137 (62) March 2012 A 7471 E

Zuckerindustrie
Sugar Industry 3

The Product Carbon Footprint of EU beet sugar

by Ingo Klenk, Birgit Landquist and Oscar Ruiz de Imaña

Reprint from SUGAR INDUSTRY / ZUCKERINDUSTRIE 137 (2012) No. 3, 169–177, and No. 4

Verlag Dr. Albert Bartens, Berlin, Germany

Bartens

Ingo Klenk, Birgit Landquist, Oscar Ruiz de Imaña

The Product Carbon Footprint of EU beet sugar

Die Treibhausgasbilanz von EU-Rübenzucker

The calculations made to obtain the PCF of EU white sugar from sugar beet have revealed that the results are extremely sensitive to methodological choices and this article provides some recommendations in that regard. A comparison of EU beet sugar with two examples of raw cane sugar imported and refined in the EU, showed that the PCF range for EU refined cane sugar is on average similar, if not higher (642–760 kg CO_{2eq}/t sugar) than the total methodological PCF range for the EU beet sugar average case (242–771 kg CO_{2eq}/t sugar). A review of the published literature revealed, on the one hand, that land use change emissions for cane sugar can be very significant but are rarely taken into account, and on the other hand, that overseas transport and refining adds a significant amount of emissions to the PCF of raw cane sugar imported into the EU. An overall land use efficiency comparison between cane and beet production systems also concluded that significantly more land (51%) is required by cane systems to produce an equivalent set of products (sugar and co-products) with an equivalent amount of GHG emissions. Finally, the limitations of PCFs as a tool to evaluate the overall environmental sustainability of EU beet sugar were also analysed.

Key words: sugar beet, white sugar, Product Carbon Footprint (PCF), greenhouse gas (GHG) emissions, cane sugar

Berechnungen der Treibhausgasbilanz (bzw. Product Carbon Footprint PCF) von EU-Weißzucker aus Zuckerrüben ergaben, dass das Ergebnis sehr stark durch die Wahl der Methodik beeinflusst wird. Dieser Artikel enthält daher diesbezügliche Methodikempfehlungen. Der PCF von EU-Rübenzucker (Mittelwert) wurde mit zwei Beispielen für importiertem und in der EU raffinierten Rohrohzucker verglichen. Es zeigte sich, dass der PCF von importiertem raffinierten Rohrzucker im Durchschnitt vergleichbar, wenn nicht sogar höher ist (642–760 kg CO_{2eq}/t Zucker) als die methodisch bedingte, vollständige Ergebnisbandbreite im Falle von EU-Rübenzucker (242–771 kg CO_{2eq}/t Zucker). Eine Auswertung von Veröffentlichungen zum Betreff zeigte einerseits, dass für Zuckerrohr Emissionen aus Landnutzungsänderungen erheblich sein können, jedoch selten berücksichtigt werden; andererseits, dass Überseetransporte und Raffination signifikante Anteile am PCF von in die EU importierten Rohrohzucker haben. Aus einem Vergleich der Flächennutzungseffizienz von Produktionssystemen auf Basis von Zuckerrohr bzw. Zuckerüben konnte gefolgert werden, dass der Flächenbedarf von Produktionssystemen auf Basis von Zuckerrohr signifikant höher ist (51 %), um einen vergleichbaren Warenkorb an Produkten zu erzeugen (Zucker und Nebenprodukte) – dies bei Treibhausgasemission in vergleichbarer Höhe. Abschließend wurden die Limitierungen des PCFs bei der umfassenden Ermittlung der ökologischen Nachhaltigkeit von EU-Rübenzucker untersucht.

Schlagwörter: Zuckerrübe, Weißzucker, Treibhausgasbilanz, Treibhausgasemissionen, Rohrzucker

1 Introduction to carbon footprints and sugar

Carbon footprints provide an estimate of the total amount of greenhouse gases (GHG) which are emitted during the life-cycle of goods or services. Businesses, governments and other stakeholders use carbon footprints in order to gain an understanding of the emissions of GHGs from consumer products and also companies. Product Carbon Footprints (PCFs) can be used for different purposes and that in turn influence the level of detail, accuracy and therefore complexity required when conducting an assessment of the GHG impact of the product[1]. According to a World Bank study (*Brenton* et al., 2010), carbon footprint accounting methods have undergone rapid development over recent years, with no less than 16 different methodologies developed or undergoing development since 2007. These range from nationally and internationally recognized standards such as those based on ISO, to proprietary supermarket systems which aim to satisfy an increasing market demand for 'climate relevant' information along supply chains and towards consumers (*Finkbeiner*, 2009).

Carbon accounting methods differ both in approach and calculation methodology. These methodological differences are reflected in the great variability of results from study to study but also from data set to data set (within the same methodology). Moreover, the different types of GHG emissions that can be taken into account across a product life-cycle and the choice of what emissions are included or not ('system boundaries') can also play an important role in the final result.

For primary food products, such as sugar, the main sources

[1] The ILCD (International Reference Life Cycle Data System) Handbook (2010) in particular distinguishes 3 main goal situations (A, B, C) related to, respectively, decisions based on Life-Cycle Assessments (LCAs) at a 'micro' level, 'meso-macro' level and for 'accounting' purposes.

of GHG emissions are farming, raw material processing and transport. Land use change emissions (LUC), can also be a significant source of emissions. GHG emissions linked to LUC occur when a previously uncultivated area (e.g. degraded land or forests) is converted into cultivated land (direct LUC). A change in cultivation on existing agricultural land from a specific crop to another can indirectly cause a direct LUC somewhere else (indirect LUC), if the crop being replaced is subsequently cultivated in new and former uncultivated land. The negative impact of this type of LUC in the increase of emissions is largely undisputed. To agree, though, on a fair and accurate way to calculate these emissions has proven a far more challenging – and contentious – issue, in particular when LUC effects are deemed to be indirect.

So far, no comprehensive attempt has been made to evaluate the typical carbon footprint of EU beet sugar and compare the latter with the PCF of alternative products such as imported cane sugar or isoglucose consumed in the EU.

This paper has two main objectives: first, to estimate the typical carbon footprint of sugar produced from sugar beet grown in the EU based on various carbon footprinting methodologies and secondly, to compare the derived beet sugar carbon footprint figures to the carbon footprints of its main alternative products as consumed in the EU such as refined cane sugar and glucose and fructose syrups derived from starch based on publicly available data.

2 Literature review of published PCFs for sugar

In recent years, very diverse PCF numbers for sugar (cane- or beet-based) have been published although the details of the methodologies and the calculations behind those figures have not always been made available. Therefore, this article will focus mainly on published studies which provide a minimum of details thus, allowing to attempt a meaningful classification.

