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Methodological complexities of product carbon footprinting: a sensitivity analysis of key variables in a developing country context

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ABSTRACT

Product carbon footprinting schemes adopt different analytical methodologies. The calculations can also be affected by limited data availability and uncertainty surrounding the value of key variables. The combination of these factors reduces the validity of comparing carbon footprints between products and countries.

We used data from sugar production in Zambia and Mauritius to test how variations in methodology affected the product carbon footprint (PCF). We calculated a PCF according to PAS 2050 and explored the sensitivity of the results to the variation of key variables.

Results showed that land use change emissions can dominate PCFs. The largest potential impact came from assuming global worst case data for land use change emissions where a product's origin is unknown (+1900%). The issue of land use change can lead to high carbon footprints for products from developing countries where more natural vegetation is still being converted and data are most lacking. When land use change is not important, variables such as electricity emission factors, capital inputs and loss of soil carbon had significant impacts on the PCF.

This analysis highlights the large effect of methodology on PCFs. These results are of particular concern for developing countries where data are scarce and the use of global worst case data may be prescribed. We recommend the development of more precise emission factors for tropical countries and bio-regions, and encourage the transparent use of PCF methodologies, where data sources, uncertainties and variability are explicitly noted.

1. Introduction

Carbon footprints provide an estimate of the total amount of greenhouse gases (GHGs) emitted during the life cycle of goods and services, i.e. from the extraction of raw materials, production, transportation, storage and use to waste disposal. They are calculated by businesses, governments and other stakeholders in order to understand the emissions of GHGs from consumer products, including food (Bolwig and Gibbon, 2009). Businesses can use the results of a carbon footprint to

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achieve emissions reductions throughout their own operations, to influence different elements of their supply chains, and/or to communicate their carbon footprint to their customers, sometimes via carbon labels on products (Bolwig and Gibbon, 2009; Sinden, 2009). The focus of this paper is on product carbon footprinting (PCF) and all subsequent discussions refer to PCFs only, where PCF is used as an abbreviation for both 'product carbon footprint' and 'product carbon footprinting'.

The development of methods to calculate carbon footprints has been relatively rapid, and in order to ensure widespread acceptance of the methods, these developments have had to respond to government policy and corporate agendas. Indeed the development of many PCF methods has proceeded at a faster pace than have the measurement and scientific understanding of actual GHG emissions emanating from the varied production systems that occur around the globe (Brenton et al., 2009). This is a particular problem in agricultural systems where quantitative understanding of GHG emissions is incomplete (Sonesson et al., 2009), and is often a particular difficulty for developing countries (Edwards-Jones et al., 2009a).

Carbon footprinting methodologies are mainly being designed in industrialised countries. Modern supply chains, however, are international in nature and many food items consumed in Europe, North America and other industrialised countries are produced in developing countries. This situation, coupled with the lack of scientific knowledge on GHG emissions from developing countries, means that there is a risk that carbon accounting and labelling instruments will not adequately represent production systems in developing countries. Such a situation is important as there are fears that low income countries might suffer from trade restrictions as a consequence of climate related policies and/or a reduction of export opportunities (McGregor and Vorley, 2006; Brenton et al., 2009; Kasterine and Vanzetti, 2010).

The framework for carbon footprinting is provided by life cycle thinking and existing methods for Life Cycle Assessment (LCA). However, the needs of PCFs are not fully met by either the existing standards for LCA (ISO, 2006a,b) or standards for company GHG accounting such as the GHG Protocol developed by the World Resources Institute (WRI). One of the problems with the existing ISO standards for LCA is that they allow considerable flexibility, leaving decisions up to the practitioner which may vary according to the aim of a particular analysis. This limits their use for comparative purposes. As a result additional principles and techniques that address essential aspects of carbon footprinting need to be developed and established. Because of the international nature of supply chains, many stakeholders agree that there is a need for an international standard to be developed. Although organisations such as ISO and WRI have started work on this, the resulting standards are not yet available. In the meantime, several accounting schemes and methods are emerging, many of them driven by businesses wishing to compete on 'green' credentials and achieve and document emissions reductions in their supply chains (Brenton et al., 2009; Kasterine and Vanzetti, 2010).

At least 13 different methodologies for calculating the carbon footprint of products were operative or under development in 2009. Countries in which both public and private standards were being developed at that time included the UK, Germany, France, Switzerland, Sweden, New Zealand, USA, Japan, Korea and Thailand (see Bolwig and Gibbon, 2009 for further discussion of these schemes). The schemes varied greatly in approach and methodology and were mainly established by governments and businesses, particularly supermarket chains. Some agri-food industry associations are also preparing standard methodologies, e.g. the international dairy industry for the calculation of the carbon footprint of milk and dairy products and similar international initiatives in the red meat and apple sectors (Carbon Trust, pers. comm., February 2010). Although several schemes were already being implemented in 2009, the British PAS 2050 (BSI, 2008a) was the only finalised PCF methodology which had detailed calculation methods in the public domain at that time.

Some of these schemes communicate GHG emissions numerically (e.g. PAS 2050), whilst others attempt to guide consumers to supposedly 'climate friendly' products without providing precise figures on GHG emissions (e.g. the German eco-label Blauer Engel and the Swedish organisations KRAV and Svenskt Sigill). Some stakeholders feel that even if an international standard was developed there might still be demand for more specific requirements that cannot be agreed internationally, leaving scope for a range of standards at the national or business level (UK retailer, pers. comm.). Different schemes might also emerge as a result of differing views on how to calculate GHG emissions or through differing strategies on how to communicate the climate change impact of products.

It is important that decision makers understand both the differences in approaches adopted by the different PCF methods, and how these can influence the results obtained. Further, if they are to use PCFs in a meaningful way they must be aware of the uncertainty that surrounds all carbon footprinting calculations. Failure to do so may lead to incorrect interpretation of results and misleading conclusions, e.g. in comparative analyses. The aim of the research presented here was to calculate the carbon footprint of cane sugar using PAS 2050 as a baseline, and to assess the variation in the carbon footprints which might arise from differences between calculation methodologies. The results of this analysis are then used to highlight some of the difficulties associated with estimating carbon footprints for products from developing countries.

