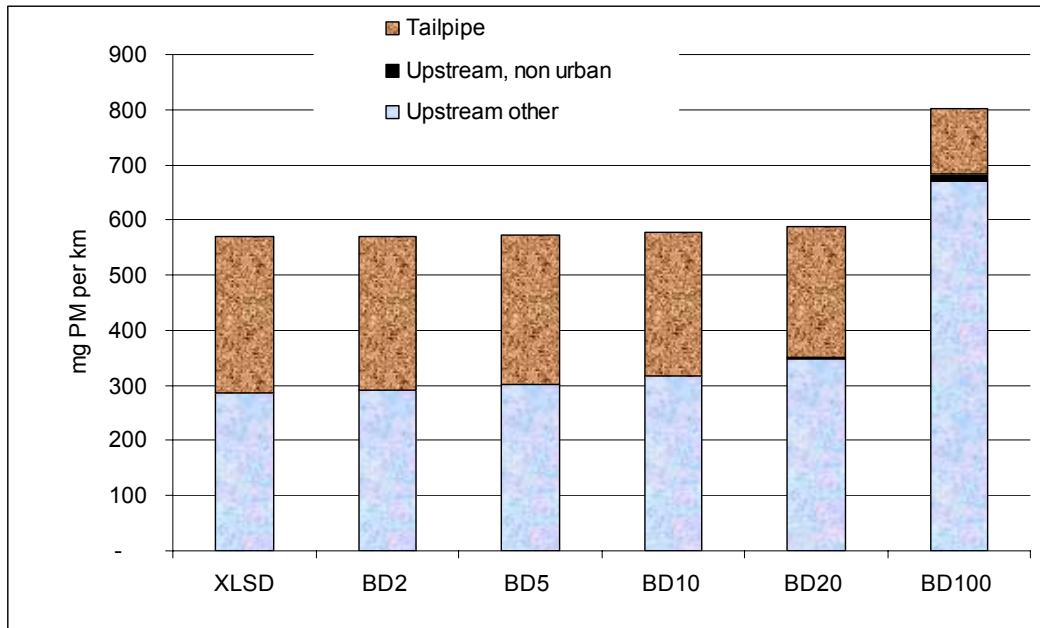
Figure 11-40: Canola XLSD biodiesel blends particulate matter (PM10) emissions in mg/km for a truck

11.2.2 Palm oil (existing plantations) biodiesel blends with XLSD

Table 11.8: Upstream and tailpipe emissions (per km) for XLSD biodiesel blends using palm oil from existing plantations

Impact category	Unit	XLSD	BD2	BD5	BD10	BD20	BD100
CO_2 (Upstream)	g CO_2	129	128	127	124	120	81
Methane (Upstream)	g CH_4	1.35	1.33	1.29	1.24	1.12	0.15
N_2O (Upstream)	g N_2O	0.001	0.006	0.014	0.028	0.055	0.275
Sequestration	g CO_2	0.000	0.000	0.000	0.000	0.000	0.000
Other	g CO_2-e	0.000	0.001	0.001	0.003	0.005	0.027
CO_2 (Tailpipe)	g CO_2	692	679	659	626	560	0
Methane (Tailpipe)	g CH_4	0.01	0.01	0.01	0.01	0.01	0.01
N_2O (Tailpipe)	g N_2O	0.016	0.016	0.016	0.016	0.016	0.015
CO (Upstream)	g CO	3.15	3.14	3.12	3.09	3.03	2.75
CO (Tailpipe)	g CO	2.81	2.78	2.75	2.69	2.57	1.79
NO_x (Upstream)	g NO_x	8.75	8.78	8.83	8.90	9.05	10.33
NO_x (Tailpipe)	g NO_x	8.40	8.43	8.47	8.53	8.67	9.84
NMVOC (Upstream)	g NMVOC	1.63	1.62	1.59	1.55	1.46	0.74
NMVOC (Tailpipe)	g NMVOC	0.72	0.71	0.71	0.71	0.71	0.69
Particles (Upstream)	mg PM10	286	283	278	271	258	208
Particles (non-urban)	mg PM10	0	0	0	1	1	7
Particles (Tailpipe)	mg PM10	283	278	271	260	238	119
Greenhouse equivalents total	g CO_2-e	855	842	823	790	725	175
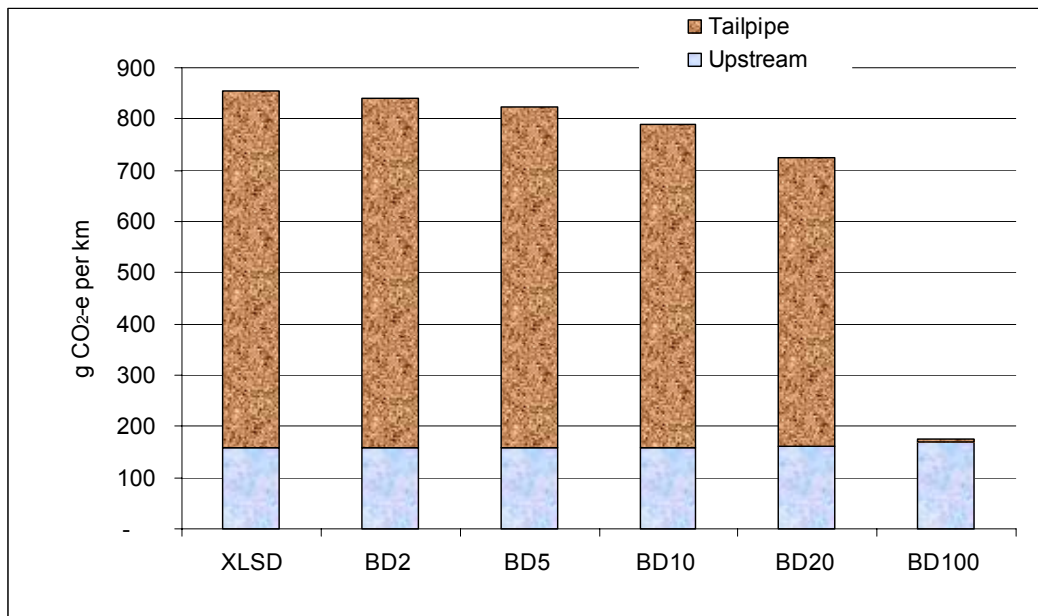
Figure 11-41: Palm oil (existing plantations) XLSD biodiesel blends greenhouse gas emissions in g/km for a truck
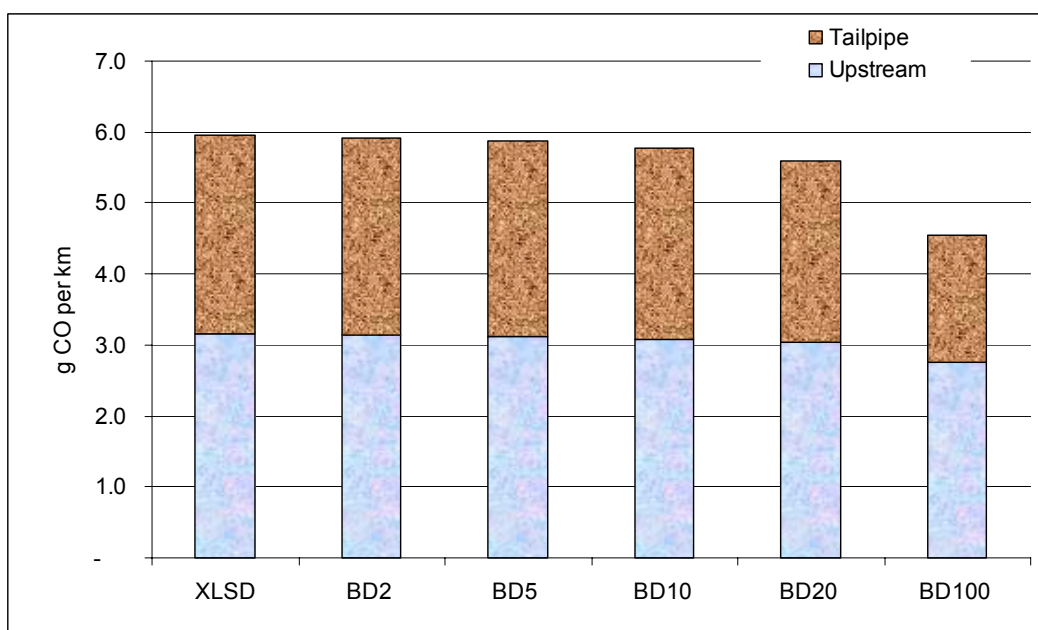
Figure 11-42: Palm oil (existing plantations) XLSD biodiesel blends carbon monoxide emissions in g/km for a truck

Figure 11-43: Palm oil (existing plantations) XLSD biodiesel blends emissions of oxides of nitrogen in g/km for a truck

Figure 11-44: Palm oil (existing plantations) XLSD biodiesel blends total non-methanic hydrocarbon emissions in g/km for a truck
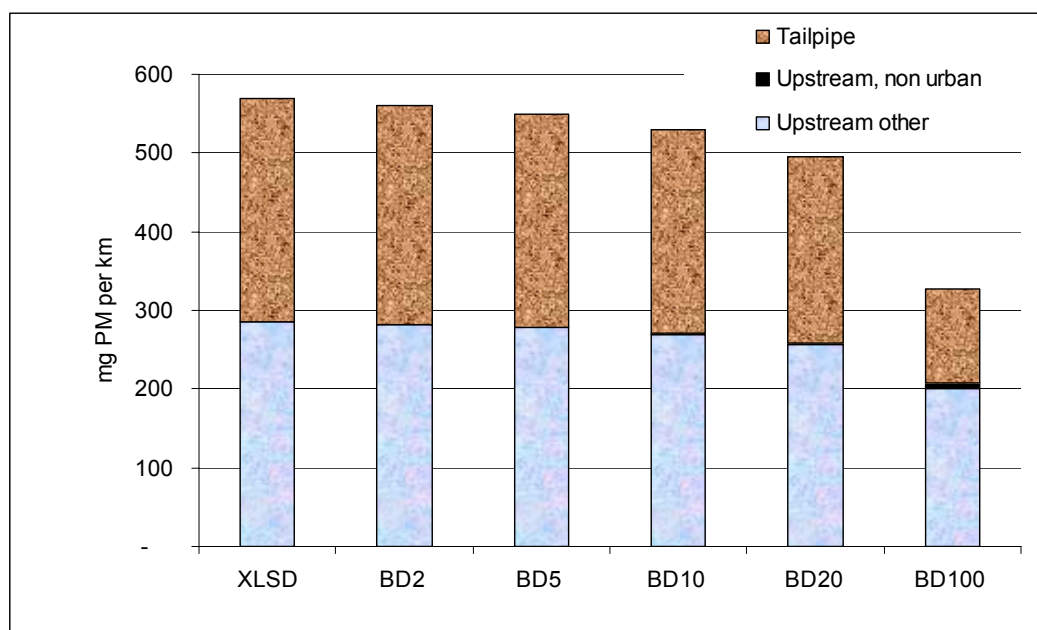
Figure 11-45: Palm oil (existing plantations) XLSD biodiesel blends particulate matter (PM10) emissions in mg/km for a truck

11.2.3 Palm oil (cleared rainforest) biodiesel blends with XLSD

Table 11.9: Upstream and tailpipe emissions (per km) for XLSD biodiesel blends using palm oil from cleared rainforest

Impact category	Unit	XLSD	BD2	BD5	BD10	BD20	BD100
CO_2 (Upstream)	g CO_2	129	282	513	898	1670	7981
Methane (Upstream)	g CH_4	1.35	1.33	1.29	1.24	1.12	0.15
N_2O (Upstream)	g N_2O	0.001	0.006	0.014	0.028	0.055	0.275
Sequestration	g CO_2	0.000	0.000	0.000	0.000	0.000	0.000
Other	g CO_2-e	0.000	0.001	0.001	0.003	0.005	0.027
CO_2 (Tailpipe)	g CO_2	692	679	659	626	560	0
Methane (Tailpipe)	g CH_4	0.01	0.01	0.01	0.01	0.01	0.01
N_2O (Tailpipe)	g N_2O	0.016	0.016	0.016	0.016	0.016	0.015
CO (Upstream)	g CO	3.15	3.14	3.12	3.09	3.03	2.75
CO (Tailpipe)	g CO	2.81	2.78	2.75	2.69	2.57	1.79
NO_x (Upstream)	g NO_x	8.75	8.78	8.83	8.90	9.05	10.33
NO_x (Tailpipe)	g NO_x	8.40	8.43	8.47	8.53	8.67	9.84
NMVOC (Upstream)	g NMVOC	1.63	1.62	1.59	1.55	1.46	0.74
NMVOC (Tailpipe)	g NMVOC	0.72	0.71	0.71	0.71	0.71	0.69
Particles (Upstream)	mg PM10	286	283	278	271	258	208
Particles (non-urban)	mg PM10	0	0	0	1	1	7
Particles (Tailpipe)	mg PM10	283	278	271	260	238	119
Greenhouse equivalents total	g CO_2-e	855	996	1209	1564	2275	8075
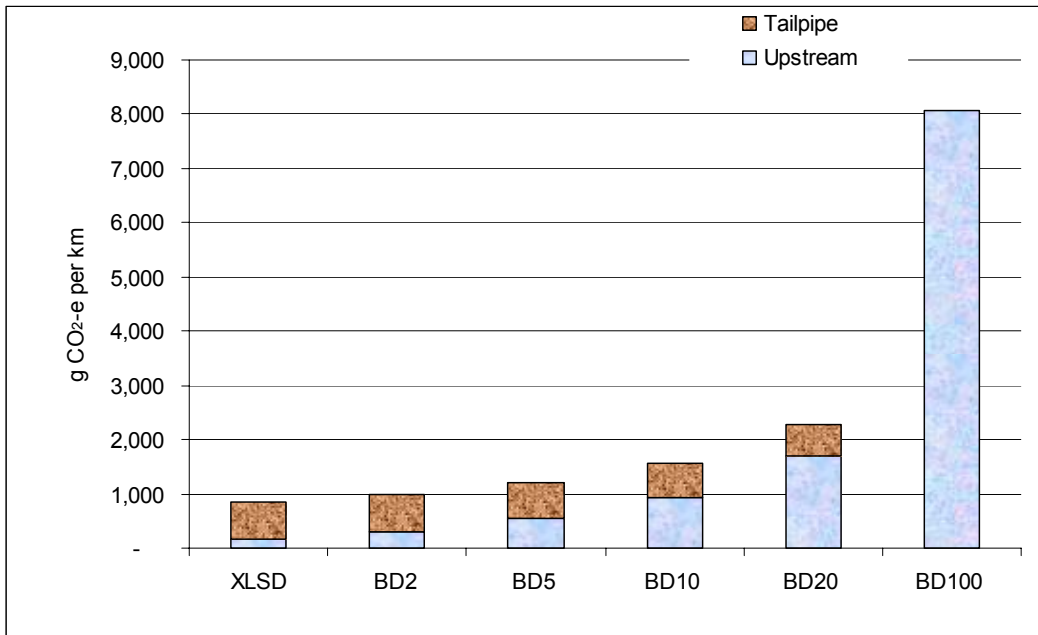
Figure 11-46: Palm oil (cleared rainforest) XLSD biodiesel blends greenhouse gas emissions in g/km for a truck
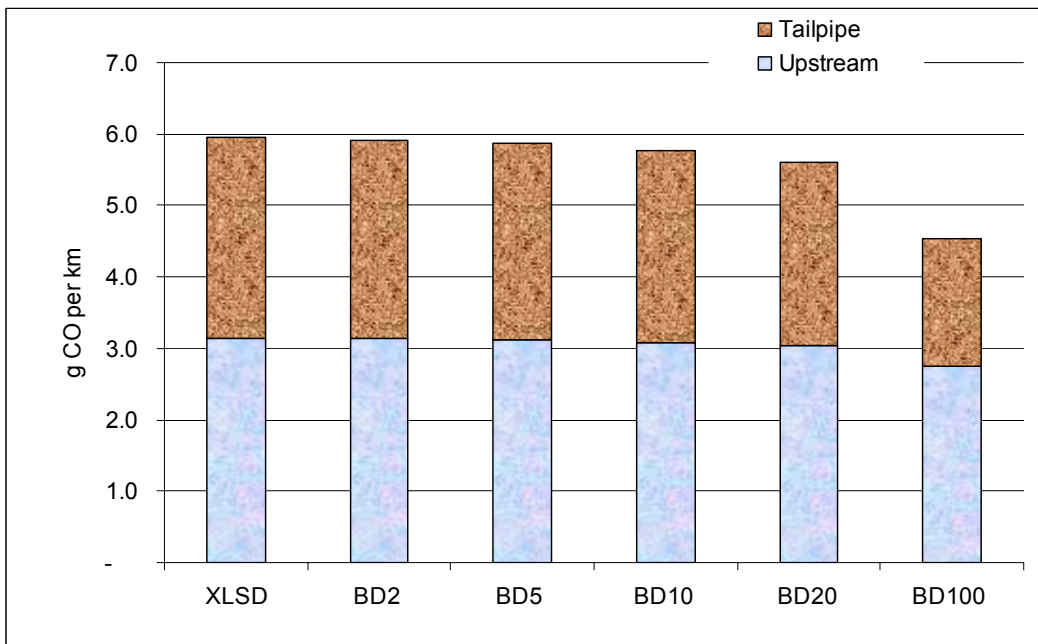
Figure 11-47: Palm oil (cleared rainforest) XLSD biodiesel blends carbon monoxide emissions in g/km for a truck