Existing publications on the Product Carbon Footprint (PCF) of sugar can be divided into two categories: those assessing the full life-cycle, i.e. from cultivation of sugar crops up to and including the consumer use phase (further on called "cradle to grave" assessments) and those assessing only a part of the life-cycle, e.g. from cultivation up to and including the production facility of the final product such as the sugar factory or mill (further on called "cradle to gate" assessments). White sugar is a ready-made ingredient used for a multiplicity of purposes and does not lead *per se* to specific GHG emissions in the use phase. In addition to the varying emissions related to transport to different sugar users (through retail shops, restaurants or the food processing industry), the multiplicity of possible uses for sugar also makes it very difficult to identify a single appropriate and representative model for the use phase. Maybe for that reason, "cradle to grave" data appear to be clearly in the minority with regards to sugar (essentially reduced to the studies of *Kägi* and *Wettstein*, 2008; Climatop, 2010 and the GEMIS database[2]). A compilation of methodological details and results can be found in Table 1.

Table 1: Literature review for PCF of beet sugar, cane sugar and isoglucose

Source	Product	Region of production	Region of use
GEMIS, version 4.2 (2004)	Sugar	Unknown	Unknown
GEMIS, version 4.7 (2011)	Sugar		
	Sugar, organic		
British Sugar (2008)	Beet sugar	UK	UK
Chappert and *Toury* (2011) – Cristal Union	Beet sugar	France	Not relevant (partial PCF)
Climatop (2010a), validity 1.9.2009-30.8.2010	Beet sugar	Switzerland and Germany	Switzerland
Climatop (2010b), validity 1.10.2010-30.9.2012	Beet sugar	Switzerland and Germany	Switzerland
Fereday et al. (2010)	Beet sugar	US	Not relevant (partial PCF)
Kägi and *Wettstein* (2008)	Beet sugar	Switzerland	Switzerland
Nordic Sugar (2009)	Beet sugar	Northern Europe	Not relevant (partial PCF)
Setzer / BASF (2005)	Beet sugar	Germany	Not relevant (partial PCF)
Suiker Unie (2011)	Beet sugar	Netherlands	Not relevant (partial PCF)
Climatop (2010a), validity 1.9.2009-30.8.2010	Cane sugar	Colombia	Switzerland
Climatop (2010a), validity 1.9.2009-30.8.2010	Cane sugar	Paraguay	Switzerland
Climatop (2010b), validity 1.10.2010-30.9.2012	Cane sugar	Colombia	Switzerland
Climatop (2010b), validity 1.10.2010-30.9.2012	Cane sugar	Paraguay	Switzerland
Fereday et al. (2010)	Cane sugar	US?	Not relevant (partial PCF)
Hattori et al. (2008)	Cane sugar	SW Japan / Thailand	Japan
Kägi and *Wettstein* (2008)	Cane sugar	Colombia	Switzerland
Kägi and Wettstein (2008)	Cane sugar	Paraguay	Switzerland
Plassmann et al. (2010)	Cane sugar	Mauritius	Not relevant (partial PCF)
Plassmann et al. (2010)	Cane sugar	Zambia	
Rein (2010)	Cane sugar	Unknown	Not relevant (partial PCF)
Seabra et al. (2011)	Cane sugar	Brazil Center-South	Not relevant (partial PCF)
Setzer / BASF (2005)	Cane sugar	Brazil	Not relevant (partial PCF)
Yuttiham et al. (2011)	Cane sugar	Eastern Thailand	Not relevant (partial PCF)
Wiltshire et al. (2009) from *Plassmann* et al. (2010)	Cane sugar	Zambia	Not relevant (partial PCF)
Setzer / BASF (2005)	Isoglucose from winter wheat	Germany	Not relevant (partial PCF)
Setzer / BASF (2005)	Isoglucose from US corn	US, dry milling process	Not relevant (partial PCF)
Setzer / BASF (2005)	Isoglucose from US corn	US, wet milling process	Not relevant (partial PCF)

[2] GEMIS is a public domain software/database for eco-balancing. GEMIS was originally developed in Germany by Öko-Institut and Gesamthochschule Kassel (GhK).

Quality	System limits	Co-products	Co-product acccounting method	PCF in g CO_{2eq} kg^{-1} sugar
Unknown	Unknown	Unknown	Unknown	1,468
				1,514
				1,331
White sugar	Cultivation – delivery to customer	Carbonatation lime, animal feed, surplus electricity, topsoil	PAS 2050	600
Unknown	Unknown	Unknown Co-production of sugar and ethanol	Upper heating value	561
White sugar	Full life-cycle	Unknown	Unknown	590
White sugar	Full life-cycle	Unknown	Unknown	680
Unknown	Cultivation – sugar factory	Molasses, beet pulp, betaine, rafinate	Economic value allocation (92% of emissions to sugar)	1,040
White sugar	Full life-cycle	Molasses, surplus electricity	Unknown	600
White sugar	Cultivation – sugar factory	Unknown	Unknown	675
White sugar	Cultivation – sugar factory	Exhausted pulp, waste water, off-gases, beet soil, carbonatation lime, molasses	Economic value allocation (94% of emissions to sugar, only pulp and molasses accounted)	610
White sugar	Cultivation – sugar factory	Molasses, beet pulp and carbonatation lime	Economic value allocation	480
Raw sugar	Full life-cycle	Unknown	Unknown	410
Organic raw sugar			Unknown	340
Raw sugar	Full life-cycle	Unknown	Unknown	530–540
Organic raw sugar			Unknown	450
Unknown	Cultivation – refinery	Surplus electricity, molasses	Surplus electricity: GHG credit (height unclear); molasses: economic value allocation; surplus electricity: GHG credit (91% of emissions allocated to sugar)	630
Unknown (refined)	Cultivation – refinery	Molasses, surplus electricity	Unclear if considered at all	534 (only CO_2?)
Raw sugar	Full life-cycle	Molasses (feed), ethanol, surplus electricity	Allocation (80–85% of emissions to sugar)	425
Organic raw sugar				340
Unknown (refined)	Cultivation – port in English Channel	Bagasse, molasses	Economic value allocation (91.7% of emissions to sugar)	400
	LUC – port in English Channel	None	Not relevant	2,100
Unknown	Cultivation – sugar factory	Molasses, surplus electricity	Molasses: economic value allocation Surplus electricity: GHG credit (72% of emissions to sugar)	307
Raw sugar	Cultivation – sugar factory	Surplus bagasse, surplus electricity	GHG credit (bagasse replacing fuel oil and surplus electricity replacing electricity from natural gas)	234
Raw sugar	Cultivation – sugar factory	Bagasse, waste water, filter cake, molasses	Economic value allocation (82% of emissions to sugar)	210
Unknown	Cultivation – sugar factory	None	Not relevant	550
Unknown	Cultivation – factory outlet in UK	Unknown	PAS 2050	870
Unknown	Cultivation – starch factory	Bran, pulp, gluten, "Grießkleie", "Nachmehl"	Economic value allocation (62% of emissions to glucose)	780
Unknown	Cultivation – starch factory	DDGS	Economic value allocation (84% of emissions to glucose)	640
Unknown	Cultivation – starch factory	"Kleberfutter", germ oil, gluten	Economic value allocation (83% of emissions to glucose)	1,100

2.1 'Cradle to gate' studies

In the category "cradle to gate", PCF studies for beet sugar have been published by *Setzer* (2005), and *Fereday* et al. (2010). For beet sugar, PCF values ranged from 610 g CO_{2eq}/kg sugar for German sugar (*Setzer*, 2005) to 1040 g CO_{2eq}/kg sugar for US beet sugar (*Fereday* et al., 2010). Both studies made a comparison with other types of sugars. In particular, *Setzer* assessed white beet sugar produced in Germany and used in chemical fermentation processes and compared the results to raw sugar produced from Brazilian cane and with isoglucose produced from German wheat and US corn. *Fereday* et al. (2010) provided PCFs for beet and refined cane sugar produced in the USA. A few European companies producing sugar from beet have published PCF numbers in recent years although most of the details relating to the calculations are not publicly available. Therefore, those PCF numbers will not be dealt with in this section but can nevertheless be found in Table 1.