2. Methods

2.1. *Background to PAS 2050*

PAS 2050 is built upon the existing ISO 14040/44 standards for LCA which it further clarifies and specifies for the calculation of carbon footprints of goods and services (BSI, 2008a,b; Sinden, 2009). This methodology accounts for emissions of all GHGs including CO_2, N_2O, CH_4 and families of gases such as hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs), and each gas is converted into a CO_2 equivalent value.

PAS 2050 specifies rules for identifying the system boundary and data quality rules for secondary data. GHG emissions from energy use, combustion processes, chemical reactions, refrigerant losses and other fugitive gases, operations, service provision and delivery, land use change, livestock, other agricultural processes and waste have to be included in the assessment. The unit of analysis should be the unit in which the product is actually consumed by the end user. Non-CO_2 emissions from livestock, their manure and soils are to be calculated in accordance with the highest tier approach set out in IPCC (2006) guidelines or the highest tier approach employed by the country in which the emissions arise. Any changes in the carbon content of soils are excluded other than those from direct land use change due to the considerable uncertainty in their assessment. Capital goods are also not included in the PAS 2050 methodology, although this category might be of significance for agricultural products, where agricultural machinery has been shown to have an impact (Weidema et al., 1995). In addition, PAS 2050 makes provisions for carbon storage in products and delayed emissions from the use phase and final disposal of a product; however, these did not apply to the case studies presented here. Emissions related to human energy inputs, transport of consumers to and from shops, transport of employees to and from work and animals providing transport services are excluded from the carbon footprint calculation.

2.2. Data collection

Primary data were collected from three sugar cane estates (Farms A, B and C) and one refinery (Refinery A) in Zambia in April 2009, and from one sugar cane estate (Farm D) and one refinery (Refinery B) in Mauritius in April and May 2009. Data collection was carried out by interviewing farm owners, agricultural managers and factory managers, and wider industry contacts were also interviewed to gain insights into the structure of the industry at country level. In total, 35 person days were spent in the two case study countries collecting data. Cane sugar was chosen for the case study because it is an important export product for many developing countries.

2.3. Description of case study sites

The carbon footprint of products can be commercially sensitive. In order to protect their confidentiality only very limited information on the farms and refineries that participated in the project are provided here. Although not described in detail here the study farms were typical of the sugar cane production systems in both countries. It must be stressed, however, that due to the small sample size and potential variation in farming and refining methods, the results should not be interpreted to be statistically representative of either country.

2.4. Calculating the product carbon footprint

The PCF for the case studies was calculated according to PAS 2050 (BSI, 2008a). The analyses included all emissions from cultivation, processing and transport to a European port. Primary data collected from the farms and refineries was used as much as possible. Emission factors were extracted from the Ecoinvent database (Althaus et al., 2007; Nemecek et al., 2007; Spielmann et al., 2007), Carbon Trust (2008) and IEA (2007). The grid electricity emission factor for Mauritius was calculated by P.N.K. Deenapanray, CDM National Project Coordinator, UNDP (pers. comm., 7 May 2009). Direct emissions from land use change, i.e. the conversion of non-agricultural to agricultural land, were calculated according to IPCC (2006) as required by PAS 2050 for products arising from land that was converted to cropland since 1990. This applied only to Farms A, B and C as no land use change after 1990 had occurred on Farm D.

Emissions from diesel use for the conversion of native vegetation to cropland were included in the calculations for Farms A to C and allocated over a 100-year time period. Diesel usage for large de-rocking as carried out on parts of Farm D ten years ago to remove large rocks and level the land to allow mechanical harvesting was also included and allocated over 100 years.

The sugar industry can have multiple outputs: sugar; molasses which are an input to alcohol distilleries; and sometimes export of electricity which is produced from excess bagasse to the national grid. GHG emissions were allocated between these outputs using economic allocation, i.e. in proportion to the economic value of each co-product. This was only relevant to Refinery B where 91.7% of GHG emissions were allocated to the white sugar, 5.7% to the bagasse and 1.6% to the molasses. No export of electricity to the national grid occurred in Refinery A, and molasses were given to the local livestock industry at no cost, so that all GHG emissions from the cultivation and refining of the sugar were allocated to the raw sugar at the refinery gate.

Because Refinery A was not exporting outside of Africa at the time of interview, data on the logistics of exporting sugar were collected from a nearby refinery. About 90% of the raw sugar from this refinery was transported by road or rail to Durban (South Africa, 2200 km). The remaining 10% were trucked to Beira (Mozambique, 2000 km). GHG emissions from this transport stage were calculated based on these distances and modes of transport. Refinery B was located an undisclosed distance from the port on the small island of Mauritius, and sugar was transported there by truck. Sugar produced in both countries was shipped from these ports to their markets which are mainly in Europe and USA. Results presented here are for sugar delivered to a destination port in the English Channel.

2.5. Calculation of land use change emissions

The estimation of emissions resulting from the conversion of non-agricultural land to cropland according to the IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006) involves estimates of annual changes in carbon stocks for above-ground biomass, dead organic matter and soil organic matter. Due to very limited data availability on below-ground biomass stocks in perennial cropland, these are not included in the calculations.

For our case studies, emissions resulting from land use change were only relevant for sugar cane production in Zambia. Although sugar cane is a perennial plant, the calculations were carried out as if it was an annual plant. This decision was made because all above-ground biomass is removed yearly during harvest, and although the amount of root biomass will increase during the 5–7-year cycle this increase in below-ground carbon stocks is not included in the IPCC methodology due to a lack of data. Pre-conversion vegetation was taken to be tropical dry forest (IPCC, 2006) based on remaining habitats surrounding the case study farms.