Figure 11-48: Palm oil (cleared rainforest) XLSD biodiesel blends emissions of oxides of nitrogen in g/km for a truck

Figure 11-49: Palm oil (cleared rainforest) XLSD biodiesel blends total non-methanic hydrocarbon emissions in g/km for a truck
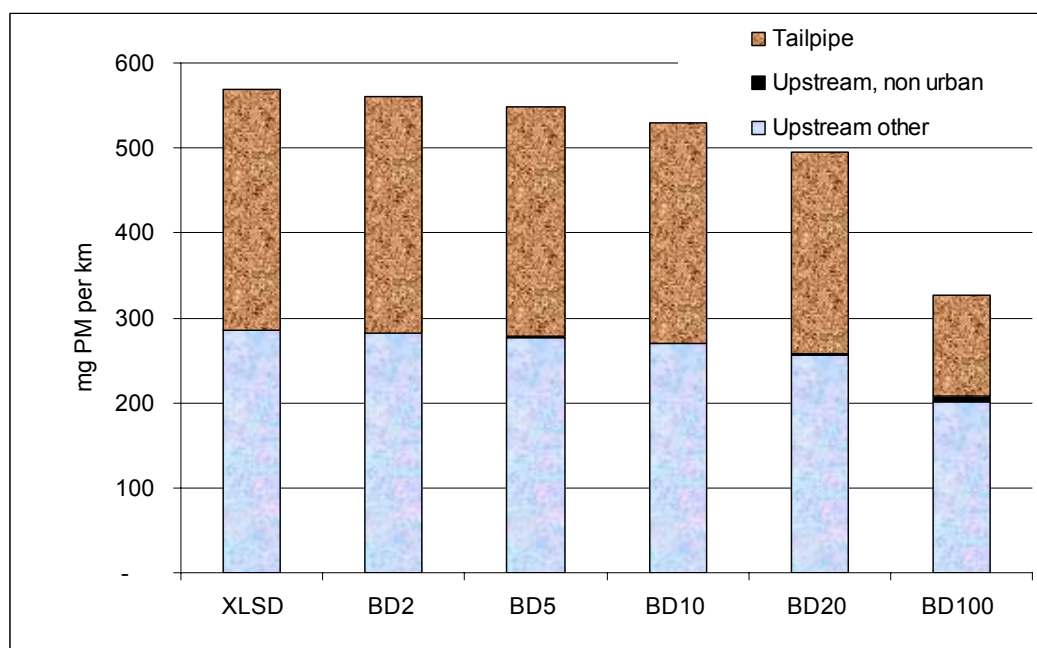
Figure 11-50: Palm oil (cleared rainforest) XLSD biodiesel blends particulate matter (PM10)
emissions in mg/km for a truck

11.2.4 Palm oil (cleared peat swamp forest) biodiesel blends with XLSD

Table 11.10: Upstream and tailpipe emissions (per km) for XLSD biodiesel blends using palm oil
from cleared peat swamp forest

Impact category	Unit	XLSD	BD2	BD5	BD10	BD20	BD100
CO_2 (Upstream)	g CO_2	129	479	1004	1880	3639	18014
Methane (Upstream)	g CH_4	1.35	1.33	1.29	1.24	1.12	0.15
N_2O (Upstream)	g N_2O	0.001	0.006	0.014	0.028	0.055	0.275
Sequestration	g CO_2	0.000	0.000	0.000	0.000	0.000	0.000
Other	g CO_2-e	0.000	0.001	0.001	0.003	0.005	0.027
CO_2 (Tailpipe)	g CO_2	692	679	659	626	560	0
Methane (Tailpipe)	g CH_4	0.01	0.01	0.01	0.01	0.01	0.01
N_2O (Tailpipe)	g N_2O	0.016	0.016	0.016	0.016	0.016	0.015
CO (Upstream)	g CO	3.15	3.14	3.12	3.09	3.03	2.75
CO (Tailpipe)	g CO	2.81	2.78	2.75	2.69	2.57	1.79
NO_x (Upstream)	g NO_x	8.75	8.78	8.83	8.90	9.05	10.33
NO_x (Tailpipe)	g NO_x	8.40	8.43	8.47	8.53	8.67	9.84
NMVOC (Upstream)	g NMVOC	1.63	1.62	1.59	1.55	1.46	0.74
NMVOC (Tailpipe)	g NMVOC	0.72	0.71	0.71	0.71	0.71	0.69
Particles (Upstream)	mg PM10	286	283	278	271	258	208
Particles (non-urban)	mg PM10	0	0	0	1	1	7
Particles (Tailpipe)	mg PM10	283	278	271	260	238	119
Greenhouse equivalents total	g CO_2-e	855	1193	1700	2546	4245	18108
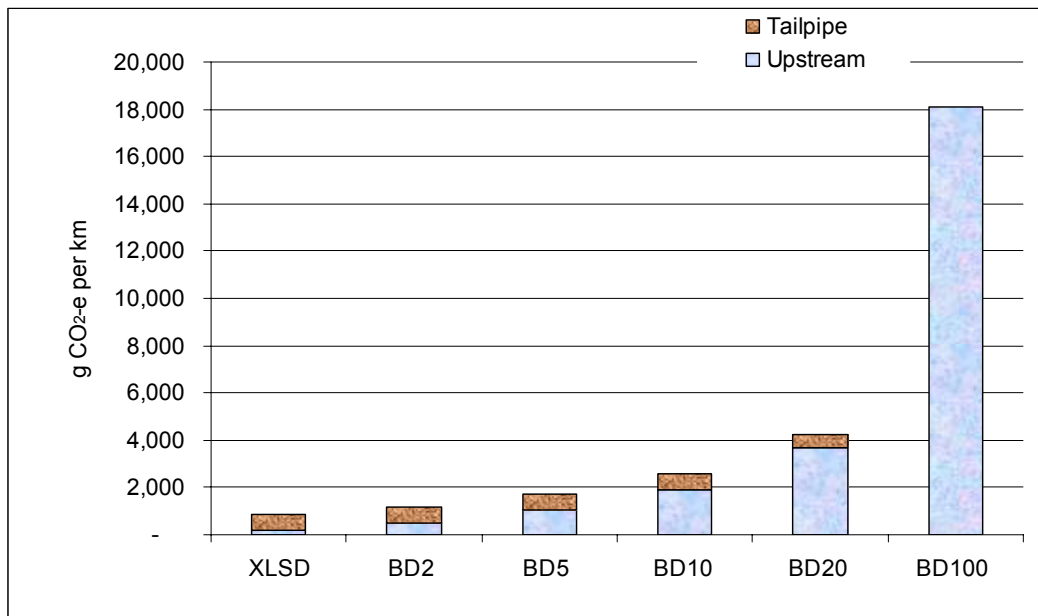
Figure 11-51: Palm oil (cleared peat swamp forest) XLSD biodiesel blends greenhouse gas emissions in g/km for a truck
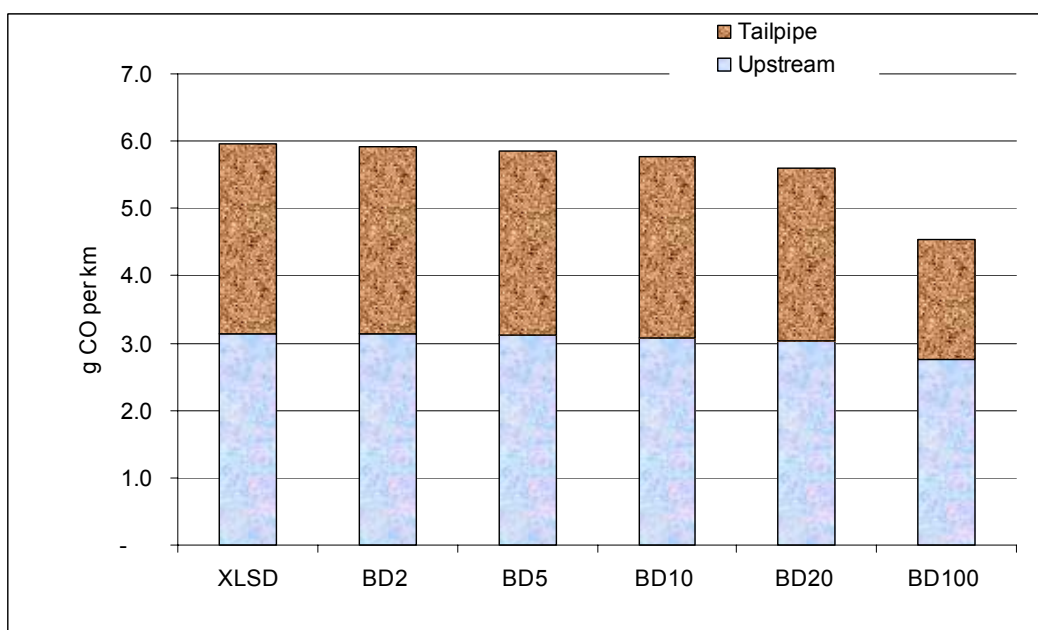
Figure 11-52: Palm oil (cleared peat swamp forest) XLSD biodiesel blends carbon monoxide emissions in g/km for a truck
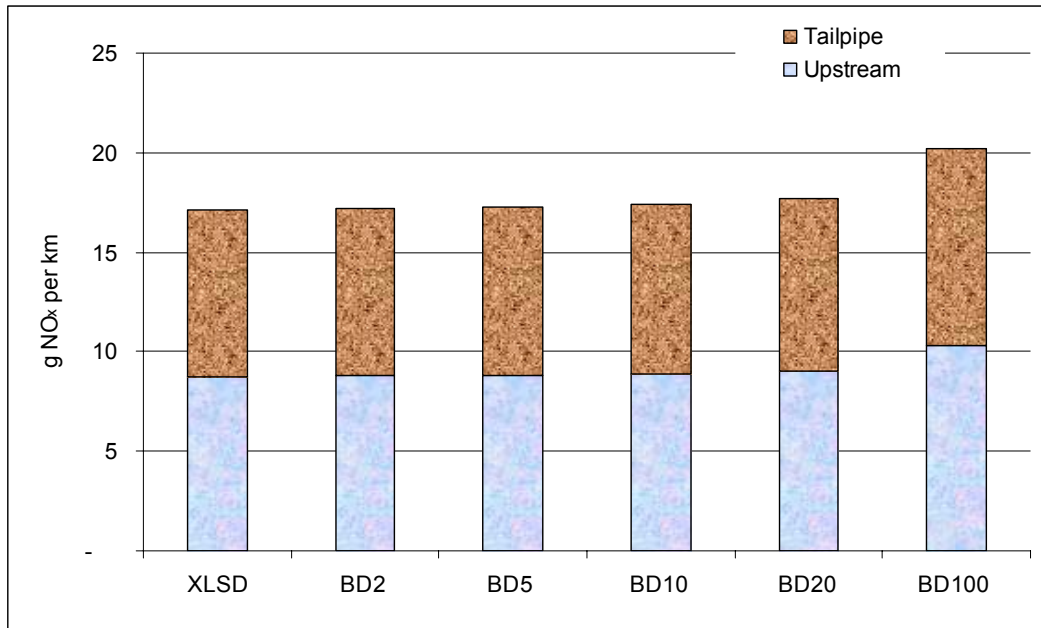
Figure 11-53: Palm oil (cleared peat swamp forest) XLSD biodiesel blends emissions of oxides of nitrogen in g/km for a truck
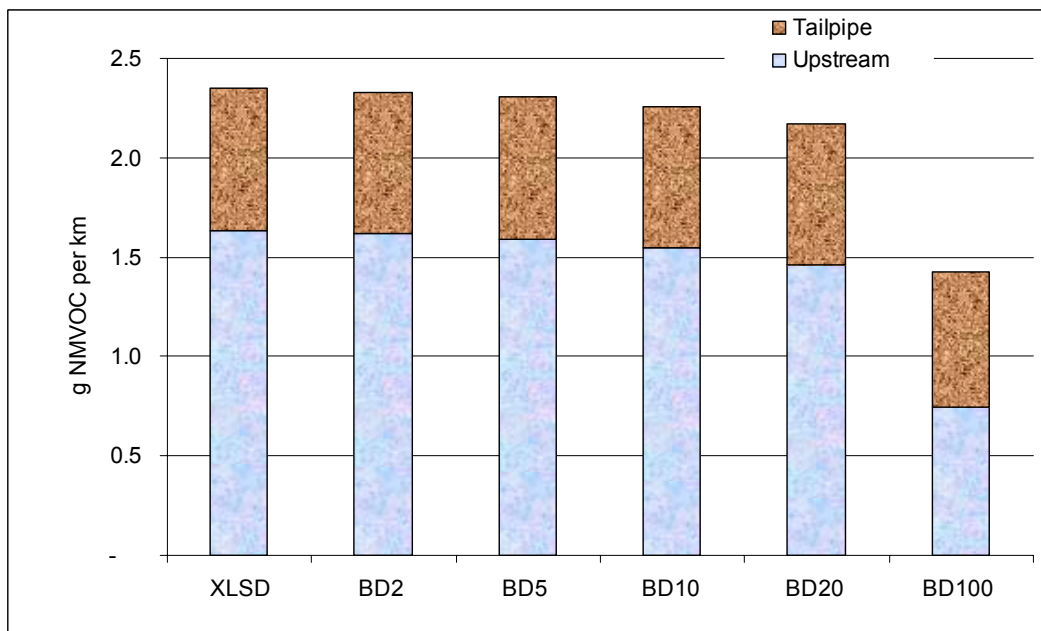
Figure 11-54: Palm oil (cleared peat swamp forest) XLSD biodiesel blends total non-methanic hydrocarbon emissions in g/km for a truck
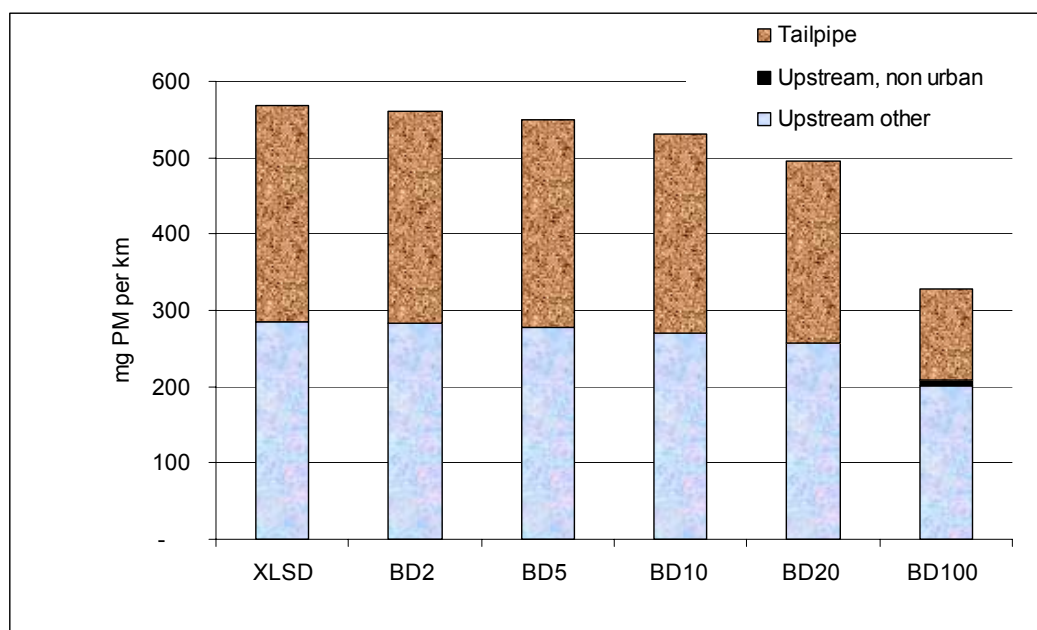
Figure 11-55: Palm oil (cleared peat swamp forest) XLSD biodiesel blends particulate matter (PM10) emissions in mg/km for a truck