For cane sugar far more literature on PCF is available than for beet sugar with a broad variation of regional validity (i.e. definition of the areas where beet and cane are cultivated and where sugar is produced and used), system limits, process setups and methodologies used. Figures for cane sugar vary significantly from 210 g CO_{2eq}/kg sugar for Brazilian cane raw sugar (*Setzer*, 2005) up to 630 g CO_{2eq}/kg sugar for cane white sugar from the USA (*Fereday*, 2010). Within that range other values have been published: 234 g CO_{2eq}/kg sugar for Brazilian Center-South cane raw sugar (*Seabra* et al., 2011), 307 g CO_{2eq}/kg sugar for a supposedly 'typical' cane growing and sugar mill setup producing raw sugar[3] (*Rein*, 2010) and 550 g CO_{2eq}/kg sugar for cane sugar (of unknown, raw or white, quality) produced in eastern Thailand (*Yuttitham*, 2011). For raw cane sugar produced in South Africa, *Mashoko* et al. (2010) report more than 500 g CO_{2eq}/kg sugar[4] whereas *Fereday* et al. (2010) reported 630 g CO_{2eq}/kg sugar for cane white sugar from the USA.

Going one step further, some studies have also considered the emissions related to the transport of cane raw sugar for refining from the producing country up to a refining facility in the importing country. Figures vary considerably according to the origin of the sugar: 400 g CO_{2eq}/kg sugar for imported sugar from Mauritius up to 870 g CO_{2eq}/kg sugar for imported Zambian cane sugar, both delivered at a refining outlet in the UK (*Plassmann* et al., 2010; *Wiltshire* et al., 2009). Those studies concluded that overseas transport had a significant impact on the PCF of imported cane sugar. Finally, *Hattori* et al. (2008) provided a PCF of 534 g CO_{2eq}/kg sugar for raw cane sugar from Thailand transported to and refined in Japan[5].

When referring to published PCFs for cane sugar, it must be kept in mind that direct land use change (LUC) can have a significant impact on those PCFs, in particular for sugar originating from tropical countries. However, emissions due to direct LUC appear to be rarely accounted for in most of the published PCFs for cane sugar. This is apparently partly due to lack of data on previous and on-going conversion of forest land to crop land (*Rein*, 2010). In his article about the 'typical' carbon footprint of cane sugar, *Rein* (2010) considered direct LUC conversion from natural vegetation to cane growing to cause a substantial increase in calculated carbon emissions although he did not include nor quantify that effect in his own calculations. *Plassman* et al. (2010) found that sugar from Zambia delivered to a harbour in the English Channel could reach up to 2100 g CO_{2eq}/kg sugar if GHG emissions from direct land use change were included, that being one of the rare articles to actually account for that effect.

GHG emissions for glucose and fructose syrups derived from starch (isoglucose or HFCS as it is most commonly known in the USA) can be derived from *Setzer* (2005). For German winter wheat used as raw material he reports 780 g CO_{2eq}/kg isoglucose whereas for the US corn-based variant, values range from 640 g CO_{2eq}/kg (dry milling process) to 1100 g CO_{2eq}/kg isoglucose (wet milling process).

2.2 "Cradle to grave" studies

"Cradle to grave" studies are deemed to include the full life-cycle of the product also including the use phase. *Kägi* and *Wettstein* (2008) and Climatop (2010) made a cradle to grave assessment for beet sugar from Switzerland (white sugar quality) and compared the results with cane sugar from Colombia (raw sugar quality) and organic cane sugar from Paraguay (raw sugar quality). The two Swiss-based studies of *Kägi* and *Wettstein* (2008) and Climatop (2010) show a varying range of results ranging from 410–540 g CO_{2eq}/kg sugar for imported Colombian raw cane sugar and 340–450 g CO_{2eq}/kg sugar for organic raw sugar imported from Paraguay. The latest GEMIS database version 4.7 (2011) also distinguishes between conventional sugar – GHG emissions of 1514 g CO_{2eq}/kg sugar – and organic sugar – GHG emissions of 1331 g CO_{2eq}/kg sugar. It remains unclear if these figures were calculated for beet or cane sugar and how the calculations were carried out. It is worth noting that the GEMIS 2011 figures (1514 g CO_{2eq}/kg sugar) represent an increase from previously published GEMIS figures (GEMIS 4.2 of 2004 provided a figure of 1468 g CO_{2eq}/kg sugar); whereas, over the past decades – at least for EU beet sugar – agricultural inputs (such as fertilizer application rates) decreased whilst beet/sugar yield increased in parallel, as well as fuel demand of sugar factories which were reduced by process optimization measures. In general terms the values published in 2008 by *Kägi* and *Wettstein* were those in the lower range whereas the 2010 values published by Climatop represented a significant increase. That was also the case for Swiss

[3] This 'typical' setup is supposed to reflect a global average. Therefore a GHG credit for surplus electricity of 150 g CO_{2eq}/MJ is given, which means an electricity mix containing a good share of fossil fuels. On the other hand some of the figures used for cultivation and processing appear to be close to the situation of Brazil's Centre-South region, in principle, a high-efficiency sugar producing region.

[4] The article by *Mashoko* et al. (2010) on South African raw sugar presents its data in a way that can be easily misread (see for example, *Rein* (2011) which refers, for that article, to a value of 364 kg CO_2 'equivalent'/t of sugar) whereas in fact *Mashoko* et al., (2010) provide separate values for CO_2, CH_4 and N_2O and not the total CO_2 equivalent. Taking into account the global warming potential (GWP) of the various gases emitted, the total exceeds 500 g CO_2 equivalent/t of raw sugar).