2.6. The impact of key variables on the case study product carbon footprints

Including and/or excluding key variables in the PCF calculation is analogous to considering the differences between PCF methodologies. As the details of the different methodologies mentioned in the Introduction were not available at the time of writing, it was not possible to undertake direct comparisons between methods. However, by considering the impact of specific variables on the final carbon footprint of sugar, it is possible to understand the importance of differences that may emerge between the various PCF methodologies once they are fully developed. The following analyses are not intended to be a critique of the PAS 2050 methodology, rather the PAS 2050 carbon footprint was taken as the baseline because of the availability of its detailed methodology. The impact of adding or subtracting certain variables from this baseline was used to understand the sensitivity of the PCF to potential differences in accounting methodologies. The analysis undertaken here stops at the receiving port of the importing destination country, and as a result the impact of variables further down the supply chain, which may differ between PCF methods, is not considered here (e.g. inclusion or exclusion of the use phase or consumer shopping trips).

3. Results

3.1. Description of case study farms and refineries

Sugar grown in Zambia supplies the domestic market and is exported to the EU and USA. Annual cane yields on the Zambian farms ranged from 70 to 150 t/ha. Irrigation was mainly by centre pivot systems and some additional small areas of canal and sprinkler irrigation. All three farms had converted most or all of their cultivated land from native vegetation since 1990 which meant emissions from land use change had to be included in the baseline carbon footprint. Fertilisers were applied at least twice per year. No pesticides were used on any of the farms. Planting, fertiliser application and harvest were carried out manually. At harvest, burning was practised to remove excess vegetation and snakes before manual cutting. Extracted raw sugar yields vary year to year according to the percentage sucrose content of cane but averaged around 12% of cane weight.

Farm D, on Mauritius, was a long-established sugar estate where conversion of the land to cropland occurred over 100 years ago. The growing cycle consisted of 6–7 years of re-growth from the underground stalk after the first harvest in the planting year (ratoon years). About 65% of the area under sugar cane was irrigated using drip irrigation and pivot systems. During the ratoon years, a vinasse-based fertiliser naturally rich in potassium was applied. No ripeners or pesticides were used. At harvest, cane leaves were left on the soil surface and no burning was practiced. Manual labour was employed for planting and the application of base dress fertilisers, while harvesting was undertaken by mechanical chopper harvesters. Large scale de-rocking was undertaken on parts of Farm D over ten years ago.

Refinery A in Zambia was powered by renewable energy in the form of bagasse, making this an energy self-sufficient processing system. The output from Refinery A was raw sugar. Refinery B on Mauritius used bagasse as an energy source for sugar processing, but also exported energy generated from excess bagasse to the national electricity grid, making bagasse an important co-product of the sugar processing. Another economic co-product from this refinery was molasses which are used by rum distilleries. About 10% of cane weight was recovered as sugar. Data collected from Refinery B included all processes up to the production of white sugar ready for consumption and are therefore not directly comparable with Refinery A which produced raw sugar.

3.2. Carbon footprint of sugar cane delivered to the refinery

Total GHG emissions from the cultivation of sugar cane up to the point of delivery to the refinery varied between 26 and 210 kg CO_2e/t sugar cane (Table 1). Land use change emissions which were only relevant to Farms A–C made the largest contribution to the carbon footprint of the sugar cane from these farms (66–77%). In contrast, Farm D had not converted any land since 1990, and therefore no land use change related emissions had to be included in the calculations. Partly as a result of this the PCF of sugar cane from Farm D was 2.5–8 times lower than for the other three farms. Other reasons for inter-farm variation were differences in farming practices, e.g. the amount of fertilisers applied, intensity of irrigation and associated use of electricity, as well as average yields per hectare.

3.3. Carbon footprint of refined sugar up to the import gate

The major input in terms of GHG emissions for both refineries was the sugar cane (Table 2). The input for Refinery A was sugar cane from Farm C. All other inputs such as diesel and chemicals together accounted for less than 5% of GHG emissions at the refinery gate. The total carbon footprint for raw sugar leaving Refinery A and white refined sugar from Refinery B was 1731 and 255 kg CO_2e/t sugar, respectively (Table 3).

Transportation by rail and truck to ports for shipping to Europe added 201 and 5.4 kg CO_2e/t of sugar from Refinery A and B, respectively. This difference was due to the much greater distance of Refinery A from the nearest port (up to 2200 km) than Refinery B which was located relatively close to port. Overseas shipping to Europe had a similar impact for both case study countries, amounting to 130 kg CO_2e/t for sugar from Refinery A and 138 kg CO_2e/t for sugar for Refinery B. Overall, these transportation steps added 331 and

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Table 1 – Percentage of GHG emissions per tonne of sugar cane for each input and ecosystem emissions for four sugar cane estates up to the delivery of the sugar cane to the local refinery. Also shown is the total carbon footprint in kg CO_2e/t sugar cane, including rounding of the final figure to two significant figures as required by PAS 2050 (BSI, 2008a).

		Farm A	Farm B	Farm C	Farm D
Emissions from the production of inputs					
Diesel usage	%	2.8	3.0	7.2	19.7
Electricity from national grid	%	0.1	0.2	0.3	23.8
N	%	8.8	8.4	10.8	19.6
P_2O_5	%	1.0	1.2	1.4	0.0
K_2O	%	2.0	0.8	1.9	4.2
S	%	0.0	0.1	0.1	0.0
Fe	%	0.02	0.01	0.03	0.0
B	%	0.1	0.1	0.1	0.0
Zn	%	0.0	0.1	0.1	0.0
Cu	%	0.0	0.01	0.0	0.0
Mn	%	0.0	0.3	0.0	0.0
Lime	%	0.0	0.0	0.009	0.0
Pesticides	%	0.0	0.0	0.7	0.0
Emissions from ecosystem processes					
Land use change emissions	%	76.2	77.4	66.1	0.0
N_2O from N fertiliser	%	8.9	8.5	10.9	32.8
CO_2 from lime application	%	0.0	0.0	0.3	0.0
Total kg CO_2e/t sugar cane		210	92	64	26

Table 2 – Percentage of GHG emissions per tonne of raw sugar (Refinery A) and white sugar (Refinery B) for each input and total carbon footprint in kg CO_2e/t sugar leaving the refinery (including economic allocation between outputs).