11.2.5 Tallow biodiesel blends with XLSD

Table 11.11: Upstream and tailpipe emissions (per km) for XLSD biodiesel blends using tallow

Impact category	Unit	XLSD	BD2	BD5	BD10	BD20	BD100
CO_2 (Upstream)	g CO_2	129	128	128	126	124	104
Methane (Upstream)	g CH_4	1.35	1.33	1.29	1.24	1.12	0.16
N_2O (Upstream)	g N_2O	0.001	0.007	0.016	0.031	0.062	0.312
Sequestration	g CO_2	0.000	0.000	0.000	0.000	0.000	0.000
Other	g CO_2-e	0.000	0.000	0.000	0.000	0.000	0.001
CO_2 (Tailpipe)	g CO_2	692	679	658	624	557	0
Methane (Tailpipe)	g CH_4	0.01	0.01	0.01	0.01	0.01	0.01
N_2O (Tailpipe)	g N_2O	0.016	0.016	0.016	0.016	0.016	0.015
CO (Upstream)	g CO	3.15	3.14	3.12	3.09	3.04	2.83
CO (Tailpipe)	g CO	2.81	2.78	2.74	2.68	2.55	1.74
NO_x (Upstream)	g NO_x	8.75	8.78	8.82	8.88	9.01	10.06
NO_x (Tailpipe)	g NO_x	8.40	8.42	8.46	8.51	8.62	9.55
NMVOC (Upstream)	g NMVOC	1.63	1.62	1.59	1.55	1.46	0.74
NMVOC (Tailpipe)	g NMVOC	0.72	0.71	0.71	0.71	0.71	0.67
Particles (Upstream)	mg PM10	286	282	278	270	256	203
Particles (non-urban)	mg PM10	0	0	0	0	0	1
Particles (Tailpipe)	mg PM10	283	278	271	259	237	115
Greenhouse equivalents total	g CO_2-e	855	842	823	792	728	209
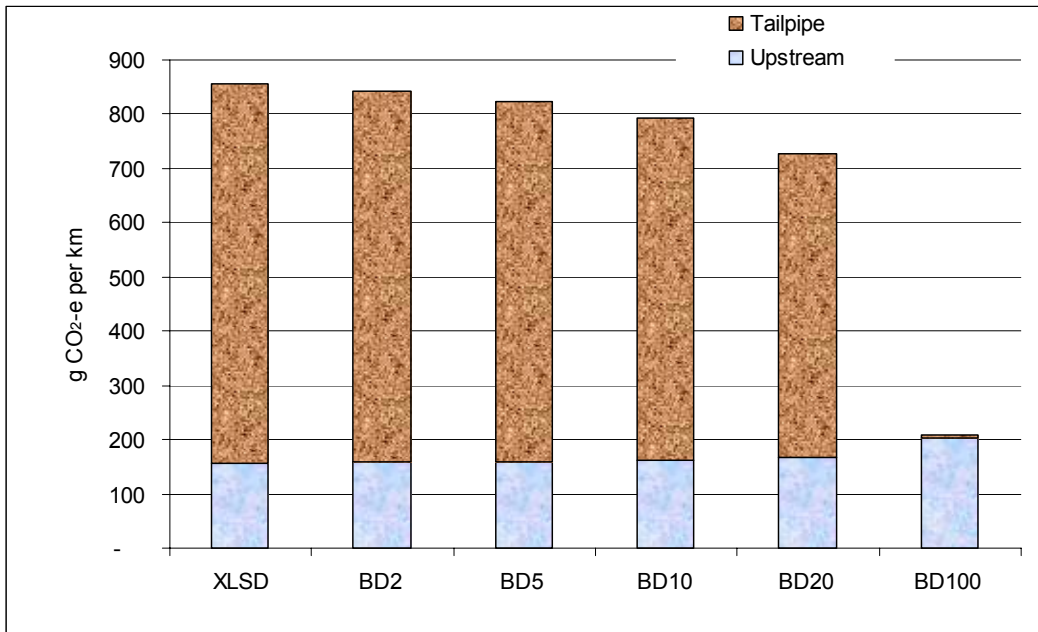
Figure 11-56: Tallow XLSD biodiesel blends greenhouse gas emissions in g/km for a truck
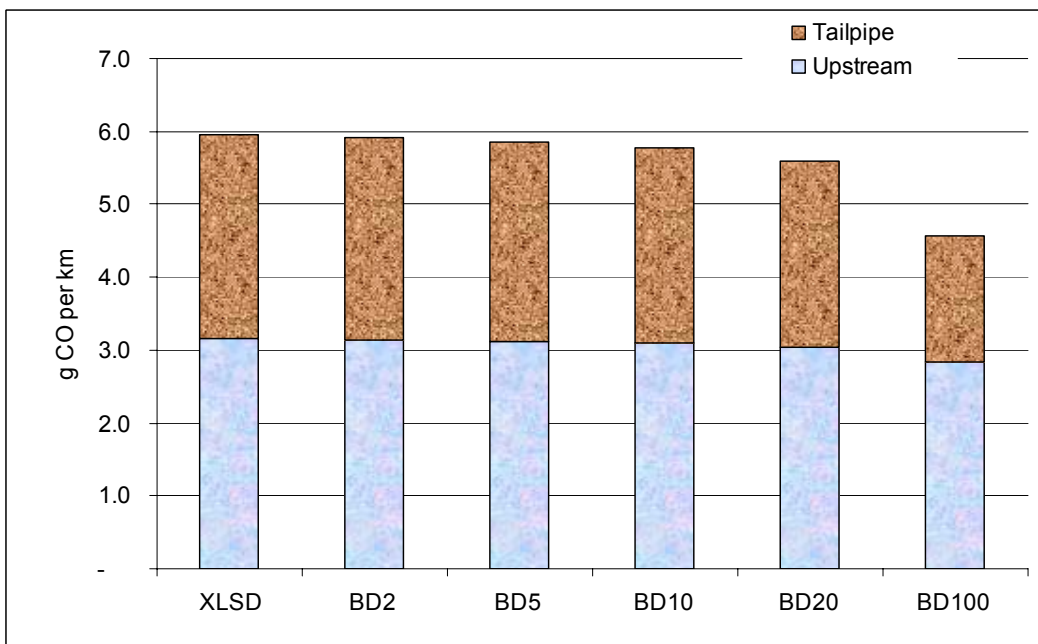
Figure 11-57: Tallow XLSD biodiesel blends carbon monoxide emissions in g/km for a truck
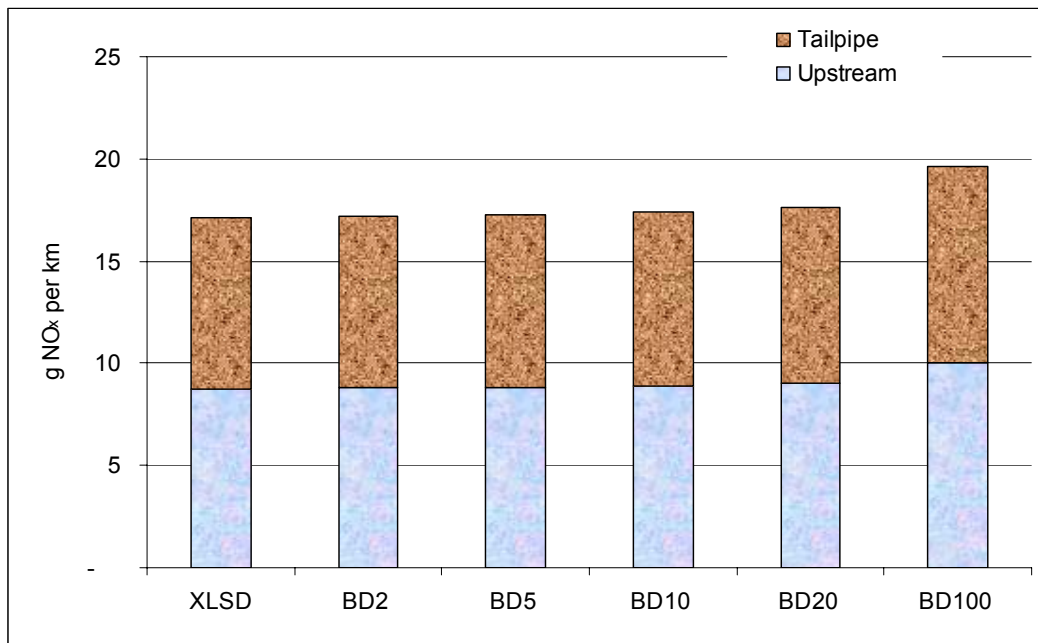
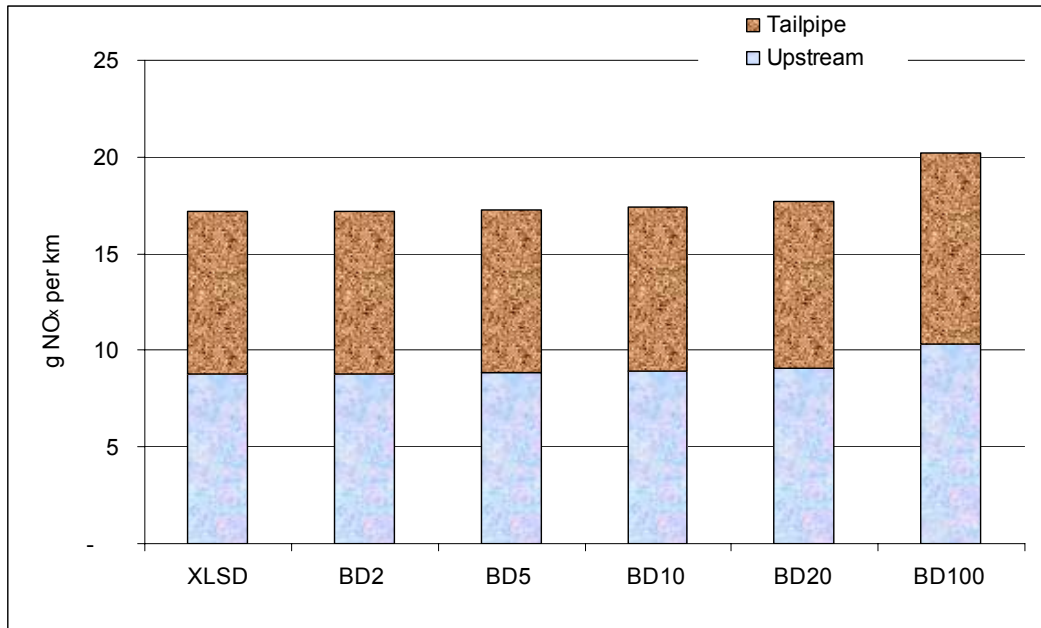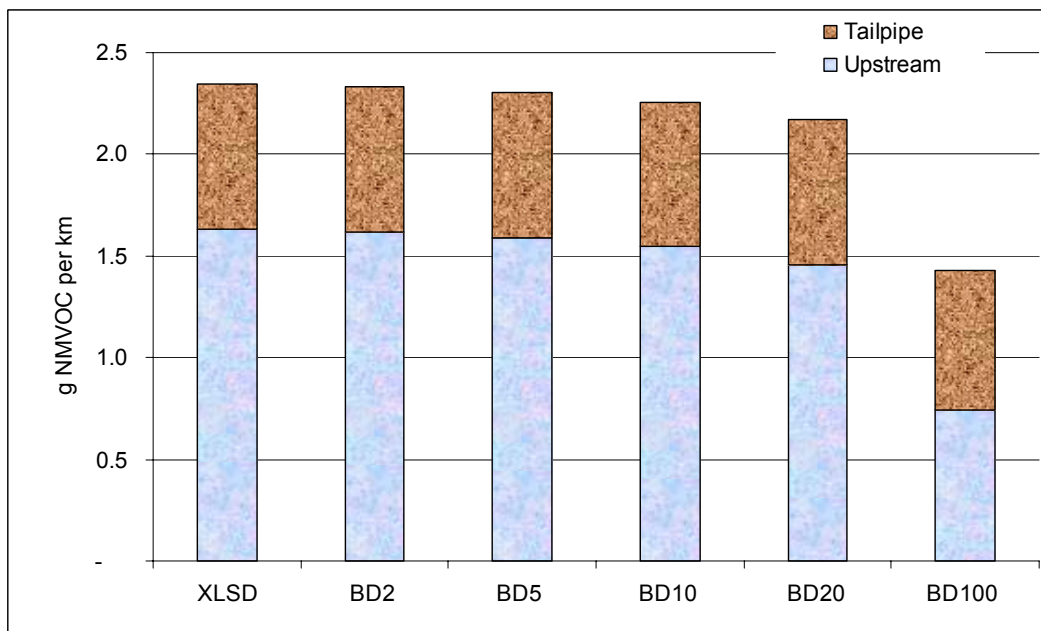Figure 11-58: Tallow XLSD biodiesel blends emissions of oxides of nitrogen in g/km for a truck
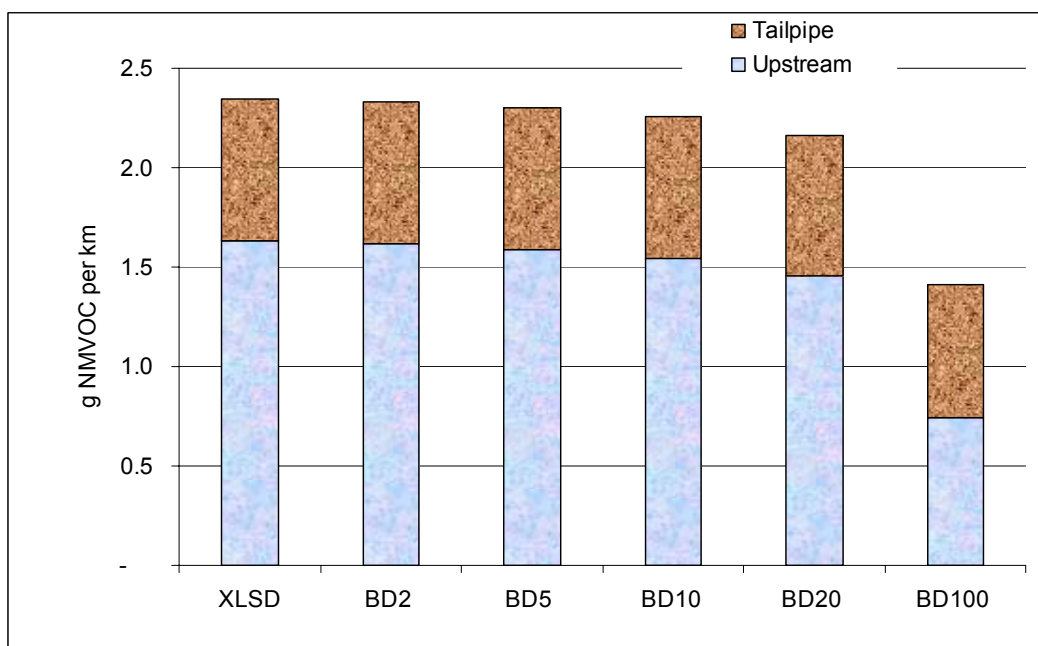
Figure 11-59: Tallow XLSD biodiesel blends total non-methanic hydrocarbon emissions in g/km for a truck
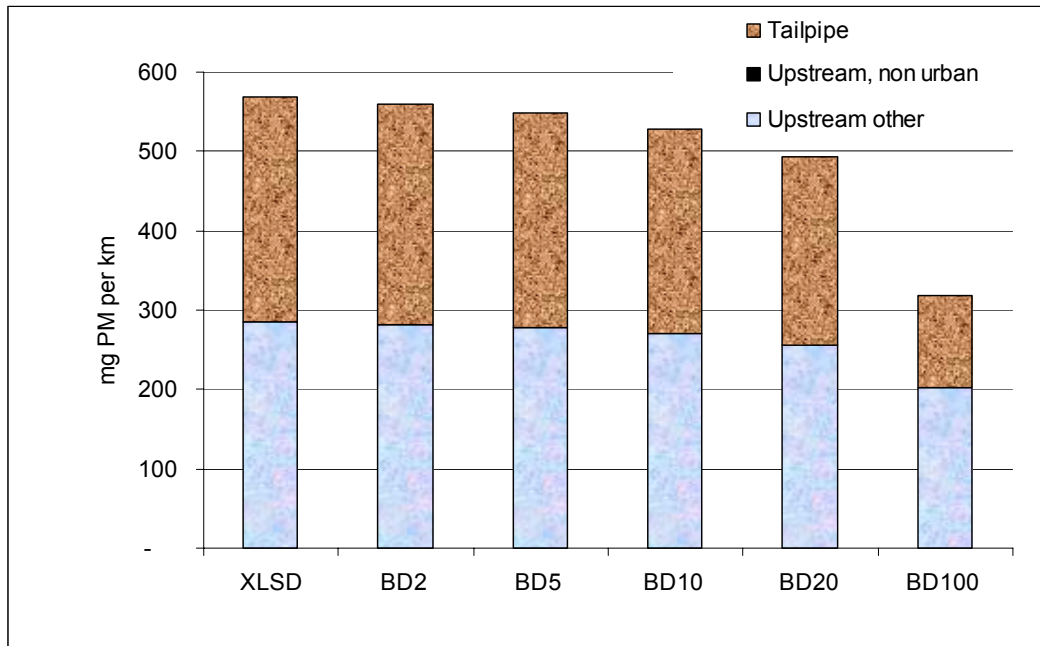
Figure 11-60: Tallow XLSD biodiesel blends particulate matter (PM10) emissions in mg/km for a truck