[5] The PCF values provided by *Hattori* et al. (2008) for the imported raw material, Thai raw sugar, before transport to Japan and refining (i.e. 118 g CO_2/kg sugar), appear strikingly low when compared to the values (550 g CO_{2eq}/kg sugar) published in the specific study on Thai sugar by *Yuttiham* et al. (2011). At this stage, it cannot be ruled out that their data refers only to direct CO_2 emissions and not to all greenhouse gases combined (expressed as CO_{2eq}) which, if that is the case, would stress the significant impact of N_2O and CH_4 emissions from cane cultivation on the final PCF results.

beet sugar whose footprint increased between 2008 and 2010, from 590 to 680 g CO_{2eq}/kg sugar. Both for the Swiss-based studies and the GEMIS database it remains unclear what were the reasons for the increase in the absolute PCF figures for those types of sugar within a relatively short time period.
It appears from the above screening of published literature that there is significant variability of PCFs for sugar. That variability is due to multiple factors including, but not limited to, differences in product types and qualities, different geographical scopes, different impacts being considered (e.g. for cane sugar the inclusion or not of overseas transport or LUC), different system boundaries ("cradle to gate" vs. "cradle to grave"), different factory process setups and different co-product accounting methods (e.g. GHG credits from surplus electricity). In such a complex context, it would be clearly inappropriate to simply take those PCFs at face value and compare them with one another without taking into account the different sets of methods and assumptions underlying those calculations.

3 Methodology used in this study

Within this study, "cradle to gate" PCFs of EU beet sugar were calculated. The system limits are from cultivation of sugar beet up to and including the sugar factory, but excluding the packaging, distribution and use of the sugar (see Fig. 1). Processes in the background system such as the emissions related to the production of fertilizers and fuel were included whereas manufacturing and maintenance of machinery and infrastructure were not taken into account. The outputs from the analysed system are the following co-products: sugar, molasses, wet pulp, pressed pulp, dried pulp with molasses, sugar factory lime (a liming fertilizer), beet soil, surplus electricity and surplus heat. The functional unit on which PCF results are expressed is one tonne of white sugar.
Data for sugar beet cultivation and transport emissions were taken from the Biograce (2011) database. These data are officially used within the EU renewable energy directive (RED) to assess GHG emissions associated with bioethanol from sugar beet and serve in the present case as a generic average of the specific GHG emission of sugar beet cultivation. For data related to the sugar beet transport distances and emissions from beet sugar production, EU average figures for the sector were used. Average EU beet sugar factory emissions were calculated based on an EU-wide study conducted by ENTEC for the European Association of Sugar Producers (CEFS) in 2010. The data covered the period 2005–2008, which does not fully reflect the massive closure of, often less-efficient, factories which took place throughout that period and until the end of the last decade, as a result of the EU sugar market reform. A base-case reflecting the average emissions of EU beet sugar production was calculated including an average of EU beet pulp drying practices.[6] Since there are sugar beet factories either producing wet/pressed beet pulp or drying the beet pulp, two variations of the factory setup, 'no drying' (scenario 1) and 'all beet pulp is dried' (scenario 2) were also assessed. For details of the data used see Tables 2 to 5.

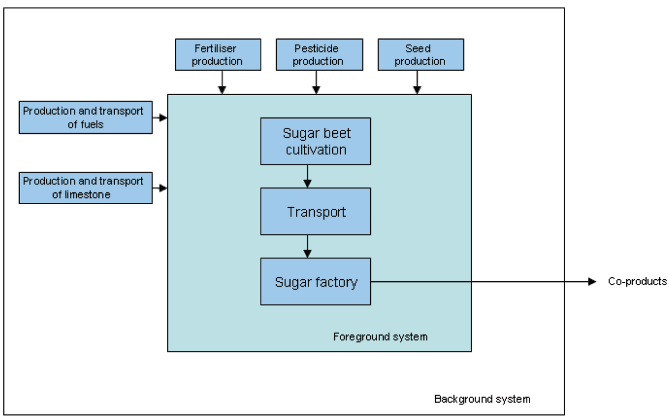

Fig. 1: System boundaries of the analysed system

[6] Based on the EU average for the period 2005–2008 that was an average production of 7% wet pulp, 31% pressed pulp and 62% dried pulp (source: estimate based on CEFS (2010) for the period 2005–2008 on the basis of a standardised dry matter content for beet pulp of, respectively, 13% ('wet pulp'), 22% ('pressed pulp') and up to 92% ('dried pulp').

Table 2: Greenhouse warming potential (GWP) factors used (Source: IPCC, 2007)

GWPs (IPCC, 2007)	CO_{2eq}
CO_2	1
CH_4	25
N_2O	298

Table 3: Data used for sugar beet cultivation, sugar beet transport and as inputs of sugar factory

	Unit	Amount	Source
Sugar beet cultivation (Input)			
Diesel	$L\ ha^{-1}\ year^{-1}$	177	
Nitrogen fertilizer	$kg\ N\ ha^{-1}\ year^{-1}$	120	
CaO fertilizer	$kg\ ha^{-1}\ year^{-1}$	400	
Potassium (K_2O)	$kg\ K_2O\ ha^{-1}\ year^{-1}$	135	Biograce (2011)
Phosphorous (P_2O_5)	$kg\ P_2O_5\ ha^{-1}\ year^{-1}$	60	
Pesticides	$kg\ ha^{-1}\ year^{-1}$	1.3	
Seed	$kg\ ha^{-1}\ year^{-1}$	6	
Field N_2O emissions	$kg\ N_2O\ ha^{-1}\ year^{-1}$	3.27	
Sugar beet cultivation (Output)			
Sugar beet (clean)	$t\ ha^{-1}\ year^{-1}$	68.9	Biograce (2011)
Dirt tare	% on sugar beet	8.9	CEFS
Sugar beet (with tare)	$t\ ha^{-1}\ year^{-1}$	75.0	
Beet transport			
Average distance	km	45	CEFS
Transport mode	% road by truck	100	Assumption
Spec. diesel consumption	$MJ\ t^{-1}\ km^{-1}$	0.94	Biograce (2011)
Beet sugar factory (Input)			
Process steam production			
Spec. fuel consumption	$kWh\ t^{-1}$ sugar	1522	ENTEC (2010)
Lime kiln operation			
Spec. fuel consumption	$kWh\ t^{-1}$ sugar	74.2	ENTEC (2010)
	$t\ t^{-1}$ sugar	0.0096	*
Spec. limestone consumption	$t\ t^{-1}$ sugar	0.12	ENTEC (2010)
Fuel transport	km	400	**
Limestone transport	km	400	**
Pulp drier			
Spec. fuel consumption	$kWh\ t^{-1}$ pulp dry substance	1370	ENTEC (2010)

* For lower heating value of 7.7 MJ kg^{-1} (GEMIS 4.5). ** Assumption (100% by truck).