	Refinery A	Refinery B
Sugar cane	99.99	95.88
Grid electricity	0.0	0.10
Diesel usage	0.0	0.01
Water	0.0	0.68
Lime	0.01	0.03
Other flocculants/coagulants	0.0	0.01
Other flocculants/coagulants	0.0	0.003
Caustic soda	0.002	0.64
Phosphoric acid	0.0	0.74
Cationic colour precipitant	0.0	1.16
Sodium chloride	0.0	0.59
Sulphur	0.0	0.17

143 kg CO_2e/t sugar for Refinery A and B, respectively (Table 3), bringing the total carbon footprint to 2100 kg CO_2e/t of raw sugar for Refinery A and 400 kg CO_2e/t of white sugar for Refinery B at delivery in Europe.

Table 3 – Carbon footprint in kg CO_2e/t sugar (including economic allocation between outputs) at the refinery gate, for transportation steps to port and from shipping to Europe, and total carbon footprint for sugar at the import gate in Europe for raw sugar (Refinery A) and white sugar (Refinery B), including rounding of the final figure to two significant figures as required by PAS 2050 (BSI, 2008a).

	Refinery A	Refinery B
Total kg CO_2e/t sugar at refinery gate	1731	255
In-country land transport (inc. to port)	201	5.4
Transport to Europe	130	138
Total kg CO_2e/t sugar at import port	2100	400

4. Sensitivity of the product carbon footprint to key variables

4.1. *Sugar cane delivered to refinery*

Including or excluding certain variables from the PCF of sugar cane delivered to refineries can have significant impacts on the final result as shown in Fig. 1 and discussed below.

4.1.1. *Rounding of final reported figure*

PAS 2050 requires that results are rounded to two significant figures (which might be displayed on a carbon label) because rounding is expected to ameliorate the uncertainties attached to the calculations to some extent. The impact of this operation on the carbon footprint of sugar cane was very low in both percentage and absolute terms.

4.1.2. *Non-country-specific electricity emission factor*

Use of non-country-specific electricity emission factors may occur if a PCF methodology did not specify that the analyst has to use a country-specific emission factor, or if a country-specific emission factor was not available from easily accessible sources such as IEA (2007). It may be necessary to use less specific emission factors when considering developing countries with poor levels of available data, e.g. from other countries or larger scale aggregated emission factors such as an average emission factor for Africa. However, this may mask much variation in emission factors between countries. For example, currently electricity in Zambia is generated almost solely from hydropower, whereas the electricity mix on Mauritius is largely based on fuel oil and coal. As a result Zambia and Mauritius have very low and high country-specific emission factors, respectively. Because of this the consequences of not using a country-specific emission factor for electricity differ for farms in Mauritius and Zambia. Using an

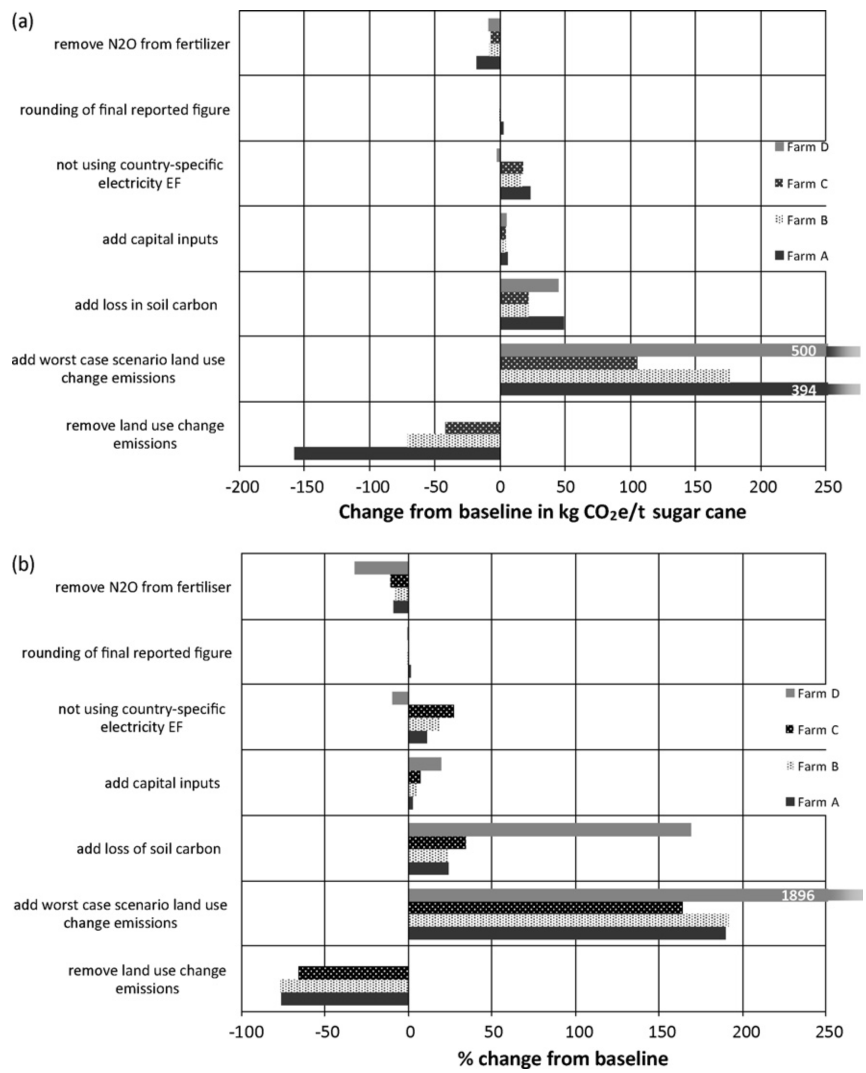

Fig. 1 – Change in carbon footprint of sugar cane delivered to refinery, caused by changing key variables from the baseline calculation. (a) Change from baseline in kg CO_2e/t sugar cane and (b) percentage change. Baseline calculated according to PAS 2050 (BSI, 2008a). Land use change emissions were only relevant to the baseline calculations for Farms A–C. EF = emission factor.

average emission factor for Africa (IEA, 2007) caused increases of around 18–23 kg CO_2e/t sugar cane (11–27%) for Farms A–C, while the opposite result was obtained for Farm D on Mauritius, where it reduced the carbon footprint by 10%.