11.2.6 Used cooking oil biodiesel blends with XLSD

Table 11.12: Upstream and tailpipe emissions (per km) for XLSD biodiesel blends using used cooking oil

Impact category	Unit	XLSD	BD2	BD5	BD10	BD20	BD100
CO_2 (Upstream)	g CO_2	129	128	127	126	123	101
Methane (Upstream)	g CH_4	1.35	1.33	1.29	1.23	1.11	0.14
N_2O (Upstream)	g N_2O	0.001	0.001	0.001	0.001	0.001	0.001
Sequestration	g CO_2	0.000	0.000	0.000	0.000	0.000	0.000
Other	g CO_2-e	0.000	0.000	0.001	0.002	0.004	0.019
CO_2 (Tailpipe)	g CO_2	692	679	658	624	557	0
Methane (Tailpipe)	g CH_4	0.01	0.01	0.01	0.01	0.01	0.01
N_2O (Tailpipe)	g N_2O	0.016	0.016	0.016	0.016	0.016	0.015
CO (Upstream)	g CO	3.15	3.12	3.08	3.02	2.90	2.10
CO (Tailpipe)	g CO	2.81	2.78	2.74	2.68	2.55	1.74
NO_x (Upstream)	g NO_x	8.75	8.77	8.81	8.86	8.97	9.87
NO_x (Tailpipe)	g NO_x	8.40	8.42	8.46	8.51	8.62	9.55
NMVOC (Upstream)	g NMVOC	1.63	1.62	1.59	1.55	1.46	0.74
NMVOC (Tailpipe)	g NMVOC	0.72	0.71	0.71	0.71	0.71	0.67
Particles (Upstream)	mg PM10	286	281	274	262	241	125
Particles (non-urban)	mg PM10	0	0	0	0	0	0
Particles (Tailpipe)	mg PM10	283	278	271	259	237	115
Greenhouse equivalents total	g CO_2-e	855	840	818	782	709	109
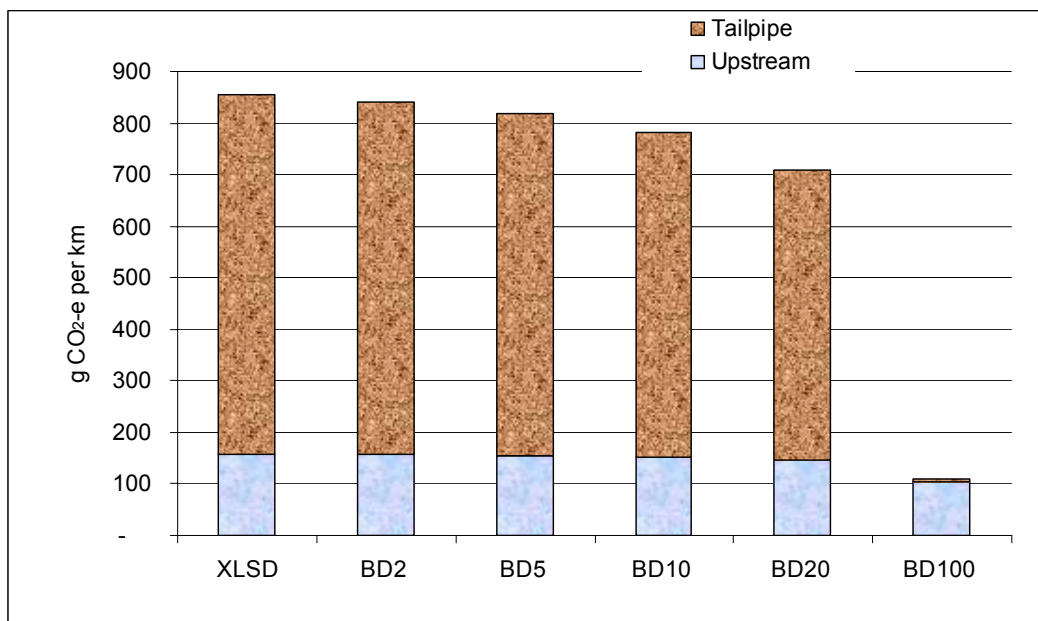
Figure 11-61: Used cooking oil XLSD biodiesel blends greenhouse gas emissions in g/km for a truck
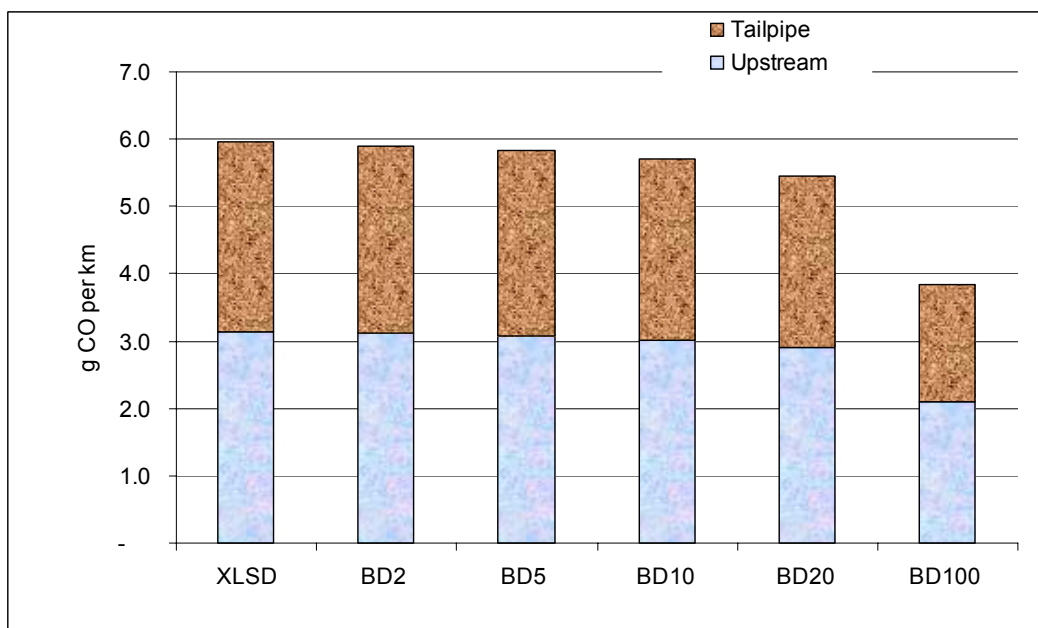
Figure 11-62: Used cooking oil XLSD biodiesel blends carbon monoxide emissions in g/km for a truck
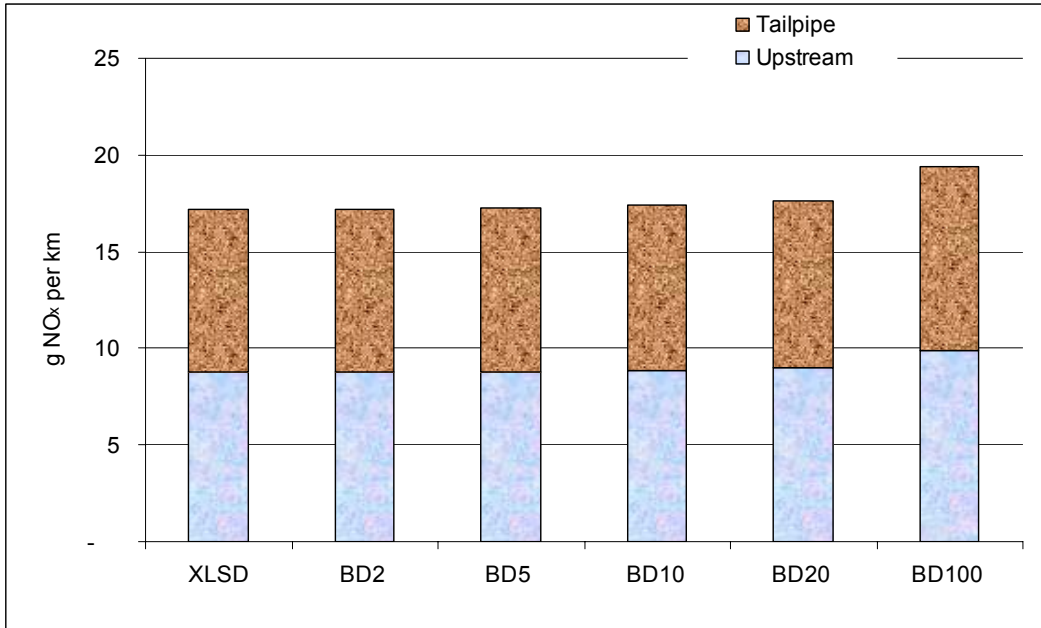
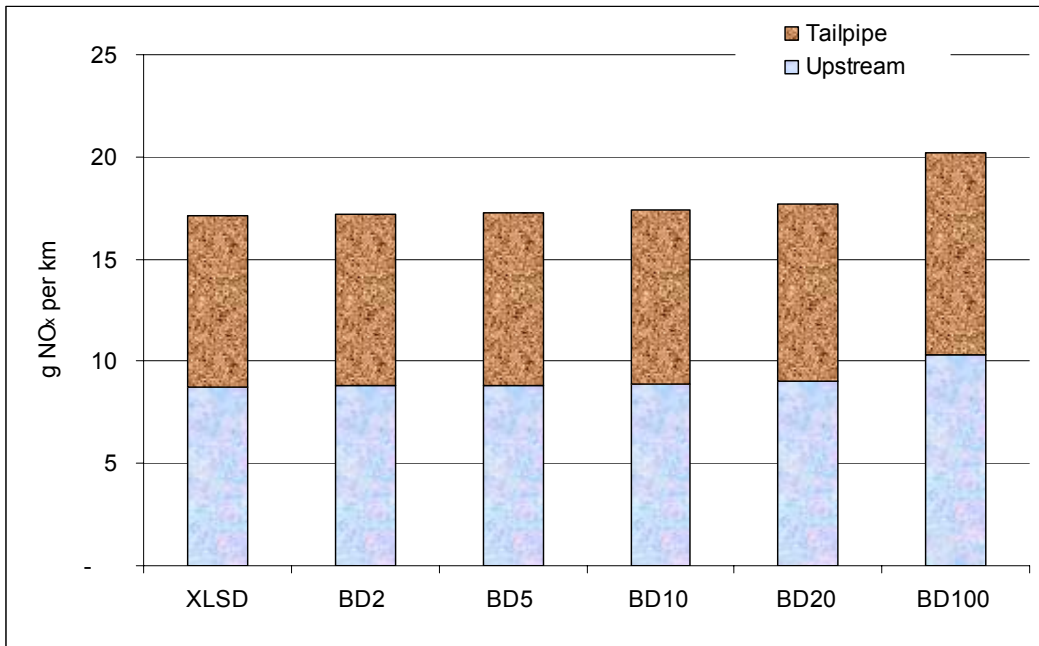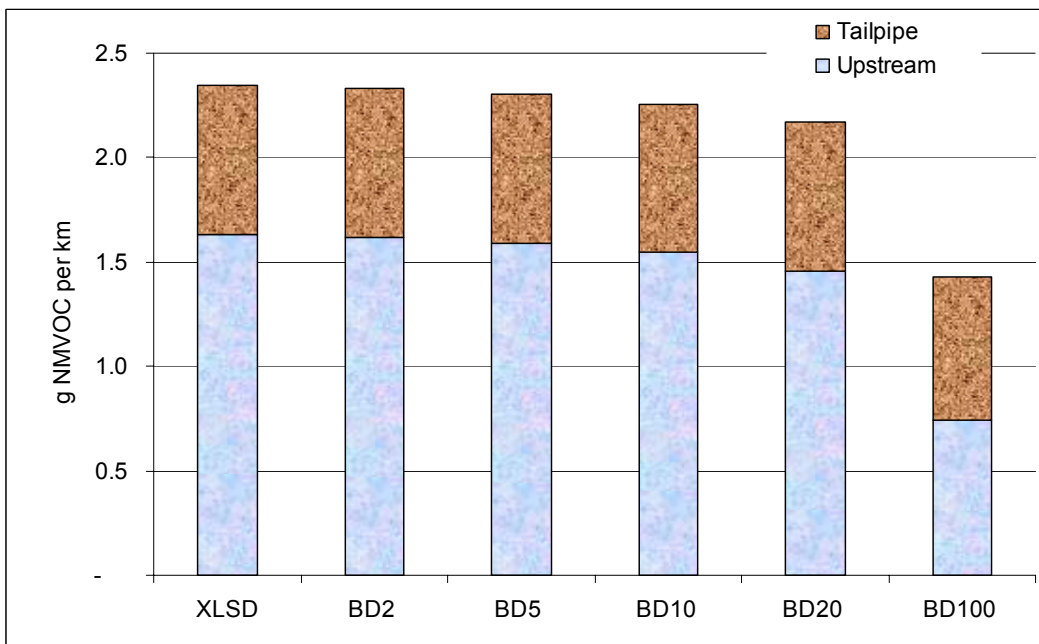Figure 11-63: Used cooking oil XLSD biodiesel blends emissions of oxides of nitrogen in g/km for a truck
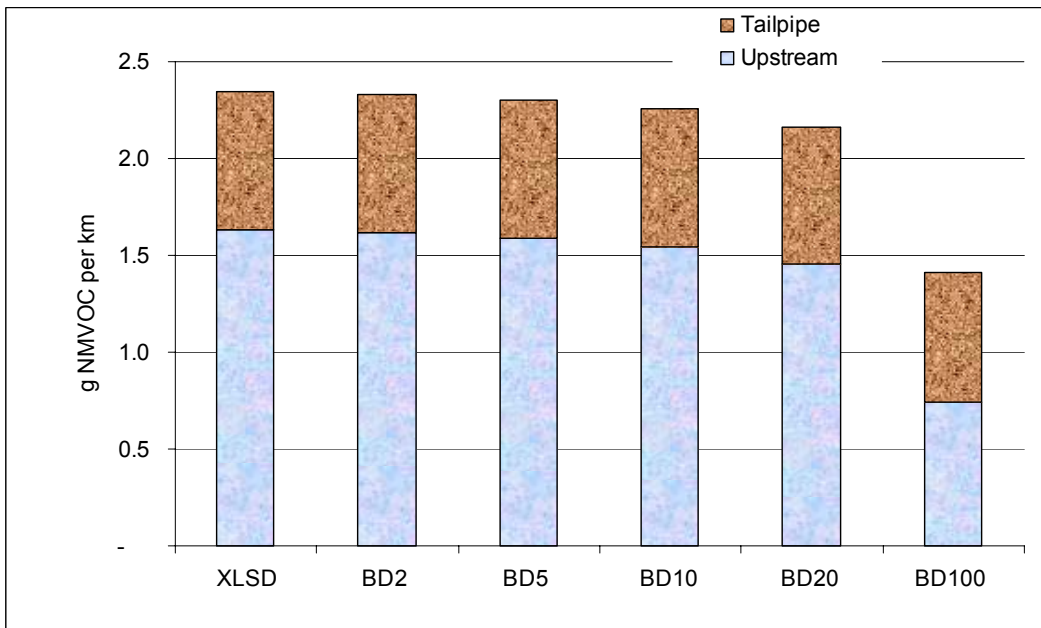
Figure 11-64: Used cooking oil XLSD biodiesel blends total non-methanic hydrocarbon emissions in g/km for a truck
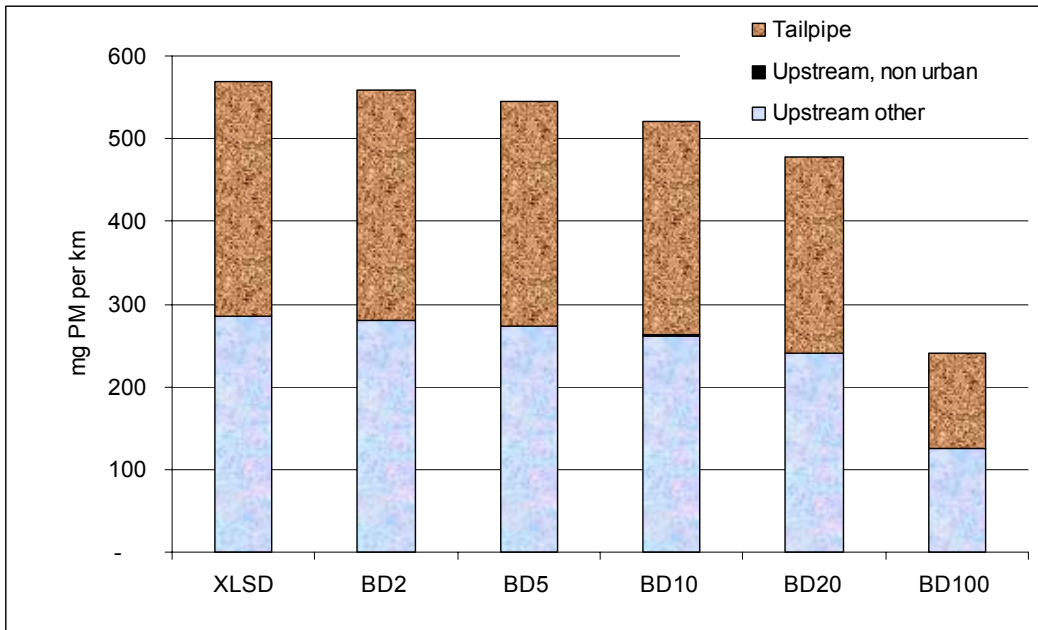
Figure 11-65: Used cooking oil XLSD biodiesel blends particulate matter (PM10) emissions in mg/km for a truck