Table 4: Data used for sugar factory output

Beet sugar factory (output)	Unit	Amount			Source
		EU average	Scenario 1 (drying of full amount of beet pulp)	Scenario 2 (no drying of beet pulp)	
White sugar	$t\ t^{-1}$ sugar beet	0.128	0.128	0.128	CEFS (2010)
Beet soil	$t\ t^{-1}$ sugar beet	0.137	0.137	0.137	CEFS (2010)
Carbonatation lime	$t\ t^{-1}$ sugar beet	0.027	0.027	0.027	Estimate
Molasses	$t\ t^{-1}$ sugar beet	0.02	0.02	0.04	Estimate
Wet pulp	$t\ t^{-1}$ sugar beet	0.03	0	0	CEFS (2010)
Pressed pulp	$t\ t^{-1}$ sugar beet	0.07	0	0.227	CEFS (2010)
Dried pulp with molasses	$t\ t^{-1}$ sugar beet	0.051	0.072	0	CEFS (2010)
thereof beet pulp	$t\ t^{-1}$ sugar beet	0.031	0.05	0	CEFS (2010)
Net electricity export	$kWh\ t^{-1}$ sugar	29.4	29.4	29.4	ENTEC (2010)
Net steam/heat export	$kWh\ t^{-1}$ sugar	2.94	2.94	2.94	ENTEC (2010)

Table 5: Specification of sugar factory outputs

Beet sugar factory (output)	Dry substance in %	Digestible energy in $MJ\ kg^{-1}$ dry substance	Lower heating value (LHV) in $MJ\ kg^{-1}$
White sugar	100	16.8	16.92
Beet soil	65	0	0
Carbonatation lime	70	0	0
Molasses	80	12.29	10.4
Wet pulp	13	12.1	0.0
Pressed pulp	22	12.1	1.6
Dried pulp with molasses	92	12.1	14.5

Sugar factories produce a set of different products including, but not limited to, sugar, beet pulp, molasses and sugar factory lime (i.e. it is a multifunctional process). In order to establish the PCF of the product beet sugar, at first the total GHG emissions of the whole system were identified and then followed the stepwise procedure of ISO 14044 norm for emissions accounting, which can be summed up as follows:

– Step 1: Allocation should be avoided by dividing the unit process into independent sub-processes or by expanding the product system to include the additional functions related to the co-products and calculating GHG credits for the co-products (substitution method).
– Step 2: Where allocation cannot be avoided (i.e. step 1 cannot be applied or is inadequate), the inputs and outputs of the system should be partitioned between its different products or functions in a way that reflects the underlying physical relationships between them.
– Step 3: Where physical relationship alone cannot be established or used as the basis for allocation, the inputs should be allocated between the products and functions in a way that reflects other relationships between them. For example, input and output data might be allocated between co-products in proportion to the economic value of the products.

In the present study, the authors decided to apply the most common accounting methods across all steps (1 to 3 above) as a way of identifying possible biases in the choice of accounting methodologies and in order to explore the practical difficulties and challenges associated with the implementation of some of those accounting methods.

The first step in the ISO hierarchy, consisting in the division of the system into separate sub-processes, could not be implemented in order to solve the multi-functionality of the production process. System expansion (also called 'substitution') was then analysed. In that context several equally adequate substitution products could be identified for the main co-products, which, in turn, resulted in significantly different PCFs for sugar. This is because some of those co-products can either be used in different sectors (like molasses) or – as in the case of feed products – a group of equivalent products exists. To show the extreme variation of results depending on the type of substitute products selected, the authors have chosen

Table 6: Sugar factory outputs and their competing products (substitutes)

Beet sugar factory (output)	Competing products (substitutes)	Chosen substitutes for example I	Chosen substitutes for example II
White sugar	Refined cane sugar	Not relevant	Not relevant
Beet soil	Agricultural soil	Not accounted for	Not accounted for
Carbonatation lime	Mineral lime fertilizer	Mineral lime fertilizer	Mineral lime fertilizer
Molasses	**As feed:** fodder cereal (e.g. barley), **As raw material for fermentation industry:** raw, thin or thick juice; cane molasses	Thick juice from sugar beet	Fodder barley
Wet pulp Pressed pulp	Fodder cereal (barley, wheat); corn whole plant for silage	Corn whole plant for silage	Fodder barley
Dried pulp with molasses	Fodder cereal (barley, wheat); wheat bran; citrus; corn gluten feed; lucerne (alfalfa); spent grains (from breweries)	Fodder barley	Dried lucerne (alfalfa)
Electricity	Electricity from grid	EU average grid intensity	Marginal electricity: coal
Steam / heat	Steam/heat produced by 3rd parties	Not accounted for	Not accounted for

Table 7: Data used to calculate GHG credits

	Unit	Amount	Source
Mineral lime fertilizer			
CaO content carbonatation lime	kg CaO kg^{-1}	0.27	*Bürcky* and *Märländer* (2000)
Thick juice from sugar beet			
Energy demand / surplus electricity compared to sugar beet production	%	90	Assumption
Spec. thick juice production	kg thick juice kg^{-1} sugar	1.7	Assumption
Substitutes for co-product credits: – Beet soil: not accounted for – Carbonatation lime: mineral lime fertilizer – Wet pulp & pressed pulp: corn whole plant for silage – Dried pulp: fodder barley – Surplus electricity: EU average grid intensity – Surplus heat/steam: not accounted for			Assumption
Corn whole plant for silage			
Diesel	L ha^{-1} $year^{-1}$	105	Biograce (2011)
Nitrogen fertilizer	kg N ha^{-1} $year^{-1}$	51.7	
CaO fertilizer	kg ha^{-1} $year^{-1}$	1,600	
Potassium (K_2O)	kg K_2O ha^{-1} $year^{-1}$	25.8	
Phosphorous (P_2O_5)	kg P_2O_5 ha^{-1} $year^{-1}$	34.5	
Pesticides	kg ha-$^{-1}$ $year^{-1}$	2.4	
Seed	kg ha^{-1} $year^{-1}$	0	
Field N_2O emissions	kg N_2O ha^{-1} $year^{-1}$	0.82	
Corn yield	t corn dry substance ha^{-1} $year^{-1}$	7.5	Assumption
Dry substance content of corn	%	35	DLG Futterwerttabellen (1997)
Digestible energy	GJ t^{-1} corn	3.7	
Fodder barley			
Diesel	L ha^{-1} $year^{-1}$	100	Assumption
CaO fertilizer	kg ha^{-1} $year^{-1}$	150	Assumption
Nitrogen fertilizer	kg N ha^{-1} $year^{-1}$	98	EFMA (data for EU 15, 2004/05)
Potassium (K_2O)	kg K_2O ha^{-1} $year^{-1}$	28	
Phosphrous (P_2O_5)	kg P_2O_5 ha^{-1} $year^{-1}$	35	
Pesticides	kg ha^{-1} $year^{-1}$	2.0	Assumption
Seed	kg ha^{-1} $year^{-1}$	120	*Kaltschmitt* and *Reinhardt* (1997)
Field N_2O emissions	kg N_2O kg^{-1} N applied	0.021	IPCC (2006)
Barley yield	t barley ha^{-1} $year^{-1}$	4.2	EFMA (data for EU 15, 2004/05)
Digestible energy	GJ t^{-1} barley	11.3	DLG-Futterwerttabellen (1997)
Dried lucerne (alfalfa)			
Diesel	L ha^{-1} $year^{-1}$	50	Assumption
Nitrogen fertilizer	kg N ha^{-1} $year^{-1}$	15	*Hanff* et al. (2008)
CaO fertilizer	kg ha^{-1} $year^{-1}$	320	
Potassium (K_2O)	kg K_2O ha^{-1} $year^{-1}$	256	
Phosphrous (P_2O_5)	kg P_2O_5 ha^{-1} $year^{-1}$	33	
Pesticides	kg ha^{-1} $year^{-1}$	0	Assumption
Seed	kg ha^{-1} $year^{-1}$	12	*Peyker* and *Degner* (1996)
Field N_2O emissions	kg N_2O kg^{-1} N applied	0.021	IPCC (2006)
Fuel for drying (diesel)	GJ t^{-1} dried protein	41.868	COPA COGECA et.al. (2007)
Lucerne yield	t lucerne dry substance ha^{-1} $year^{-1}$	8.7	*Hanff* et al. (2008)
Dry substance lucerne	%	40	
Protein content lucerne	kg raw protein t^{-1} dry substance	200	
Dry substance after drying	%	88	
Digestible energy	GJ t^{-1} dried lucerne	7.2	DLG Futterwerttabellen (1997)
EU average grid intensity			
Emission factor of grid electricity	g CO_{2eq} kWh^{-1} electricity	465.1	Biograce (2011)
Marginal electricity: coal			
Emission factor of coal	g CO_{2eq} kWh^{-1} coal	400.61	Biograce (2011)
Power plant	%	40	Assumption