4.1.3. *Adding capital inputs*

Accounting for emissions from the production and maintenance of farm machinery added relatively little to the PCF of Farms A–C (3–7%). The percentage increase was greater on Farm D (20%), as unlike Farms A–C, the baseline PCF did not include any emissions from land use change.

Excluding capital items from agricultural PCFs may tend to disadvantage products from developing countries, as they often use less material capital than industrialised countries and depend more on human capital. However, they cannot get any credit for their reduced use of capital from PCFs undertaken according to methodologies such as PAS 2050 that exclude capital inputs from the calculations. If future carbon accounting schemes were to include GHG emissions embodied in capital inputs in their calculations then this might benefit developing countries, but further research is needed to investigate this.

4.1.4. *Loss of soil carbon*

Carbon is lost from soils due to cultivation and other management activities. These latter variables are currently excluded from PAS 2050 due to the difficulty in accurately estimating this emission source. However, an LCA analyst following the ISO guidelines (ISO, 2006a,b) might choose to include them in their analysis, and as can be seen in Fig. 1, including loss of soil carbon in the calculation can cause relatively large increases in the PCFs. The impact of doing so on the case study farms varied, with Farm D being particularly affected (over 170% increase) due to its comparatively low baseline carbon footprint. Even on Zambian farms, where land use change emissions tended to dominate all other emissions,

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the inclusion of soil carbon losses resulted in an increase of up to 34% in the total PCF. The figure used for the calculation of soil carbon losses per hectare was taken from Woomer et al. (1997) and relates to continuous vegetable cultivation in Kenya. This figure was applied to all case study farms due to the lack of more specific figures for sugar cane and Zambia and Mauritius. The differences in the results are thus due solely to the different yields on the farms. Further research is needed to enable a more accurate assessment of the impact of this emission source for different countries, regions and crops. The potential of soils to sequester carbon is also an important issue that is currently excluded from carbon accounting schemes, and should be investigated further.

4.1.5. *Land use change: worst case scenario*

In cases where the origin of a product is not known, PAS 2050 requires that land use change emissions are based on a global worst case scenario. Currently, this is represented by the conversion of tropical forest to annual cropland in Malaysia. The reason for the requirement to use this worst case scenario is to encourage users of PAS 2050 to make every effort to report the origin of agricultural products (BSI, 2008a). While this may be an important aim the result of making this worst case scenario assumption on Farm D is an increase in GHG emissions of nearly 1900% (Fig. 1). This is much higher than on Farms A–C because the baseline for Farm D did not include any land use change emissions. In contrast, land use change emissions from converting tropical dry forest to cropland were included in the baseline figure for Farms A–C, thereby decreasing the impact of the worst case variable. However, assuming the global worst case still increased the PCFs on these farms by up to over 190%. Therefore, this one variable can make a very large difference to the PCF, and including the worst case assumption in carbon accounting methodologies presents a major problem to producers of commodities such as sugar, which are often sold either as multiple-origin products or ingredients within a product, the source of which may vary seasonally and may be unknown.

4.1.6. *Exclusion of land use change emissions*

Removing this emission category from the calculation reduced the PCF of sugar cane from the Zambian farms by up to 77%,