Figure 11-66 to Figure 11-69 diagrammatically illustrates the life-cycle greenhouse gas emissions from BD2, BD5, BD10 and BD20 for different feedstock sources. Figure 11-70 and Figure 11-71 illustrate the results for 100% biodiesel (BD100) compared with ULS diesel and XLS diesel. The latter graph has the Y-axis truncated to show the differences between the non palm oil based fuels.
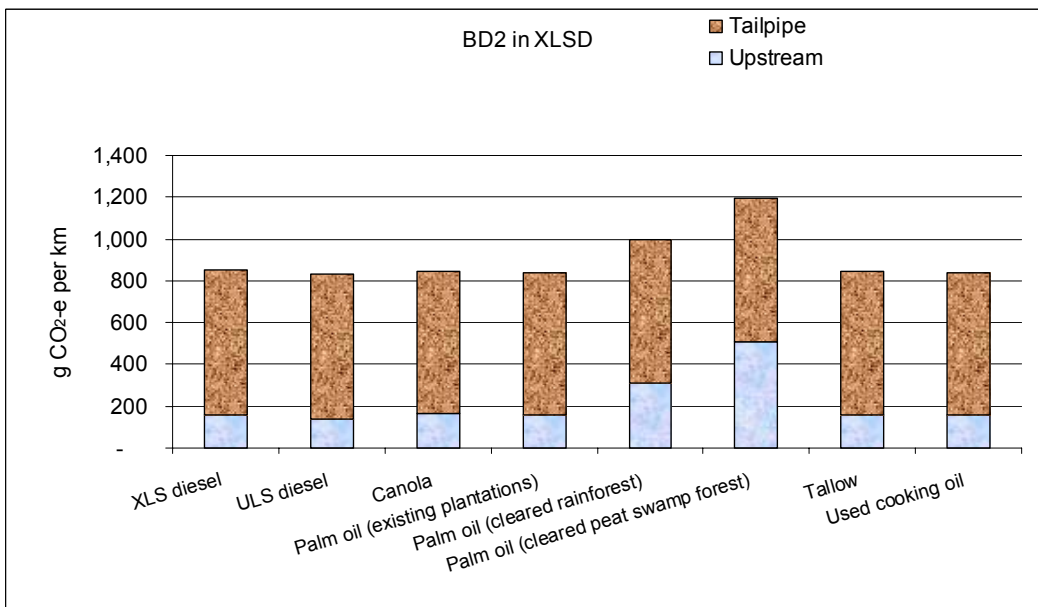
Figure 11-66: Full life cycle GHG emissions from 2% XLSD biodiesel (per km NEPM rigid truck)
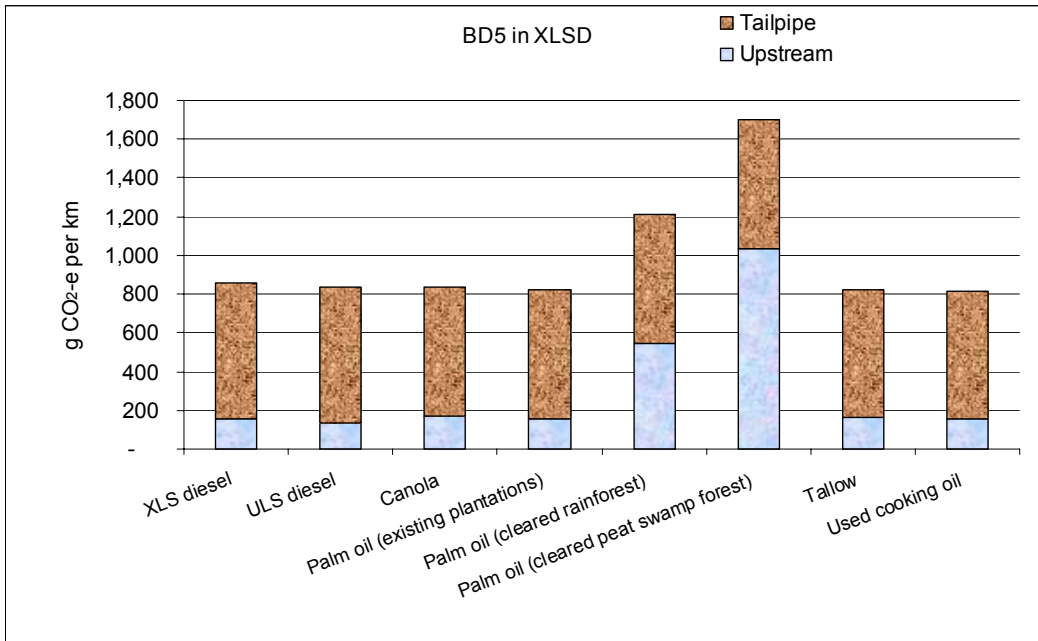
Figure 11-67: Full life cycle GHG emissions from 5% XLSD biodiesel (per km NEPM rigid truck)
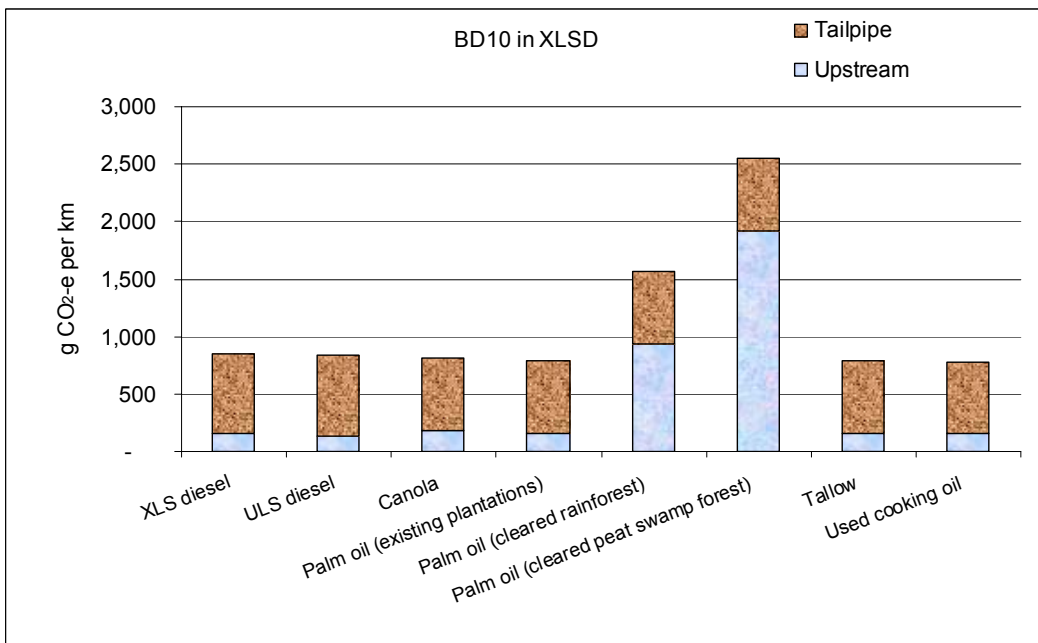
Figure 11-68: Full life cycle GHG emissions from 10% XLSD biodiesel (per km NEPM rigid truck)
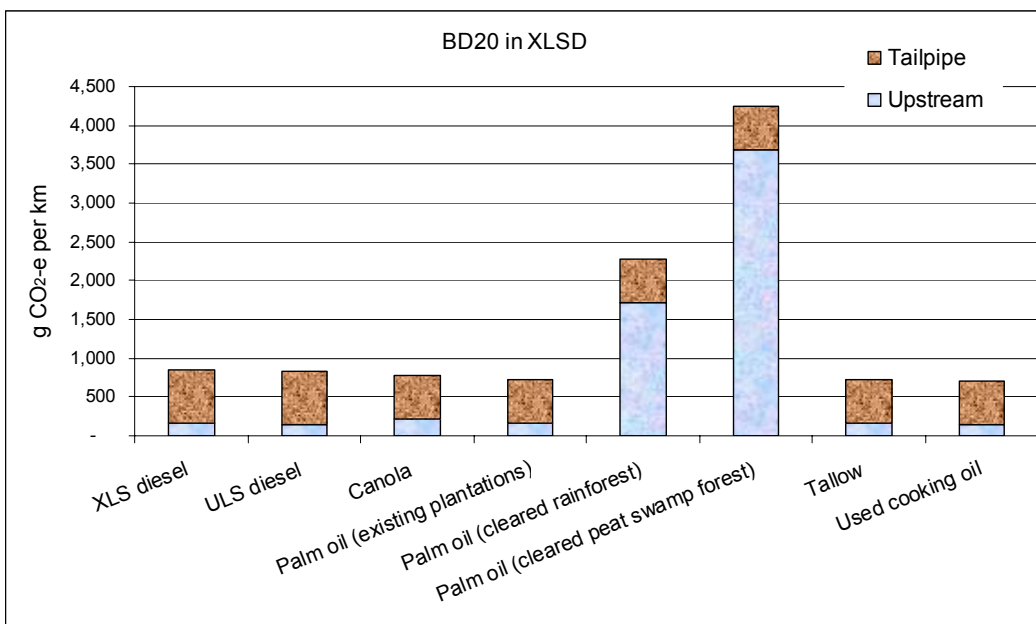
Figure 11-69: Full life cycle GHG emissions from 20% XLSD biodiesel (per km NEPM rigid truck)
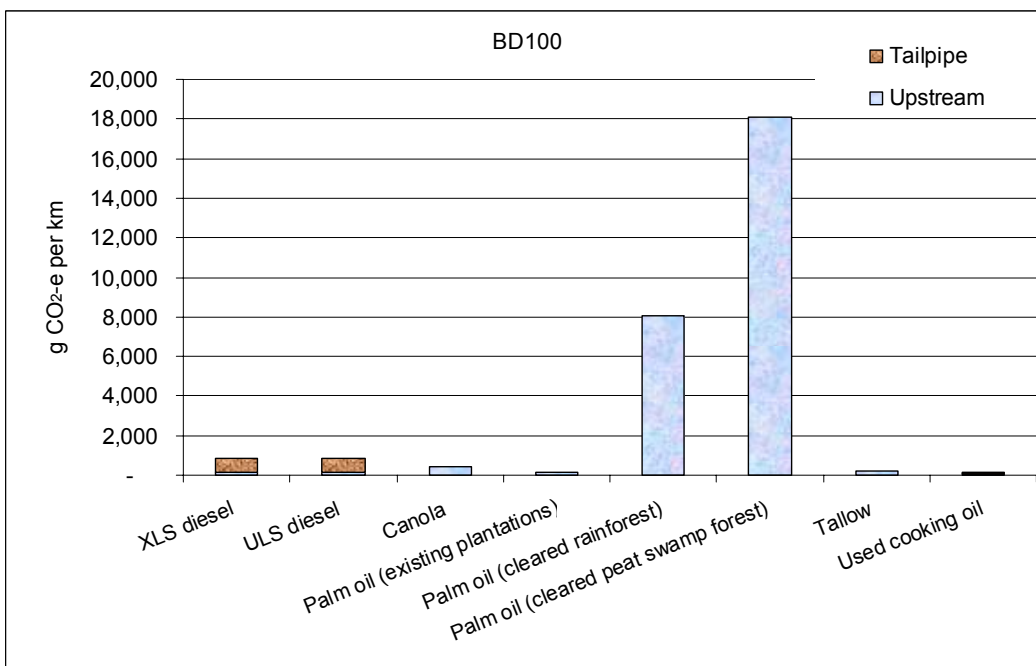
Figure 11-70: Full life cycle GHG emissions from 100% biodiesel - BD100 (per km NEPM rigid truck)
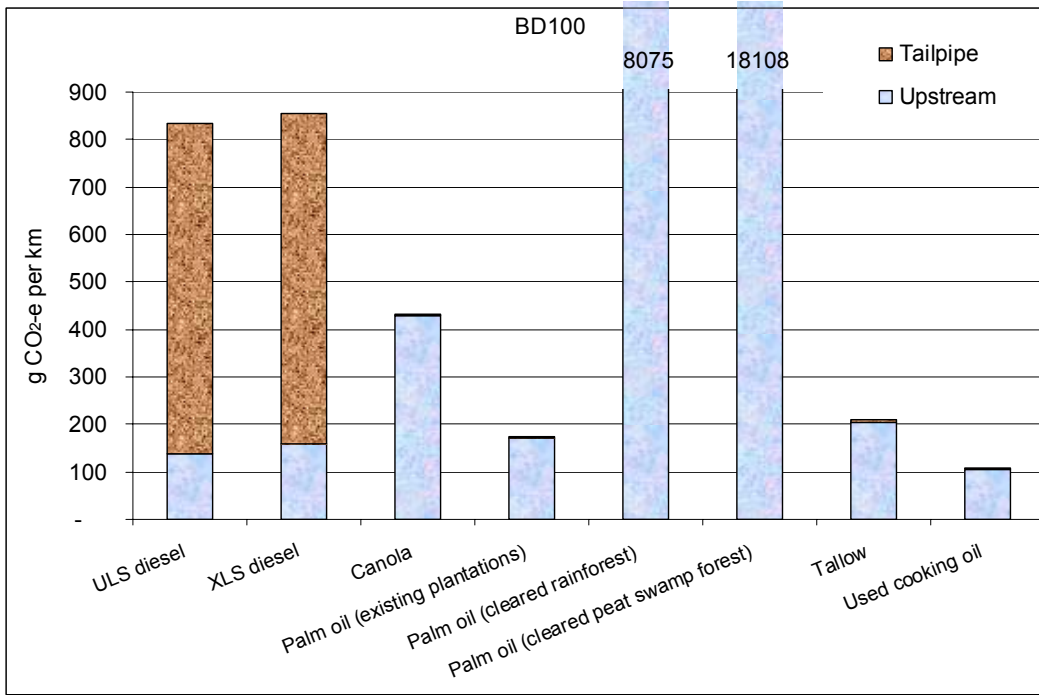
Figure 11-71: Full life-cycle GHG emissions from 100% biodiesel - BD100 (per km NEPM rigid truck) (truncated Y axis)

12   DISCUSSION AND CONCLUSIONS

The upstream processes of growing and harvesting canola lead to upstream GHG emissions that are approximately 3.5 times higher than upstream emissions from refining the diesel. Tallow has upstream GHG emissions that are approximately 50% higher than the upstream emissions of diesel, whereas those of used cooking oil are slightly lower. Upstream GHG emissions of palm oil depend on whether the plantation was established before 1990, in which case the emissions associated with land clearing and with soil disturbance are not counted as greenhouse gas emissions under present methods of carbon accounting.   In this case upstream greenhouse gas emissions are approximately 25% higher than the upstream emissions associated with diesel refining. If, however, rain forest or peat swamp forest is cleared for palm oil growing, then the upstream emissions range from 50 to 136 *times* higher.