two examples of 'substitution scenarios' based on different substitutes (for details see Table 6 and Table 7). In that context, no substitute was accounted for beet soil or surplus heat (Table 8) which, in practice, means that no emission credit was given for those two outputs.

Additionally, PCFs of beet sugar were also calculated by allocation based on a physical criteria (step 2 of the ISO 14044 hierarchy). Four possible physical relationships could be identified and were subsequently used: mass (wet), mass (dry substance) and energy (as digestible energy and lower heat-

Table 8: Chosen substitutes

Co-product	Substitute chosen: Example I	Substitute chosen: Example II
Beet soil	Not accounted for	
Carbonatation lime	Mineral lime fertilizer	
Molasses	Thick juice	Fodder barley
Wet pulp	Corn whole plant (for silage)	Fodder barley
Pressed pulp		
Dried pulp with molasses (incl. pulp drying)	Fodder barley	Lucerne (alfalfa), dried
Surplus electricity	EU grid mix	Marginal electricity (from hard coal)
Surplus heat	Not accounted for	

ing value, LHV). Surplus electricity production was assessed homogeneously across the four allocation scenarios through the substitution method (using EU grid average).

For the economic allocation methodology (the lowest ranked in the ISO hierarchy) no less than 5 different price references applicable to EU beet sugar were identified (see also Fig. 2): (1) the EU regulatory reference price for white sugar – an official EU price related to a standardised estimate of EU beet sugar production costs, (2) the EU average market price for bulk sugar for food uses, (3) the EU average market price for bulk sugar for non-food uses, (4) the World market price for white sugar – as an indication of EU sugar export prices – and finally (5) an EU-mix price that would reflect a combination of the previous three types [(2) to (4)] of sugar prices according to the share of the different EU beet sugar sales (based on public statistics for food, non-food markets and exports). When combined with the three different factory settings analysed (base case, no drying of beet pulp and drying 100% of the pulp) no less than 15 different PCFs for the same beet sugar were identified under economic allocation. All of them are shown in the results section of this article. For co-products other than sugar the same price was used in all variations.

3.1 Cut-off criteria, assumptions and limitations

With regard to farming operations, all N-fertilizer was assumed to be in the form of mineral fertilizer, as there is no publicly available figure known for the average use of organic

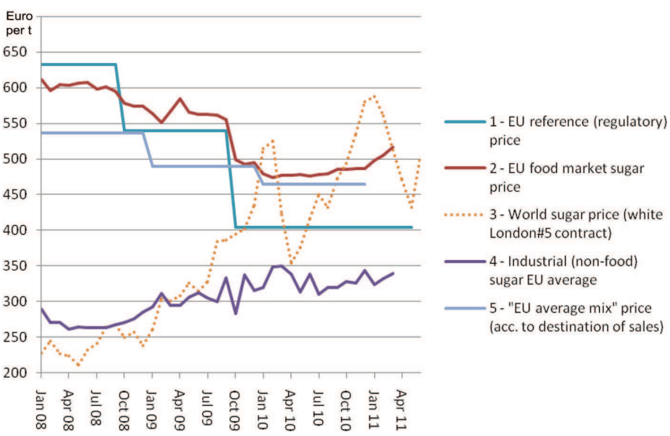

Fig. 2: A selection of different prices applicable to EU beet sugar and their evolution throughout several years. All prices are shown in EUR/t (Source: Data from European Commission and other public sources).

fertilizer (e.g. manure) in sugar beet cultivation in Europe. All the basic inputs to sugar beet cultivation were included, that is, seed, fertilisers, pesticides and diesel consumption for field work. Nitrous oxide, soil emissions (N_2O, commonly known as laughing gas) from farming were included according to Biograce (i.e. 2.7% of applied N is emitted as N_2O). Transport of sugar beet and adherent soil was also accounted for, and it was assumed that all transports are by 40-t truck. The emissions related to the return of empty trucks delivering beet to the factories were also accounted for in the Biograce data.

GHG emissions linked to LUC (land use change, direct or indirect) were estimated to be negligible because all land used to grow beet, at least in the EU, is already arable land.

With regard to factories, very small inputs were excluded. Specifically, most process chemicals used in sugar production such as NaOH or HCl for pH correction or antifoaming agents were assumed not to be significant for the overall result because they were used only in small quantities. However, as limestone is a processing aid used in larger amounts (approx. 2% per tonne of beet processed), it therefore was included.[7]

For surplus steam, which some factories co-produce, substitutes were difficult to establish, because they depend on the local situation. Since the resulting GHG credit for surplus steam was expected to be small as an EU average, no GHG credit for surplus steam was calculated. Potential emissions from water treatment systems were, on the other hand, not taken into account because there is insufficient data available about the different types of water treatment systems in operation in EU beet sugar factories.

The emission factors of the process inputs used in the calculations are listed in Table 9.

3.2 Calculation of a comparable PCF for cane sugar used for refining

For the supply of cane sugar to the EU the most common scenario is the production of raw cane sugar in a tropical country, which is then transported as bulk sugar to a refinery located within a European harbour to produce white cane sugar. However, raw cane sugar imports that are consumed as such (i.e. raw) constitute a different product and moreover represent very limited amounts out of the total amount of sugar consumed in Europe.[8] For that reason raw cane sugar as a final product was not considered for the purpose of this comparison. Semi-white sugar originating directly from cane sugar mills ('plantation white sugar') is not typically consumed as such in the EU and was also not considered to be a full substitute of crystal white sugar (from beet or cane), notably for applications such as soft drinks and pharmaceutical products which often require very high purity (e.g. very low levels of ash and other plant material, even at trace levels[9]), very low sugar colour levels and specific crystal sizes among other quality requirements.[10]

---

7 From a procedural point of view, when calculating the PCF of actual factories, the size of the emissions from inputs suspected to be 'small' may still need to be evaluated before these can be ruled out.