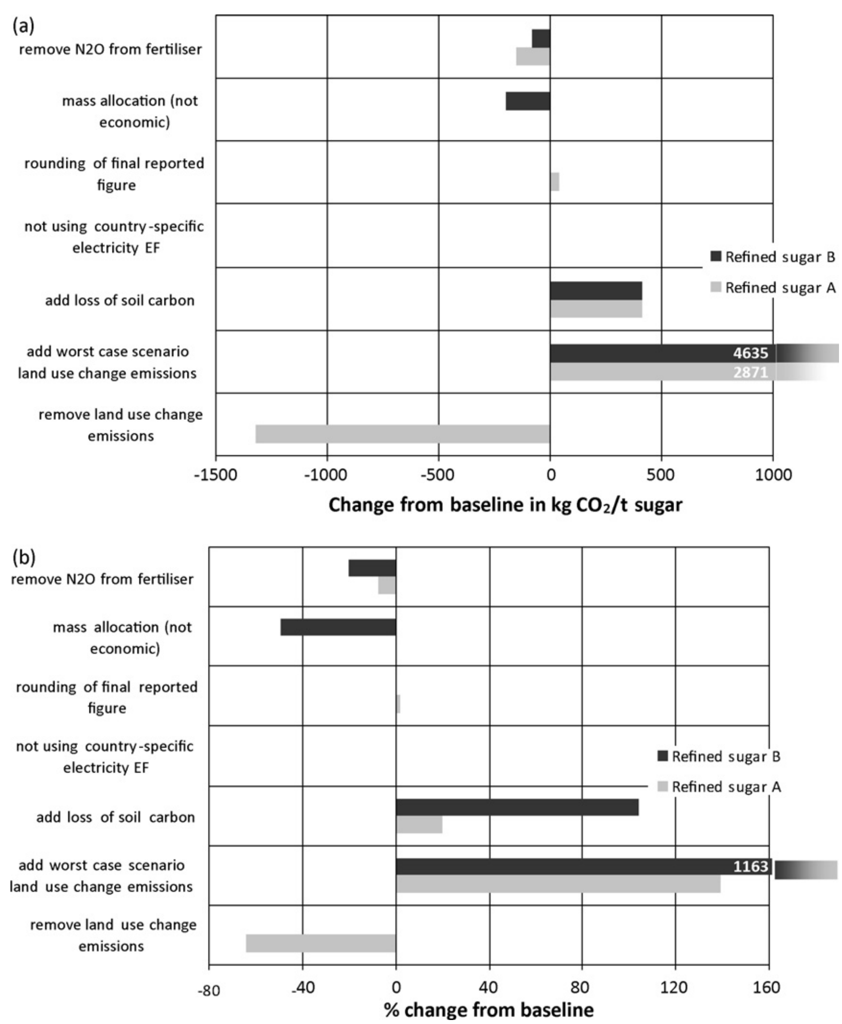

Fig. 2 – Change in carbon footprint of refined sugar delivered to a European port, caused by changing key variables from the baseline calculation. (a) Change from baseline in kg CO_2e/t sugar and (b) percentage change. Baseline calculated according to PAS 2050 (BSI, 2008a). Land use change emissions were only relevant to the baseline calculations for Farms A–C. EF = emission factor.

with the PCF of Farm A decreasing by nearly 160 kg CO_2e/t sugar cane. The impact on Farm A per tonne of cane produced was greater than Farms B and C due to its lower yields per hectare. Farm D remained unaffected by the exclusion of this variable, as land here was converted prior to 1990 and thus this emission source was not included in its baseline calculation.

4.2. *Refined cane sugar at the European import gate*

Increasing the system boundary to include refining and transport to a European port resulted in a decrease in the relative importance of some emissions sources within the carbon footprint (Fig. 2). As sugar cane contributed over 95% to the carbon footprint of sugar leaving the refinery, emissions occurring during the cultivation stage still had a very significant impact on the PCF of refined sugar prior to export. The total carbon footprint of cane sugar arriving in Europe was 2100 kg CO_2e/t raw sugar for Refinery A and 400 kg CO_2e/t of white sugar for Refinery B. The large difference between the two case studies was mainly due to the land use change emissions relevant to Refinery A. Also, the location of Refinery A in a land-locked country far from any port means that any produce destined for export must be transported long distances by road or rail prior to international shipping. Refinery B was located relatively close to a port, leading to comparatively very low transport emissions.

4.2.1. *Allocation*

Defining the method of allocation was important for the PCF of sugar from Refinery B which generated several products, whereas the sole economic output of Refinery A was sugar. When changing from economic allocation as required by PAS 2050 to mass allocation, i.e. an allocation based on the weights of the different outputs, the carbon footprint of sugar from Refinery B decreased by around 50%. This is because sugar accounted for only 22% of the mass of the co-products from this refinery, whereas it accounted for over 90% of the economic revenue.

4.2.2. *Non-country-specific electricity emission factor*

The overall carbon footprint of refined sugar was not affected by the choice of electricity emission factor for refinery operations. This is because Refinery A did not use any grid electricity at all and Refinery B used only small amounts, with the rest of the energy needed being generated from bagasse.

4.2.3. *Land use change: worst case scenario*

The impact of assuming a worst case scenario for land use change emissions was significant for refined sugar, at over 1000% increase for Refinery B and around 140% for Refinery A. Even though their relative importance is reduced compared with the carbon footprint of sugar cane at the farm gate, land use change emissions still have a major impact on the final PCF.

4.3. *Choice of emission factors*

Secondary datasets representing the environmental burdens associated with different products and processes are fundamental to standard LCA and carbon footprinting practice. However, variations between different databases often arise due to the use of different data sources and assumptions. For example, there is considerable variation between different data sources on the emissions from moving sugar from Refinery A in Zambia to the closest port in a 16-t truck (Fig. 3), with ETH (Eidgenössische Technische Hochschule Zürich, Switzerland; Frischknecht et al., 1996) suggesting the emissions of a 16-t truck are more than double those reported by Ecoinvent (Spielmann et al., 2007).

The differences between the databases are related to the different assumptions that each make. The BUWAL (Bundesamt für Umwelt, Wald und Landschaft, Swiss Agency for the Environment, Forests and Landscape) value is based on the production and burning of fuel, and assumes that a truck carries on average 50% load; Ecoinvent includes the production, maintainance, operation and disposal of the truck, as well as a proportion of emissions from the construction, maintainance and disposal of roads; ETH include the

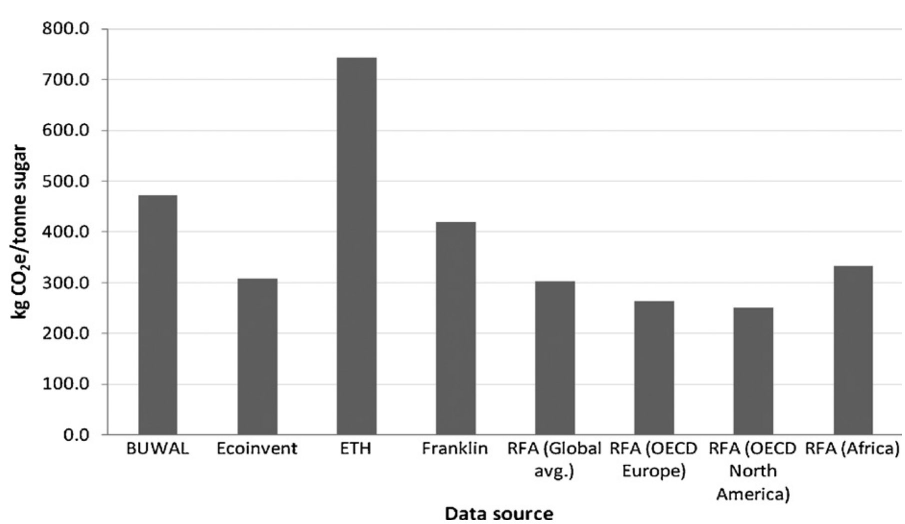

Fig. 3 – Variation between different datasets in GHG emissions in kg CO_2 equivalents per tonne of sugar transported over 2000 km by road, in a 16-t truck. Data are taken from four LCA databases (BUWAL, Ecoinvent, ETH and Franklin) and the UK Renewable Fuels Agengy (2008, truck size not specified).