When using BD100 produced from tallow, canola, used cooking oil or plantation-based palm oil then the carbon dioxide emissions are offset by the carbon dioxide sequestered during the feedstock production so that the tailpipe GHG emissions are zero, which is to say that the emissions of fossil carbon are zero. However, fossil carbon or other greenhouse gases are emitted during the growth or manufacture of the feedstock. Overall this results in a saving in total life-cycle GHG emissions when the feedstock is canola (422 g CO_2-e/km saving; 49%), tallow (646 g CO_2-e/km saving; 76%), used cooking oil (746 g CO_2-e/km saving; 87%) or palm oil from existing plantations (680 g CO_2-e/km saving; 80%) when compared to XLS diesel, which emits 855 g CO_2-e/km (Table 12.5). GHG emissions from palm oil that is sourced from cleared rain- or peat swamp forest are 8 to 21 times respectively greater than those from diesel.

The extra upstream processing required for reducing the sulfur content results in higher GHG emissions for XLS diesel compared with ULS diesel. The highest savings in GHG emissions are obtained by replacing base diesel with biodiesel from used cooking oil (725 g CO_2-e/km for ULSD to 746 g CO_2-e/km for XLSD).

The large difference between the upstream emission of tallow and used cooking oil are based on the assumption that the tallow is being taken from existing market uses and is not a waste product, whereas the used cooking oil is taken to be a true waste, with no existing market. If low-grade tallow, with no other viable markets, was available, its emission profile would be similar to that of used cooking oil. However, low-grade tallow does require more processing to produce biodiesel than high-grade (edible) tallow.

Blends with 2% biodiesel lead to much smaller GHG savings (when there are savings) or much smaller increases (when there are increases): the savings are 14-15 g CO_2-e/km for used cooking oil blends when using BD2 compared with diesel; 12-13 g CO_2-e/km for tallow biodiesel; and 7-8 g CO_2-e/km for canola oil biodiesel. Palm oil based BD2 produces savings of 12-13 g CO_2-e/km if the palm oil comes from existing plantations, but can lead to increases in GHG emissions that range from 142 to 338 g CO_2-e/km if the palm oil comes from cleared rainforest or cleared peat swamp forest respectively. If palm oil was to be grown in Australia (rather than imported from Asia), the emissions are likely to increase further because of the greater use of mechanisation in Australian agriculture, with its concomitant increase in greenhouse gas emissions.

Life-cycle emissions of CO, NMVOC, and particles are reduced when biodiesel blends are used, but emissions of NO_x may increase slightly.

Table 12.1: Summary of Greenhouse Gas Emissions (g CO_2-e/km) from BD2 for various feedstocks

	Diesel	Canola	Palm oil from existing plantation	Palm oil from rain-forest	Palm oil from peat swamp forest	Tallow	Used cooking oil
ULSD	834	827	822	976	1172	822	820
Difference		-7	-12	142	338	-12	-14
% change		-0.89%	-1.49%	17.02%	40.54%	-1.46%	-1.69%
XLSD	855	847	842	996	1193	842	840
Difference		-8	-13	142	338	-13	-15
% change		-0.92%	-1.51%	16.56%	39.51%	-1.47%	-1.70%

Table 12.2: Summary of Greenhouse Gas Emissions (g CO_2-e/km) from BD5 for various feedstocks

	Diesel	Canola	Palm oil from existing plantation	Palm oil from rain-forest	Palm oil from peat swamp forest	Tallow	Used cooking oil
ULSD	834	815	803	1189	1680	804	799
Difference		-19	-31	355	846	-30	-35
% change		-2.2%	-3.7%	42.6%	101.4%	-3.7%	-4.2%
XLSD	855	835	823	1209	1700	823	818
Difference		-20	-32	354	845	-31	-36
% change		-2.3%	-3.8%	41.4%	98.8%	-3.7%	-4.3%

Table 12.3: Summary of Greenhouse Gas Emissions (g CO_2-e/km) from BD10 for various feedstocks

	Diesel	Canola	Palm oil from existing plantation	Palm oil from rain-forest	Palm oil from peat swamp forest	Tallow	Used cooking oil
ULSD	834	797	771	1545	2527	773	763
Difference		-37	-63	711	1693	-61	-71
% change		-4.5%	-7.5%	85.2%	203.0%	-7.3%	-8.5%
XLSD	855	815	790	1564	2546	792	782
Difference		-39	-65	709	1691	-63	-73
% change		-4.6%	-7.6%	82.9%	197.9%	-7.4%	-8.5%

Table 12.4: Summary of Greenhouse Gas Emissions (g CO_2-e/km) from BD20 for various feedstocks

	Diesel	Canola	Palm oil from existing plantation	Palm oil from rain-forest	Palm oil from peat swamp forest	Tallow	Used cooking oil
ULSD	834	759	708	2259	4228	712	692
Difference		-75	-126	1425	3394	-122	-142
% change		-9.0%	-15.1%	170.8%	406.9%	-14.7%	-17.0%
XLSD	855	776	725	2275	4245	728	709
Difference		-79	-130	1421	3390	-126	-146
% change		-9.3%	-15.2%	166.2%	396.5%	-14.8%	-17.1%

Table 12.5: Summary of Greenhouse Gas Emissions (g CO_2-e/km) from BD100 for various feedstocks

	Diesel	Canola	Palm oil from existing plantation	Palm oil from rain-forest	Palm oil from peat swamp forest	Tallow	Used cooking oil
ULSD	834	433	175	8075	18108	209	109
Difference		-401	-659	7241	17274	-625	-725
% change		-48.1%	-79.0%	868.2%	2071.1%	-75.0%	-87.0%
XLSD	855	433	175	8075	18108	209	109
Difference		-422	-680	7220	17253	-646	-746
% change		-49%	-80%	845%	2018%	-76%	-87%

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14 APPENDIX A - CORRELATIONS DESCRIBED IN EPA 2002

The following correlations were developed in EPA 2002 and used to estimate emission variation in this study. However within the parameters of the correlation, all diesel fuel was assumed to be "clean diesel" and all vehicles were included in the correlation, not just those from the group E mix of vehicles (which were 1991-1993 vehicles).

Equation 14-1: Formulae for Correlations

% change in NOx =
{exp[+ 0.0010375 × (vol% biodiesel)
+ 0.0012289 × CLEAN × (vol% biodiesel)
- 0.0002732 × RAPE × (vol% biodiesel)
- 0.0009795 × ANIMAL × GROUP E × (vol% biodiesel)] - 1} × 100%

% change in PM =
{exp[- 0.0047395 × (vol% biodiesel)
+ 0.0010742 × CLEAN × (vol% biodiesel)
- 0.0045908 × GROUP E × (vol% biodiesel)
- 0.0019343 × ANIMAL × GROUP E × (vol% biodiesel)] - 1} × 100%

% change in HC =
{exp[- 0.0118443 × (vol% biodiesel)
+ 0.0047569 × CLEAN × (vol% biodiesel)] - 1} × 100%

% change in CO =
{exp[- 0.0058238 × (vol% biodiesel)
+ 0.0010853 × CLEAN × (vol% biodiesel)
+ 0.0017335 × RAPE × (vol% biodiesel)
- 0.0017116 × ANIMAL × GROUP E × (vol% biodiesel)] - 1} × 100%

where

vol% biodiesel = Value from 0 to 100
CLEAN = 1 if the base fuel is clean diesel as described in Section 10.4; otherwise, CLEAN = 0
ANIMAL = 1 if the biodiesel is produced from animal fat, tallow, or lard; otherwise, ANIMAL = 0
RAPE = 1 if the biodiesel is produced from rapeseed oil or canola oil; otherwise, RAPE = 0
GROUP E = 1 if the highway engines being evaluated are model years 1991 to 1993; otherwise, GROUP E = 0

15 APPENDIX B – LITERATURE SEARCH ON BIODIESEL EMISSIONS

Diesel engine performance and NO$_x$ emissions from oxygenated biofuels and blends with diesel fuel
Hansen, AC, Gratton, MR, Yuan, W, AF Hansen, A. C. Gratton, M. R., Yuan, W.
TRANSACTIONS OF THE ASABE, Vol. 49 (3), 2006, p. 589-595.
Increased pressure from federal and state agencies to improve air quality has resulted in extensive research into the use of biofuels to reduce diesel engine emissions. Oxygenated biofuels such as biodiesel and ethanol blended with diesel fuel are biodegradable, non-toxic, renewable alternatives to imported petroleum diesel, and their use not only creates new markets for domestic agricultural products, but also greatly reduces particulate emissions. Unfortunately, biodiesel has been shown to increase NO$_x$ emissions upwards of 10% compared to petroleum diesel. The objective of this investigation was to evaluate the performance and NO$_x$ emissions of selected biofuels and blends with petroleum-based diesel fuel in a turbocharged and intercooled diesel engine using a steady-state non-road ISO 8-mode test schedule. Test fuels included traditional No. 2 diesel and four biofuels comprising 100% soy methyl ester biodiesel, 2% biodiesel, 10% ethanol-diesel fuel, and 5% ethanol in biodiesel. Exhaust NO$_x$ emissions were monitored with a Horiba NO$_x$ analyser. Reductions in peak torque varying from less than 0.5% to about 10% were measured with the test fuels and were attributed mainly to reduced energy content. Biodiesel fuel showed a 12% increase in NO$_x$ emissions, while 2% biodiesel fuel increased emissions 2.3%. The ethanol-diesel fuel blend reduced NO$_x$ emissions by 2.7% and was highly sensitive to load, with increased temperature and NO$_x$ emissions at light load. Addition of only 5% ethanol to biodiesel suppressed NO$_x$ emissions, with only a 2.6% increase occurring. It was concluded that ethanol could act as an effective NO$_x$ emissions reducing additive.

Fueling direct injected diesel engines with 2% biodiesel blend
Schumacher, LG Soylu, S, Van Gerpen, J Wetherell, W.
APPLIED ENGINEERING IN AGRICULTURE, Vol. 21 (2) Mar 2005, p. 149-152.
The Agricultural Engineering Department at the University of Missouri-Columbia has monitored the fuelling of a 1996 Dodge pickup truck equipped with a 5.9-L (360-in.(3)) Cummins engine with a 2% blend of methyl-ester soybean oil (soydiesel/biodiesel) and petroleum diesel fuel (BD2) for more than 65,352 km (40,608 miles). The pickup averaged 7.91 km/L (18.61 miles/gallon). Analysis of engine lubrication oil suggested that the engine was wearing at a normal rate. Exhaust emissions were measured at Iowa State University. The black exhaust smoke normally observed when a diesel engine accelerates was reduced each time the engine was fuelled with BD2, but CO, HC and NO$_x$ were not affected.

Aromatic hydrocarbon emissions in diesel and biodiesel exhaust
Correa, S.M., Arbilla, G.
ATMOSPHERIC ENVIRONMENT, Vol. 40 (35), Nov 2006, p. 6821-6826.
Regulated emissions of biodiesel blends are reasonably well documented in several works, non-regulated emissions, on the contrary, lack research. In this work, mono- and polycyclic aromatic hydrocarbons (MAHs and PAHs, respectively) emission tests were performed with a heavy-duty diesel engine, fuelled with pure diesel (D) and biodiesel blends (v/v) of 2% (BD2), 5% (BD5) and 20% (BD20). The main objective of this study is to investigate the effect of the biodiesel addition on the emission profile of MAHs and PAHs. The tests were conducted using a six cylinder heavy-duty engine, typical of the Brazilian fleet of urban buses, in a steady-state condition under 1500 rpm. The PAHs were sampled with Teflon filters and XAD-2 cartridges and were identified by gas chromatograph coupled to a mass spectrometer (GC/MS) and quantified by flame ionization detection (GC/FID). The MAHs were sampled with active charcoal cartridges and analysed by GC/FID. Both MAHs and PAHs filters and cartridges were extracted with dichloromethane in an ultrasonic bath. Ten PAHs and eight MAHs were identified and the average reduction of MAHs was 4.2% (BD2), 8.2% (BD5), and 21.1% (BD20). The average reduction for PAHs was 2.7% (BD2), 6.3% (BD5), and 17.2% (BD20). However, some PAHs and MAHs emissions increased because of/due to the biodiesel blends like phenanthrene, ethyl benzene, and trimethyl benzenes.

Comparison of PAH and regulated harmful matter emissions from biodiesel blends and paraffinic fuel blends on engine accumulated mileage test
Lin, YC, Lee, WJ, Wu, TS, Wang, CT
FUEL, Vol 85 (17-18), Dec 2006, p. 2516-2523

This study investigated polycyclic aromatic hydrocarbon (PAH) and regulated harmful matter (traditional pollutant) emissions, fuel consumption, and the assessment of the inferior condition of engine oil from heavy-duty diesel engines (HDDEs) fueled with palmbio-diesel-PDF (premium diesel fuel) blends and paraffinic-palmbiodiesel blends under brand-new (the mileage was zero) engines accumulated mileage test. Experimental results indicated that the emissions of THC and CO increased with operation time but the emissions of NO_x and PAHs decreased with operation time between 0 and 300 h (18,000 km). Using palmbiodiesel-PDF blends or paraffinic-palmbiodiesel blends instead of PDF in HDDEs reduced the emissions of THC (10.7-44.2%), CO (0.664-15.6%), CO_2 (0.763-2.55%), NO_x (1.25-4.97%), PM (6.11-26.8%), total PAHs (43.0-90.2%) and total BaPeq (63.1-89.6%) significantly. (c)

Characteristics of carbonyl compounds emission from a diesel-engine using biodiesel-ethanol-diesel as fuel
Pang, XB, Shi, XY, Mu, YJ, He, H, Shuai, SJ, Chen, H, Li, RL
ATMOSPHERIC ENVIRONMENT, Vol 40 (36), Nov 2006, pp. 7057-7065

Characteristics of carbonyl compounds (carbonyls) emissions from biodiesel-ethanol-diesel (BE-diesel) were investigated in a Commins-4Bdiesel engine and compared with those from fossil diesel. Acetaldehyde was the most abundant carbonyls in the exhaust, followed by formaldehyde, acetone, propionaldehyde and benzaldehyde. Apliphatic carbonyls emitted from BE-diesel were higher than those from diesel fuel, while formaldehyde and aromatic carbonyls were less than those from diesel fuel. Total carbonyls emissions from BE-diesel were 1-12% higher than those from diesel fuel depending on engine operating conditions. The effects of engine speed and load level were also investigated carefully. It was found that total carbonyls emission was in positive correlation with the engine speed. During the constant speed/varying load tests, minimum total carbonyls emission was found at 50% load. Compared with fossil diesel, the BE-diesel was observed to significantly reduce PM emission and increase slightly NO, emission.