8 According to Eurostat data, imports of 'raw cane sugar not for refining' (code 1701 11 90) represented less than 4% of the total sugar consumed in the food market in the EU in 2010 (Eurostat trade database accessed in September 2011).

Table 9: Emission factors used

	Unit	Emission factor	Source
Cultivation (Input)			
Diesel	kg CO_{2eq} L^{-1}	3.14	Biograce (2011)
	g CO_{2eq} MJ^{-1}	87.64	
Nitrogen fertilizer	kg CO_{2eq} kg^{-1}	5.88	
CaO fertilizer	kg CO_{2eq} kg^{-1}	0.13	
Potassium (K_2O)	kg CO_{2eq} kg^{-1}	0.58	
Phosphorous (P_2O_5)	kg CO_{2eq} kg^{-1}	1.01	
Pesticides	kg CO_{2eq} kg^{-1}	10.97	
Sugar beet seeds	kg CO_{2eq} kg^{-1}	3.54	
Corn seeds	kg CO_{2eq} kg^{-1}	–	
Barley seeds	kg CO_{2eq} kg^{-1}	0.15	*Kaltschmitt* and *Reinhardt* (1997)
Lucerne (alfalfa) seeds	kg CO_{2eq} kg^{-1}	–	
Transports			
Truck for dry products	g CO_{2eq} t^{-1} km^{-1}	82.5	Biograce (2011)
Ship, ocean bulk carrier	g CO_{2eq} t^{-1} km^{-1}	17.6	Biograce (2011)
Beet sugar factory (Input)			
Fuel provision and use for process steam production	g CO_{2eq} kWh^{-1}	286.1	Fuel mix: ENTEC (2010), emissions factors Biograce (2011)
Fuel provision and use in lime kiln	g CO_{2eq} kWh^{-1}	414.6	Fuel mix: ENTEC 82010), emissions factors GEMIS 4.5
Limestone provision	kg CO_{2eq} t^{-1}	11.58	GEMIS 4.5 (only provision to market, no CO_2 from burning, since CO_2 is precipitated in the process as $CaCO_3$ again)
Fuel provision and use in pulp drier	g CO_{2eq} kWh^{-1}	303.7	Fuel mix: ENTEC, 2010 Emissions factors Biograce (2011)
Cane sugar refinery (Input)			
Fuel oil	g CO_{2eq} kWh^{-1}	305.9	Biograce (2011)

Because raw cane sugar can be supplied from various regional origins, two different examples were assessed: example I (which more or less would reflect import of cane sugar from Brazil Centre-South) assumed 400 km truck transport within the production country and 10,000 km transport by ocean carrier to a harbour within the EU. Example II (which could be applicable to imports of sugar from South-East Africa) assumed only 50 km truck transport within the production country and 5000 km transport by ocean carrier to a harbour within the EU.

Due to the absence of an existing data set available for cane sugar for refining in the EU (such as the ENTEC data set for EU beet sugar), it was decided to estimate a PCF for cane sugar used for refining in the EU based on published literature data. For that purpose, data from *Rein* (2010) were used as a basis since the latter was supposed to reflect a 'typical' PCF for cane sugar. It should be noted, however, that under closer examination, it appears, in particular, that some of its data reflects best performance levels in sugarcane growing and above-average electricity exports to the grid. This assessment is particularly relevant with regard to one major GHG emitting factor (N-fertilizer and the derived N-field emissions) and a major source of GHG 'credit' (electricity put into the public grid):

– Application rate of mineral N fertilizer is assumed to be 75 kg N/ha/a by *Rein* (2010) whereas *Yuttiham* et al. (2011) have recently reported – for the situation in Eastern Thailand (a top-three world exporter of cane sugar) N fertilizer application rates between 19 and 939 kg N/(ha · a) (199 kg N/(ha · a) on average). In Australia, another top-three world cane sugar exporter, *Renouf* and *Wegener* (2007) reported N-application rates (urea) at similar levels [167 kg N/(ha ·a) average in Queensland with a range between 140–223 kg N/(ha · a)]. Those N-use levels refer only to N in urea and do not include partial N applications though ammonium sulphate (12 kg/ha as S) or diammonium phosphate (19 kg/ha as P). Finally, in South Africa, *Mashoko* et al. (2010) reported 120 kg N/(ha · a).
– When it comes to field emissions of N_2O due to N-fertilizer application, *Rein* (2010) used a specific conversion factor (1.325% of N in nitrogen fertilizer converted to N in N_2O emissions) derived from general IPCC guidelines. Several studies, in particular with regard to sugarcane cultivation in Australia (*Denmead* et al., 2009 and *Renouf* and *Wegener*, 2007) have shown that actual N-fertilizer conversion rates for cane growing soils can be much higher due to the climatic conditions and some cultural practices in sub-tropical and tropical high-rainfall regions in which sugarcane is grown.[11]

In the present article, for beet sugar cultivation, the authors made use of the EU Biograce figures which are crop-specific and which assume that 1.718% (a higher fraction than the default IPCC value used by *Rein*) of N in nitrogen fertilizer is converted to N in N_2O emissions.

[9] That is the case, for example, with the undesirable 'Acid Beverage Floc' formation in soft drinks due to the presence of trace elements in some sugars at a level of some parts per million (ppm). Cf. *Clarke* et al. (1999).

[10] See for example *van der Poel* et al. (1998; p. 84, 98 and following): "*Advanced processes in the food industry and the development of new products have historically led to specific and sensitive analytical methods to assess sugar quality. These have revealed that even a small portion of less than 0.1% of additional non-sucrose substances in sugar affects the quality of the sugar and its behaviour during storage and either industrial processing or household use*".

[11] In particular, *Denmead* et al. (2010) refer to values oscillating between 2.8% and 21% of N in nitrogen fertiliser converted to N in N_2O emissions for different Australian sites compared with a default national inventory value of 1.25%. They enunciate as possible causes the 'climatic conditions and cultural practices in the sub-tropical and tropical high-rainfall regions in which sugarcane is grown in Australia' as being conducive to rapid carbon and nitrogen cycling.

– Although exports of surplus electricity take place – to some extent – in some countries (see *Seabra* et al., 2011, for Brazil and *Hattori* et al., 2008, for Thailand) exports of surplus electricity are only carried out by a certain fraction of cane mills and only to the extent permitted by the local situation of the mill. *Rein* (2010) used an average value of 20 kWh surplus electricity/t sugarcane. Other studies (e.g. *Seabra*, 2011) report that in Brazil Centre-South only 100 mills – out of a total exceeding 400[12] – export electricity thus resulting in a regional average of 10.7 kWh/t sugarcane, therefore *Rein*'s value seems to be high and not average.