production, maintainance, operation and disposal of the truck as well as emissions from road construction (but not maintainance or disposal), and assume 40% vehicle efficiency; and Franklin include truck and fuel production and use only. The differences between the Renewable Fuels Agency (RFA) values for Africa, OECD Europe, OECD North America and the world again show the importance of the availability and choice of country- or at least region-specific emission factors. This choice could significantly impact results for a product such as sugar from Refinery A which is transported over large distances.

These differences become important when either the analyst is unaware of them and their causes, or when only one database is available to the analyst. Indeed, either uninformed or manipulative use of emission factors from the different data sources could result in large differences in the final PCF of similar products, particularly when they are transported over large distances. The same problem applies to many other inputs to farming systems and agricultural processes, where published emission factors can vary considerably (Edwards-Jones et al., 2009b).

5. Discussion

5.1. *The carbon footprint of sugar produced in Zambia and Mauritius*

The PCF calculated according to PAS 2050 ranged from 0.03 to 0.2 kg CO_2e/kg of sugar cane delivered to the refinery. The greatest source of emissions on Farms A–C was land use change. The exclusion of these emissions from the PCF calculations resulted in Farms B, C and D having similar carbon footprints per kg of sugar cane. The comparison between farms with and without land use change since 1990 highlights two issues: first, where forest land is converted to cropland in tropical countries, emissions from land use change are likely to be very large and dominate emissions. Second, tropical countries or individual farms which are expanding their agricultural area will have much higher carbon footprints for their agricultural products calculated using PAS 2050 than countries or farms that do not convert native vegetation.

The dominating effect of the land use change emissions on the PCF of sugar cane from Farms A–C means that any efforts to change the farm management in order to reduce the PCF will only have a very small proportional effect. This will continue to be the case for the 20 years following the change in land use that PAS 2050 requires these emissions to be included in the assessment. Farm D, in contrast, might be able to reduce its carbon footprint even further by measures such as a reduction of fertiliser inputs, use of renewable energy sources and/or sugar cane varieties with increased yields that do not require increased inputs. The relatively large differences between the PCFs of sugar cane from Farms A–C in Zambia highlights the importance of calculating PCFs at farm level rather than using figures on a hypothetical average production system within a country. Only if real farm data are analysed in this way can the differences in production systems and their impact on total GHG emissions be understood and real mitigation measures applied.

5.2. *Comparison with other studies*

The non-profit foundation Myclimate estimated GHG emissions for the full life cycle of six different sugars using standard LCA methods for the Swiss supermarket chain Migros (2010): sugar cubes, granulated sugar and organic granulated sugar from sugar beet produced in Switzerland and Germany; sugar cubes and raw sugar from sugar cane produced in Columbia; and organic cane sugar from Paraguay. Out of these six products, beet sugar had the highest carbon footprint, while the organic cane sugar from Paraguay had the lowest (around 0.34 kg CO_2e/kg sugar). This analysis did not include any land use change emissions as no land use change had occurred recently on the farms in Paraguay. Overseas shipping from Paraguay to Switzerland had the largest share in the PCF, followed by GHG emissions from cultivation. For sugar from Switzerland, the cultivation of the sugar beet was responsible for the greatest proportion of GHG emissions, followed by processing. The impacts of packaging and waste disposal were found to be insignificant. Wiltshire et al. (2009) calculated the PCF of unprocessed sugar cane delivered to the local factory in Zambia as 0.05 kg CO_2e/kg and of a paper bag of processed cane sugar from Zambia at the factory outlet in the UK as 0.87 kg CO_2e/kg sugar (excluding land use change).

British Sugar have determined the carbon footprint of sugar produced in the UK from UK grown sugar beet using the PAS 2050 methodology as 0.6 kg CO_2e/kg sugar up to the delivery of the product to food and drinks manufacturers (www.britishsugar.co.uk).

Our results for farms on which no land use change had occurred (0.4 kg CO_2e/kg refined sugar delivered to Europe) are comparable to cane sugar from Paraguay, and it is unlikely that the inclusion of emissions from packaging and disposal would increase the PCF by a large amount. We could not find any other studies that had analysed GHG emissions for cane sugar on farms where land use change had occurred and are therefore unable to make any relevant comparisons. None of the results from these different analyses of the carbon footprint of sugar offer support to the idea that the 'local' production of sugar in Europe is more GHG efficient than more distant production (Edwards-Jones et al., 2008).

5.3. *Data gaps and assumptions*

Despite undertaking extensive data collection and stakeholder discussions during site visits, some data gaps still remained and assumptions had to be made in the calculations. In general, relevant data are available on Mauritius because the sugar industry is highly organised and data are collected annually by the various sugar organisations. Less detailed and reliably documented information was available in Zambia. Because of this the data collected on inputs and outputs in Zambia was potentially incomplete which may compromise the quality of the data used in the analysis. The problem of incomplete datasets would be more severe when considering products from smallholding systems, which are numerous, variable and not centrally organised. This raises two problems: if data are absent it will be necessary to make more assumptions about the processes and/or utilise industry standard data; and if understanding of the production system under analysis is poor, then some processes may be overlooked, and potentially excluded from the calculations.