Particulate emission characterization of a biodiesel vs diesel-fuelled compression ignition transport engine: A comparative study
Dwivedi, D, Agarwal, AK, Sharma, M
ATMOSPHERIC ENVIRONMENT, Vol 40 (29) Sep 2006, p. 5586-5595

This study was set out to characterize particulate emissions from diesel engines fuelled by (i) mineral diesel and (ii) BD20 (a blend of 20% biodiesel with diesel); in terms of metals and benzene soluble organic fraction (BSOF), which is an indicator of toxicity and carcinogenicity. A medium duty, transport diesel engine (Mahindra MDI 3000) was operated at idling, 25%, 50%, 75% and rated load at maximum torque speed (1800 rpm) and samples of particulate were collected using a partial flow dilution tunnel for both fuels. Collected particulate samples were analysed for their metal contents. In addition, metal contents in mineral diesel, biodiesel and lubricating oil were also measured to examine and correlate their (metals present in fuel) impact on particulate characteristics. Results indicated comparatively lower emission of particulate from BD20-fuelled engine than diesel engine exhaust. Metals like Cd, Pb, Na, and Ni in particulate of BD20 exhaust were lower than those in the exhaust of mineral diesel. However, emissions of Fe, Cr, Ni Zn, and Mg were higher in BD20 exhaust. This reduction in particulate and metals in BD20 exhaust was attributed to near absence of aromatic compounds, sulfur and relatively low levels of metals in biodiesel. However, benzene soluble organic fraction (BSOF) was found higher in BD20 exhaust particulate compared to diesel exhaust particulate.

Characteristics of SME biodiesel-fueled diesel particle emissions and the kinetics of oxidation
Jung, HJ, Kittelson, DB, Zachariah, MR
ENVIRONMENTAL SCIENCE & TECHNOLOGY, Vol 40 (16), Aug 15 2006, p. 4949-4955

Biodiesel is one of the most promising alternative diesel fuels. As diesel emission regulations have become more stringent, the diesel particulate filter (DPF) has become an essential part of the after-treatment system. Knowledge of kinetics of exhaust particle oxidation for alternative diesel fuels is useful in estimating the change in regeneration behaviour of a DPF with such fuels. This study examines the characteristics of diesel particulate emissions as well as kinetics of particle oxidation using a 1996 John Deere T04045TF250 off-highway engine and 100% soy methyl ester (SME) biodiesel (BD100) as fuel. Compared to standard D2 fuel, this BD100 reduced particle size, number, and volume in the accumulation mode where most of the particle mass is found. At 75% load, number decreased by 38%, DGN decreased from 80 to 62 nm, and volume decreased by 82%. Part of this decrease is likely associated with the fact that the particles were more easily oxidized. Arrhenius parameters for the biodiesel fuel showed a 2-3 times greater frequency factor and similar to 6 times higher oxidation rate compared to regular diesel fuel in the range of 700-825 C. The faster oxidation kinetics should facilitate regeneration when used with a DPF.

PM-10 emissions and power of a Diesel engine fueled with crude and refined Biodiesel from salmon oil
Reyes, JF, Sepulveda, MA
FUEL, Vol 85 (12-13), Sep 2006 p. 1714-1719

Power response and level of particulate emissions were assessed for blends of Diesel-crude Biodiesel and Diesel-refined Biodiesel. Crude Biodiesel and refined Biodiesel or methyl ester, were made from salmon oil with high content of free fatty acids, throughout a process of acid esterification followed by alkaline transesterification. Blends of Diesel-crude Biodiesel and Diesel-refined Biodiesel were tested in a diesel engine to measure simultaneously the dynamometric response and the particulate material (PM-10) emission performance. The results indicate a maximum power loss of about 3.5% and also near 50% of PM-10 reduction with respect to diesel when a 100% of refined Biodiesel is used. For blends with less content of either crude Biodiesel or refined Biodiesel, the observed power losses are lower but at the same time lower reduction in PM-10 emissions are attained.

PAH emissions and energy efficiency of palm-biodiesel blends fueled on diesel generator
Lin, YC, Lee, WJ, Hou, HC
ATMOSPHERIC ENVIRONMENT, Vol 40 (21), Jul 2006, p. 3930-3940

AB This study investigated the emissions of polycyclic aromatic hydrocarbons (PAHs), carcinogenic potencies (BaP$_{eq}$) and particulate matter (PM), fuel consumption and energy efficiency from the generator under steady state for seven test fuels: P0 (Premium Diesel Fuel), P10 (10% palm biodiesel+90% P0), P20, P30, P50, P75 and P100. Experimental results indicated that PAH emission decreased with increasing palm-biodiesel blends due to small PAH content in biodiesel. The mean reduction fraction of total PAHs emission factor (P0 = 1110 μg L-1) from the exhaust of diesel generator were 13.2%, 28.0%, 40.6%, 54.4%, 61.89% and 98.8% for P10, P20, P30, P50, P75 and P100, respectively, compared with P0. The mean reduction fraction of total BaPeq (P0 = 1.65 μg L-1) from the exhaust of diesel generator were 15.2%, 29.1%, 43.3%, 56.4%, 58.2% and 97.6% for P10, P20, P30, P50, P75 and P100, respectively, compared with P0. PM emission decreased as the palm-biodiesel blends increased from 0% to 10%, and increased as the palm-biodiesel blends increased from 10% to 100% because the soluble organic fraction of PM emission was high in blends with high palm-biodiesel content. The brake specific fuel consumption rose with rising palm-biodiesel blends due to the low gross heat value of palm-biodiesel. The increasing fraction of BSFC of palm-biodiesel was lower than those of soy-, soapstock-, brassica-carinate and rapeseed-biodiesel. Palm-biodiesel seems to be the most feasible biodiesel. The best energy efficiency occurred between P10 and P20, close to P15. The curve dropped as the palm-biodiesel content rose above P20. Above results revealed that palm-biodiesel was an oxygenated fuel appropriate for use in diesel engines to promote combustion efficiency and decrease PAH emission. However, adding an excess of palm-biodiesel to P0 leaded to incomplete combustion in the diesel-engine generator and inhibited the release of energy in the fuel.

Optimization of exhaust emissions of a diesel engine fuelled with biodiesel
Leung, DYC, Luo, Y, Chan, TL
ENERGY & FUELS, Vol 20 (3), May 2006, p. 1015-1023

The performance of biodiesel in a single-cylinder diesel engine was studied and optimized by varying the engine settings, including the injection timing, injection pressure, and fuel pump plunger diameter. The engine emissions were found to be lowered for particulate matters (PM) and hydrocarbon (HC) with the use of biodiesel, but an obvious increase in the oxides of nitrogen (NO$_x$) was observed, particularly at high engine loadings. The results revealed that individual adjustment of the above-mentioned parameters could not acquire a good balance between PM and NO$_x$ emissions. On the other hand, multi-parameter engine adjustment with the consideration of their cross-interactive effects can keep the benefit of reducing PM and HC without increasing NO$_x$.

Emission reduction potential of using ethanol-biodiesel-diesel fuel blend on a heavy-duty diesel engine
Shi, XY, Pang, XB, Mu, YJ, He, H, Shuai, SJ, Wang, JX, Chen, H, Li, RL
ATMOSPHERIC ENVIRONMENT, Vol 40 (14), May 2006, p. 2567-2574

Oxygenated diesel fuel blends have a potential to reduce the emission of particulate matter (PM) and to be an alternative to diesel fuel. This paper describes the emission characteristics of a three compounds oxygenated diesel fuel blend (BE-diesel), on a Cummins-4B diesel engine. BE-diesel is a new form of oxygenated diesel fuel blends consisted of ethanol, methyl soyate and petroleum diesel fuel. The blend ratio used in this study was 5:20:75 (ethanol: methyl soyate: diesel fuel) by volume. The results from the operation of diesel engine with BE-diesel showed a significant reduction in PM emissions and 2%-14% increase of NO$_x$ emissions. The change of CO emission was not conclusive and depended on operating conditions. Total hydrocarbon (THC) from BE-diesel was lower than that from diesel fuel under most tested conditions. Formaldehyde, acetaldehyde, propionaldehyde and acetone in the exhaust were measured, and the results indicated that use of BE-diesel led to a slight increase of acetaldehyde, propionaldehyde and acetone emissions. A small amount of ethanol was also detected in the exhaust from burning BE-diesel.

Diesel engine performance and emission characteristics of biodiesel produced by the peroxidation process

Lin, CY, Lin, HA
FUEL, Vol 85 (3), Feb 2006, p. 298-305

Biodiesel is an alternative fuel that is cleaner than petrodiesel. Biodiesel can be used directly as fuel for a diesel engine without having to modify the engine system. It has the major advantages of having high biodegradability, excellent lubricity and no sulfur content. In this study, the biodiesel produced by a transesterification technique was further reacted by using a peroxidation process. Four types of diesel fuel, biodiesel with and without an additional peroxidation process, a commercial biodiesel and ASTM No. 2D diesel were compared for their fuel properties, engine performance and emission characteristics. The experimental results show that the fuel consumption rate, brake thermal efficiency, equivalence ratio, and exhaust gas temperature increased while the bsfc, emission indices of CO_2, CO and NO_x, decreased with an increase of engine speed. The three biodiesels showed a higher fuel consumption rate, bsfc, and brake thermal efficiency, while at the same time exhibited lower emission indices of CO and CO_2 as well as a lower exhaust gas temperature when compared to ASTM No. 2D diesel. Moreover, the biodiesel produced with the additional peroxidation process was found to have an oxygen content, weight proportion of saturated carbon bonds, fuel consumption rate, and bsfc that were higher than the biodiesel produced without the additional process; while at the same time the brake thermal efficiency, equivalence ratio, and emission indices of CO_2, CO and NO_x, were found to be lower. In particular, biodiesel produced with the addition of the peroxidation process had the lowest equivalence ratio and emission indices of CO_2, CO and NO_x, among all of the four test fuels.

Improvement of engine emissions with conventional diesel fuel and diesel-biodiesel blends

Nabi, MN, khter, MS, Shahadat, MMZ
BIORESOURCE TECHNOLOGY, Vol 97 (3), Feb 2006, p. 372-378

In this report combustion and exhaust emissions with neat diesel fuel and diesel-biodiesel blends have been investigated. In the investigation, firstly biodiesel from non-edible neem oil has been made by esterification. Biodiesel fuel (BDF) is chemically known as mono-alkyl fatty acid ester. It is renewable in nature and is derived from plant oils including vegetable oils. BDF is non-toxic, biodegradable, recycled resource and essentially free from sulfur and carcinogenic benzene. In the second phase of this investigation, experiment has been conducted with neat diesel fuel and diesel-biodiesel blends in a four stroke naturally aspirated (NA) direct injection (DI) diesel engine. Compared with conventional diesel fuel, diesel-biodiesel blends showed lower carbon monoxide (CO), and smoke emissions but higher oxides of nitrogen (NO_x) emission. However, compared with the diesel fuel, NO_x emission with diesel-biodiesel blends was slightly reduced when EGR was applied.

NO_x emissions of alternative diesel fuels: A comparative analysis of biodiesel and FT diesel

Szybist, JP, Kirby, SR, Boehman, AL
ENERGY & FUELS, Vol 19 (4), Jul-Aug 2005, p. 1484-1492

This study explores the diesel injection and combustion processes in an effort to better understand the differences in NO_x, emissions between biodiesel, Fischer-Tropsch (FT) diesel, and their blends with a conventional diesel fuel. Emissions studies were performed with each fuel at a variety of static fuel injection timing conditions in a single-cylinder DI diesel engine with a mechanically controlled, in-line, pump-line-nozzle fuel injection system. The dynamic start of injection (SOI) timing correlated well with bulk modulus measurements made on the fuel blends. The high bulk modulus of soy-derived biodiesel blends produced an advance in SOI timing compared to conventional diesel fuel of up to 1.1 crank angle degrees, and the lower bulk modulus of the FT diesel produced a delay in SOI timing of up to 2.4 crank angle degrees. Compared to conventional diesel fuel at high load, biodiesel fuel blends produced increases in NO_x emissions of 6-9% while FT fuels caused NO_x emissions to decrease 21-22%. Shifts in fuel injection timing, caused by bulk modulus differences, were largely responsible for the NO_x increases, but pure FT diesel produced lower NO_x emissions than expected on the basis of

SOI alone. Further analysis showed that no trends were seen between NO_x and either ignition delay or maximum cylinder temperature, and only weak, or fuel-specific, relationships were seen between NO_x and maximum heat release rate and the timing of maximum heat release rate. The timing of the maximum cylinder temperature, however, did produce a relationship with NO_x emissions that was not dependent on fuel type.

The effect of biodiesel and ultra low sulfur diesel fuels on emissions in 11,000 cc heavy-duty diesel engine

Baik, DS, Han, YC
JOURNAL OF MECHANICAL SCIENCE AND TECHNOLOGY, Vol 19 (3), Mar 2005, p. 870-876

AB It seems very difficult to comply with upcoming stringent emission standards in vehicles. To develop low emission engines, better quality of automotive fuels must be achieved. Since sulfur contents in diesel fuels are transformed to sulfate-laden particulate matters as a catalyst is applied, it is necessary to provide low sulfur fuels before any Pt-based oxidation catalysts are applied. In general, flash point, distillation 90% and cetane index are improved but viscosity can be worse in the process of desulfurization of diesel fuel. Excessive reduction of sulfur may cause to degrade viscosity of fuels and engine performance in fuel injection systems. This research focused on the performance of an 11,000 cc diesel engine and emission characteristics by the introduction of ULSD, bio-diesel and a diesel oxidation catalyst, where the bio-diesel was used to improve viscosity of fuels in fuel injection systems as fuel additives or alternative fuels.

The effect of rapeseed oil methyl ester on direct injection Diesel engine performance and exhaust emissions

Labeckas, G, Slavinskas, S
ENERGY CONVERSION AND MANAGEMENT, Vol 47 (13-14), May 2006, p. 1954-1967

AB This article presents the comparative bench testing results of a four stroke, four cylinder, direct injection, unmodified, naturally aspirated Diesel engine when operating on neat RME and its 5%, 10%, 20% and 35% blends with Diesel fuel. The purpose of this research is to examine the effects of RME inclusion in Diesel fuel on the brake specific fuel consumption (bsfc) of a high speed Diesel engine, its brake thermal efficiency, emission composition changes and smoke opacity of the exhausts. The brake specific fuel consumption at maximum torque (273.5 g/kW h) and rated power (281 g/kW h) for RME is higher by 18.7% and 23.2% relative to Diesel fuel. It is difficult to determine the RME concentration in Diesel fuel that could be recognised as equally good for all loads and speeds. The maximum brake thermal efficiency varies from 0,356 to 0.398 for RME and from 0.373 to 0.383 for Diesel fuel. The highest fuel energy content based economy (9.36-9.61 MJ/kW h) is achieved during operation oil blend BD10, whereas the lowest ones belong to BD35 and neat RME. The maximum NO_x emissions increase proportionally with the mass percent of oxygen in the biofuel and engine speed, reaching the highest values at the speed of 2000 min(-1), the highest being 2132 ppm value for the BD35 blend and 2107 ppm for RME. The carbon monoxide, CO, emissions and visible smoke emerging from the biodiesel over all load and speed ranges are lower by up to 51.6% and 13.5% to 60.3%, respectively. The carbon dioxide, CO_2, emissions along with the fuel consumption and gas temperature, are slightly higher for the BD20 and BD35 blends and neat RME. The emissions of unburned hydrocarbons, HC, for all biofuels are low, ranging at 5-21 ppm levels.

Performance and exhaust emissions of a biodiesel engine

Canakci, M, Erdil, A, Arcaklioglu, E
APPLIED ENERGY, Vol 83 (6), Jun 2006, p. 594-605

In this study, the applicabilities of Artificial Neural Networks (ANNs) have been investigated for the performance and exhaust-emission values of a diesel engine fueled with biodiesels from different feedstocks and petroleum diesel fuels. The engine performance and emissions characteristics of two different petroleum diesel-fuels (No. 1 and No. 2), biodiesels (from soybean oil and yellow grease),

and their 20% blends with No. 2 diesel fuel were used as experimental results. The fuels were tested at full load (100%) at 1400-rpm engine speed, where the engine torque was 257.6 Nm. To train the network, the average molecular weight, net heat of combustion, specific gravity, kinematic viscosity, C/H ratio and cetane number of each fuel are used as the input layer, while outputs are the brake specific fuel-consumption, exhaust temperature, and exhaust emissions. The back-propagation learning algorithm with three different variants, single layer, and logistic sigmoid transfer function were used in the network. By using weights in the network, formulations have been given for each output. The network has yielded R-2 values of 0.99 and the mean % errors are smaller than 4.2 for the training data, while the R-2 values are about 0.99 and the mean%, errors are smaller than 5.5 for the test data. The performance and exhaust emissions from a diesel engine, using biodiesel blends with No. 2 diesel fuel Lip to 20%, have been predicted using the ANN model.