5.4. *Lack of country-specific emission factors*

There were few country-specific emission factors for inputs and processes in Zambia and Mauritius. This necessitated the use of emission factors from databases which were derived mostly for European systems, e.g. for the production and transport of fertilisers and agro-chemicals, which may not accurately reflect the situation in the case study countries. It is unknown whether this leads to an under- or over-estimation of the resulting emissions in this particular case, but overall this issue is a greater problem for developing countries than industrialised ones. It is important that GHG emissions and PCFs are estimated as accurately as possible because of the commercial advantages or disadvantages that might result from a low or high carbon footprint, and more research is urgently needed to develop more country-specific emission factors for developing countries.

5.5. *Problems in calculating land use change emissions*

PAS 2050 currently gives default figures for land use change emissions for 16 countries (BSI, 2008a). If the country of production is not included in PAS 2050, the value has to be calculated using IPCC (2006) methods. This presents two problems: a certain degree of technical and agro-ecological knowledge and expertise in using IPCC (2006) guidelines is required to carry out these calculations; and the amount of time needed to estimate these emissions might be more than is feasible for many commercial studies with limited resources available.

Another problem arises from the fact that many users of PAS 2050 may not actually visit the farms concerned. This makes choosing the correct pre-conversion vegetation type more difficult with potentially large consequences for the resulting PCF. Without first hand information on the vegetation in question and the support of experts, it might be difficult to judge whether the amount of biomass in the vegetation assessed is closer to the lower or the higher end of the range of possible values defined by IPCC (2006), but choosing the default value might lead to a large over- (or under-) estimation of emissions. There may be cases where a farm visit cannot help with these decisions if, for example, no natural vegetation remains near the farms. In our case studies, the farm visit suggested that even the lower end of the range of possible IPCC biomass values still over-estimated stocks at these sites as the forests on and near the farms were degraded by an unknown number of years of exploitation for fuel wood, i.e. they most likely contained less biomass than the defaults given in IPCC (2006) which appear to be defined for undisturbed and non-degraded vegetation.

IPCC (2006) allows the calculation of emissions from land use change for different forest and grassland types within a country. These emissions can vary greatly between different forest types, e.g. emissions from converting tropical moist deciduous forest to annual cropland in Mozambique are more than double those from converting tropical dry forest. This highlights the importance of knowing the pre-conversion habitat for any particular site, rather than using default factors for the worst case in any given country (such as those in PAS 2050) which may potentially lead to large overestimations of emissions.

Land use change is concentrated in tropical and developing countries expanding their agriculture, whereas the opposite trend is observed in many industrialised countries where land clearance occurred many decades ago. For example, two of our case study farms in Zambia reported their plans to further expand cane cultivation by converting uncultivated land to agriculture, in line with the planned expansion of the sugar industry in Zambia. For this reason the uncertainties and methodological problems discussed here have particular relevance for PCFs from developing countries. Although it is important to include land use change in assessments of GHG emissions, these issues should be addressed in a manner which does not disadvantage developing countries unfairly. One way to address this may be to develop accessible databases which contain data for a greater range of countries, different ecological zones and vegetation types, and to replace the global worst case scenario with regional worst case scenarios.

6. Conclusion

PCFS were calculated for cane sugar according to the methodology specified in PAS 2050. The major constraints to applying PAS 2050 to tropical regions related to the significant effort needed for data collection and the high level of expertise needed to estimate the GHG emissions related to land use change. Even after spending 35 person days collecting primary data in the relevant countries some data gaps and uncertainties remained in the understanding of the production systems. Clearly, visiting producers in developing countries is expensive and therefore not feasible in many situations, and this may have a negative impact on the completeness of the assessment (Wiltshire et al., 2009). This may cast doubts on the validity of using results from such studies in comparative analyses, including any product carbon labels that declare precise figures for GHG emissions.

Where land use change occurs in tropical countries, these values are likely to dominate the carbon footprint, and so their inclusion (or not) in any PCF methodology will have a major impact on the final results of that methodology. In addition, there are large uncertainties associated with the calculation of emissions related to land use change. Even though IPCC (2006) provides detailed guidance on how to calculate these emissions there remains significant room for error and manipulation. Of particular concern are the large scale aggregated descriptions of different forest types in different countries, and the uncertainty surrounding their carbon content. The issue of land use change can lead to high carbon footprints for products from developing countries where more natural vegetation is still being converted; at the same time, current PCF methodologies do not allow for the inclusion of carbon sequestration in perennial agroforestry crops (e.g. coffee, cocoa), precluding these countries from getting a benefit for this carbon storage. Further research is needed to develop databases that would allow the inclusion of carbon storage and soil carbon changes. Further, we strongly recommend that future PCF methodologies should use regional worst case scenarios for land use change emissions instead of a global worst case scenario if the country of origin of a product is not known. Another problem relating to the calculation of carbon footprints for products originating from developing countries is the lack of country- or region-specific emission factors which necessitates the use of emission factors originally developed for and in industrialised countries, reducing the accuracy of the analyses. For PCF to be a meaningful tool allowing comparative analyses or guiding consumers towards more climate friendly products via carbon labels stating precise figures, it is vital that more emission factors are developed that better reflect these countries' production systems. In those cases where the intention of the analysis is to identify emissions hotspots and reduce emissions from a particular supply chain instead of communicating results to consumers, this issue is less of a problem; however, even analyses undertaken by businesses for their own internal purposes could greatly benefit from country-specific emission factors that would allow more targeted mitigation measures to be taken. Where no land use change occurs, other emissions categories can have a greater relative importance (e.g. soil carbon or capital inputs), and so their inclusion can also have a significant impact on the final result. Finally, we encourage the transparent use of PCF methodologies, where data sources, uncertainties and variability are explicitly noted.

Although not analysed in this study, it is important to remember that while carbon accounting and labelling instruments are good for understanding the impacts of an activity on climate change, they are not necessarily good indicators of overall sustainability. For example, some measures that reduce GHG emissions might increase other environmental problems (Hospido et al., 2009), and a reduction of export opportunities for air freighted produce with a high PCF could impact on a large numbers of livelihoods in some of the poorest countries in the world (McGregor and Vorley, 2006).

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