Emission comparison of urban bus engine fueled with diesel oil and biodiesel' blend
Turrio-Baldassarri, L, Battistelli, CL, Conti, L, Crebelli, R, De Berardis, B, Iamiceli, AL, Gambino, M, Iannaccone, S
SCIENCE OF THE TOTAL ENVIRONMENT, Vol 327 (1-3), Jul 5 2004, p. 147-162

The chemical and toxicological characteristics of emissions from an urban bus engine fueled with diesel and biodiesel blend were studied. Exhaust gases were produced by a turbocharged EURO 2 heavy-duty diesel engine, operating in steady-state conditions on the European test 13 mode cycle (ECE R49). Regulated and unregulated pollutants, such as carcinogenic polycyclic aromatic hydrocarbons (PAHs) and nitrated derivatives (nitro-PAHs), carbonyl compounds and light aromatic hydrocarbons were quantified. Mutagenicity of the emissions was evaluated by the Salmonella typhimurium/mammalian microsome assay. The effect of the fuels under study on the size distribution of particulate matter (PM) was also evaluated. The use of biodiesel blend seems to result in small reductions of emissions of most of the aromatic and polyaromatic compounds; these differences, however, have no statistical significance at 95% confidence level. Formaldehyde, on the other hand, has a statistically significant increase of 18% with biodiesel blend. In vitro toxicological assays show an overall similar mutagenic potency and genotoxic profile for diesel and biodiesel blend emissions. The electron microscopy analysis indicates that PM for both fuels has the same chemical composition, morphology, shape and granulometric spectrum, with most of the particles in the range 0.06-0.3 mum.

Effect of gas-to-liquid diesel fuels on combustion characteristics, engine emissions, and exhaust gas fuel reforming. Comparative study
Abu-Jrai, A, Tsolakis, A, Theinnoi, K Cracknell, R Megaritis, A, Wyszynski, ML, Golunski, SE
ENERGY & FUELS, Vol 20 (6), Nov 15 2006, p. 2377-2384

New diesel-type fuels such as biodiesels and gas-to-liquid (GTL) fuel have been developed in order to aid vehicle manufacturers in achieving forthcoming emission regulations, by improving engine out emissions and exhaust gas after-treatment performance. Furthermore, synthetic fuels are virtually free of sulfur and aromatic hydrocarbons and can improve the performance and durability of the catalytic fuel reformers that are designed to provide H-2 to fuel cells, internal combustion (IC) engines, and after-treatments. Combustion and exhaust-gas reforming experiments with GTL and ultralow sulfur diesel (ULSD) were run under several engine and reformer operating regimes. Using a single cylinder bench engine, the combustion of GTL fuel (and blends with conventional diesel fuel) was found to reduce NO_x emissions substantially and improve engine thermal efficiency but led to an increase in smoke for the default injection timing in the experiment. However, by optimizing the injection timing in a GTL-fueled engine, the harmful emissions of NOx and smoke were both reduced simultaneously while still giving improvements in engine thermal efficiency. In general, it was found that the NO_x/particles tradeoff curve shifted to lower emissions for GTL fuel and GTL fuel blends. During exhaust-gas reforming, the use of GTL fuel was found to increase fuel conversion, while producing more hydrogen and less methane.

16 APPENDIX C – ACRONYMS AND ABBREVIATIONS

|	
a	annum (as in /a = per annum)
ABS	Australian Bureau of Statistics
AGO	Australian Greenhouse Office
BDx	A blend of x% biodiesel with petroleum diesel (Bx is also occasionally used)
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
CUEDC	Composite Urban Emissions Drive Cycle
DEH	Department of the Environment and Heritage (former name of the DEW)
DEW	Department of the Environment and Water Resources
E10	Petrol containing 10% ethanol by volume
FFA	Free Fatty Acids (fats unattached to other molecules in solution)
FFC	Full fuel cycle (cradle to grave or well-to-wheel analysis)
FOB	Free (or Freight) On Board – cost of freight at the point of departure
GHG	Greenhouse Gas
GWP	Global Warming Potential
ha	Hectare
HHV	High Heating Value
HV	Heavy Vehicle
IPCC	Intergovernmental Panel on Climate Change
ISO	International Standards Organisation
IVAM	A Department of the Free University of Amsterdam
K	Potassium
kL	Kilolitre (thousand litres)
kt	Kilotonne (thousand tonnes)
kWh	Kilowatt hour (3.6 MJ)
LCA	Life Cycle Analysis/Assessment
LHV	Low Heating Value
LSD	Low sulfur diesel (< 50 ppm sulfur)
MAP	Mono-ammonium phosphate
Mt	Million tonnes
MWh	Megawatt hour (3.6 GJ)
N_2O	Nitrous Oxide
NO_x	Nitrogen Oxides (mainly Nitric Oxide NO and Nitrogen dioxide NO_2)
NGGIC	National Greenhouse Gas Inventory Committee
NTP	Normal Temperature (20° C) and Pressure (1013.25 hPa – 1 atmosphere)
Ppm	Parts per million
SD	Standard Deviation
Std.	Standard
STP	Standard Temperature (0° C) and Pressure (1013.25 hPa – 1 atmosphere)
UCO	Used cooking oil (also called UVO and WVO, used/waste vegetable oil)
ULP	Unleaded petrol
v/v	Volume per volume
XLSD	Extra low sulfur diesel (<10 ppm sulfur)

17 APPENDIX D - OVERVIEW OF LCA METHOD

Life cycle assessment (LCA) is the process of evaluating the potential effects that a product, process, or service has on the environment over the entire period of its life cycle. The International Organization for Standardization (ISO 1997) has defined an LCA as:

A technique for assessing the environmental aspects and potential impacts associated with a product by:

- *compiling an inventory of relevant inputs and outputs of a product system*
- *evaluating the potential environmental impacts associated with those inputs and outputs*
- *interpreting the results of the inventory analysis and impact assessment phases in relation to the objectives of the study'.*

The technical framework for life cycle assessment consists of four components, each having a vital role in the assessment. They are interrelated throughout the entire assessment and in accordance with the current terminology of the International Organization for Standardization (ISO). The components are goal and scope definition, inventory analysis, impact assessment, and interpretation.

Figure 17-1: The components of an LCA Source (International Standards Organisation 1997)
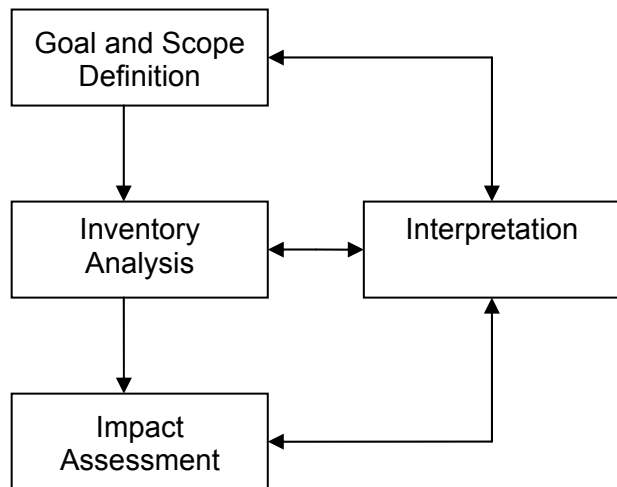
In this study the impact assessment focused on greenhouse emissions and priority air pollutants.

18 APPENDIX E - LCA ALLOCATION APPROACHES

In LCA, environmental impacts and benefits are calculated for different economic goods (products, services, materials and processes). These goods are produced by a large diversity of production systems that make up a modern industrial economy. Where a single production system produces more than one good, an approach is needed to proportion the environmental impacts of the production system to the different economic goods.

Two approaches have emerged in LCA for dealing with co-production allocation. These approaches are referred to as consequential and attributional LCA (Ekvall 2002).

Consequential LCA (sometimes referred to as change-oriented LCA, market-based LCA, marginal LCA or prospective LCA) sees LCA as a tool for measuring the consequence of a product or process substitution (including product modifications, material substitutions, regulation of interference in consumer behaviour and so on). Consequential LCA attempts to measure the impacts of additional production or a reduction in production.

Attributional LCA (also referred to as retrospective or descriptive LCA) is the more traditional approach to LCA and describes a product system that allocates co-products based on economic value, mass or other attributes of the system (when physical causation cannot be used to allocate co-products). Attributional LCA intends to measure the average impact of production.

The International LCA Standards have a hierarchy for application of allocation approaches, and the preferred approach is to use consequential LCA. This is called system boundary expansion in the standard (ISO 1997). The other option is the attributional approach which is to allocate emissions and resource uses based on a common and relevant attribute of the two co-products. This may be economic value, mass, energy, volume, sugar content, protein content and so on. The selection of a common attribute is important to the allocation procedure and will vary from instance to instance. Clearly, mass-based allocation would be inappropriate for allocating emissions between gravel and diamonds produced in diamond mines. For co-production of energy products, energy-based allocation may be appropriate. One of the most common attributional allocations is economic allocation as it represents the main driver behind production, and may be the only comparable attribute between the co-products.

The two basic approaches are shown in Figure 18-1 with co-product allocation representing the attributional approach, and system boundary expansion representing the consequential approach.

Co-product allocation
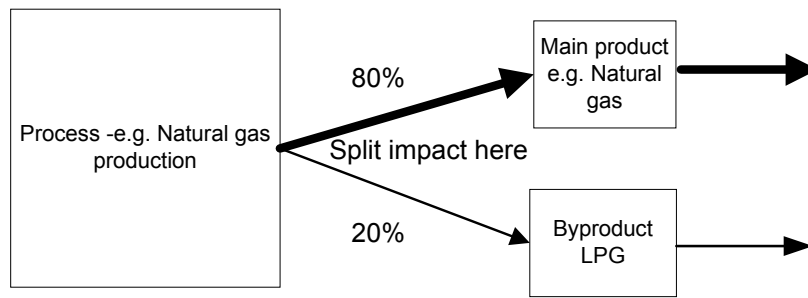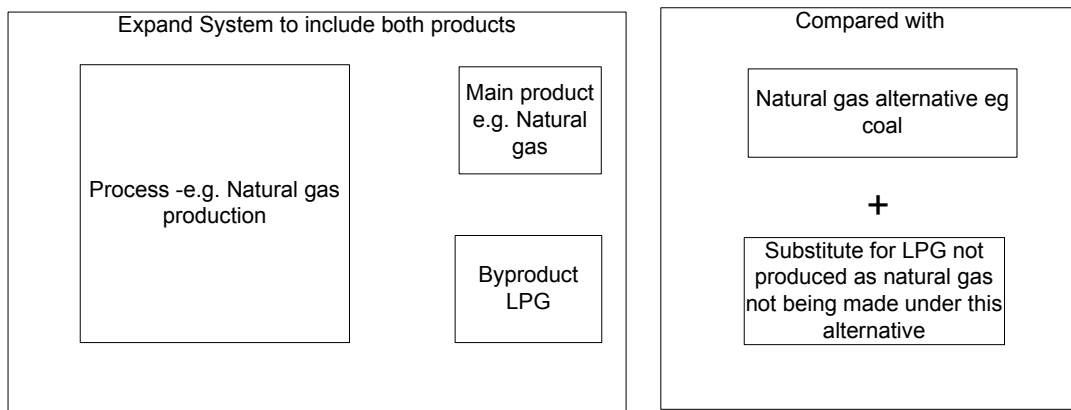

System boundary expansion

Figure 18-1: Approaches to allocation in life-cycle analysis

The problem with system boundary expansion is that it requires a good knowledge of the market forces that result in the product substitution. It is also complicated by the factor that many co-products are competing with other co-products. It is necessary then to follow the product substitution chain back to a point where a "determining" or "main" product is found which can expand or contract its production in line with economic demand.

To assist in determining the correct allocation procedure, Weidema (2000) has developed four simple rules for expanded system boundary allocations based on the level of utilisation of the by-product (or waste).
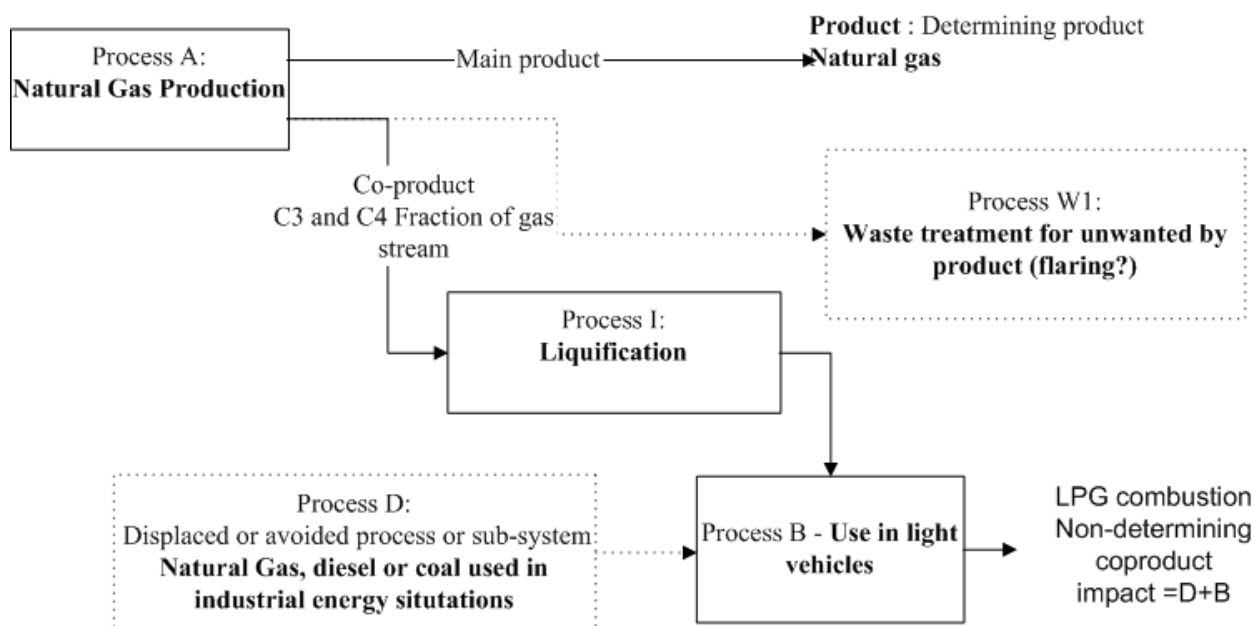
Figure 18-2: Model for system boundary expansion – Adapted from Weidema (2000)

Using the model of Figure 18-2 for reference, Weidema (2000) developed the following four rules for ascribing process impacts to different products. These are:

1) *"The co-producing process shall be ascribed fully (100%) to the determining product for this process (product A)."* In the case of Figure 18-2 all the impacts of producing natural gas are ascribed to refined natural gas.

2) *"Under the conditions that the non-determining co-products are fully utilised in other processes and actually displace other products there, product A shall be credited for the processes, which are displaced by the other co-products, while the intermediate treatment (and other possible changes in the further life cycles in which the co-products are used, which are a consequence of differences in the co-products and the displaced products) shall be ascribed to product A".* In the case of Figure 18-2 refined natural gas also carries the burdens of processing the co-products - LPG (and ethane), but also receives a credit for these co-products. The credit is equal to the impacts of providing those functions by other means. This rule holds only while all the co-product is utilised in the market place.

If the two conditions stated in rule no. 2 are not fulfilled, rule no. 3 and 4 apply, respectively:

3) *"When a non-determining co-product is not utilised fully (i.e. when part of it must be regarded as a waste), but at least partly displaces another product, the intermediate treatment shall be ascribed to product B, while product B is credited for the avoided waste treatment of the co-product".* In the case of Figure 18-2, if some LPG was being flared for want of a market, natural gas would be credited with the impacts of waste treatment, while any use of LPG would be credited with avoided emission of flaring. This is because the allocation is based on the impact of the "next tonne of product" and not the average tonne of product. So an additional tonne of refined natural gas would increase the supply of LPG, and if some LPG was being flared for want of a market before this production increase it is assumed that all of the additional LPG would be flared. (Note that this is an illustrative example only, as LPG is not routinely flared in Australia.)

4) *"When a non-determining co-product is not displacing other products, all processes in the entire life cycle of the co-product shall be fully ascribed to product A".*

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