That PCF value for cane sugar was then adjusted by adding the emissions related to the estimated transport distance to a refining facility in Europe (local transport within Europe was however set at zero km between the arrival port and the refining installation) plus emissions of raw sugar refining into white sugar derived from energy use data from *Fereday* et al. (2010). For a detailed summary of the assumptions and data used to estimate those emissions please see Table 10.

Despite their potential relevance, direct LUC effects were not calculated or added to the base figures of *Rein* (2010) as the latter reflected a hypothetical situation not related to a specific country of origin. Indirect LUC effects lack, in any case, a sufficiently clear methodology to account for those and were therefore not considered at this stage of their methodological development.

3.3 Beyond the carbon footprint of sugar: GHG and land use efficiencies of production systems

In multi-functional processes, where the total emissions of the analysed system are to be shared among different co-products, different methodological choices may significantly influence the calculated PCFs and thus result in biased comparisons between the GHG efficiency of products. An alternative approach is to compare the land use efficiency of producing a given amount of a product, e.g. white sugar, under alternative production systems (e.g. beet and cane sugar) taking into account the full set of products generated, the total GHG emitted and the total amount of land required by each production system.

In the case of beet and cane sugar, though, the two systems do not produce the same kind of products and/or not in the same amounts. Hence, the cane production system will typically generate significant amounts of sugar, molasses and surplus electricity (the latter obtained by burning the cane fibre, bagasse) whereas a typical beet production system will also produce, in addition to sugar, significant amounts of animal feed (beet pulp) and lime fertiliser (carbonatation lime) correlated with a lower production of surplus electricity. In order to make a valid comparison, the authors created two sets of 'equivalent' production systems (based on two different possible substitutes for beet pulp) to compensate for those outputs produced in greater amounts by one system or the other (see Fig. 3).[13] This system comparison makes it possible to determine overall GHG and land use efficiencies of both production systems.

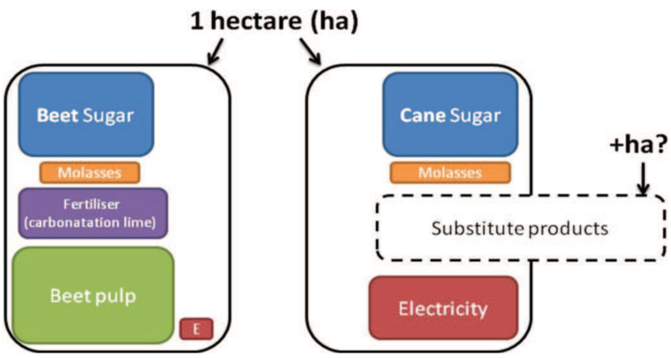

Fig. 3: Diagram representing the concept of a comparison between beet and cane production systems on the basis of the amount of land required to produce an equivalent set of products.

4 Results

4.1 Total emissions of the defined (beet) system

The overall system emissions for sugar beet cultivation, sugar beet transport and sugar production are shown in Table 11. About 32% of these emissions are associated with sugar beet cultivation, 4% with sugar beet transport and the remaining part, about 64%, with sugar beet processing in the sugar factory (see Fig. 4). Nearly 50% of the overall GHG emissions are due to the production of steam for the sugar factory process.

Compared with the EU average case described above, total emissions decreased by 11% under scenario 1 (i.e. no drying of sugar beet pulp) whereas they increased by about 7% when assuming drying of the full amount of beet pulp produced (scenario 2) (see Table 11).

Within sugar beet cultivation the main contributors to GHG emissions were N_2O field emissions (40%), nitrogen fertilizer production (29%) and diesel use (23%) (see Fig. 5).

Table 10: Data used to calculate PCF of cane sugar delivered to EU

	Unit	Amount Example I	 Example II	Source
Cane sugar production	kg CO_{2eq} t^{-1} sugar	307		*Rein* (2010)
Fraction of cultivation / cane transport / mill	%	72 / 5 / 23		*Rein* (2010)
Sugar transport to harbour	km	100	400	Assumption
Transport mode		Truck		Assumption
Sugar transport to EU harbour	km	5,000	10,000	Assumption
Transport mode		Ship		Assumption
Sugar transport from the harbour to EU refinery	km	0		Assumption
Transport mode		Truck		Assumption
Spec. fuel consumption of refinery	kWh t^{-1} sugar	794		*Fereday* et al. (2010)
Fuel used	–	Fuel oil		Assumption

12 FranceAgriMer (2011) p. 89.

13 Example I (Centre-South Brazil): raw cane sugar transport to harbour (400 km) and overseas transport by ship (10,000 km). Equivalent products (option [a]): barley (for wet and pressed sugar beet pulp) and dried lucerne/alfalfa (for dried sugar beet pulp with molasses).
Example II (South-East Africa): raw cane sugar transport to harbour (50 km) and overseas transport by ship (5000 km). Equivalent products (option [b]): corn, whole plant (for wet and pressed sugar beet pulp) and barley (for dried sugar beet pulp with molasses).

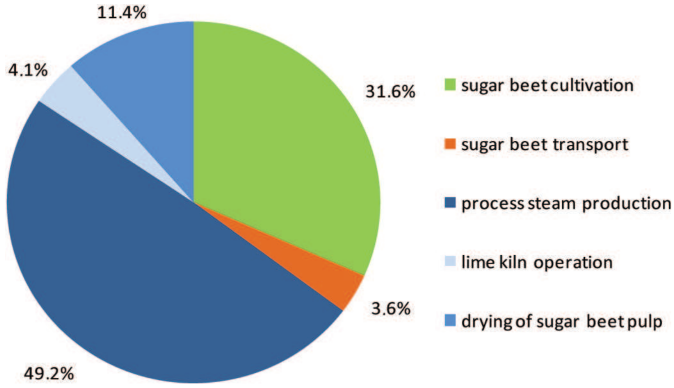

Fig. 4: Sugar beet growing, transport and processing: origin of GHG emissions in CO_{2eq}

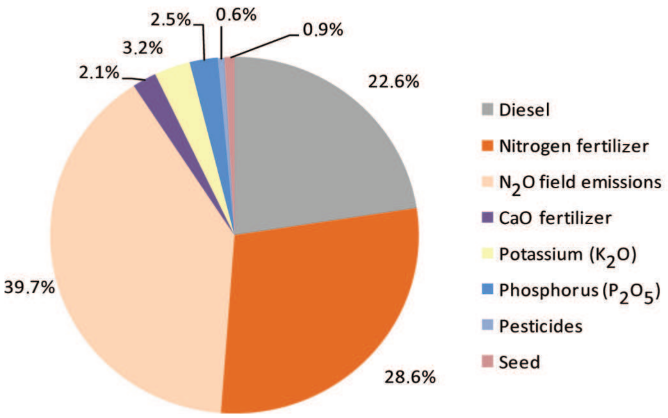

Fig. 5: Sugar beet cultivation: origin of GHG emissions in CO_{2eq}

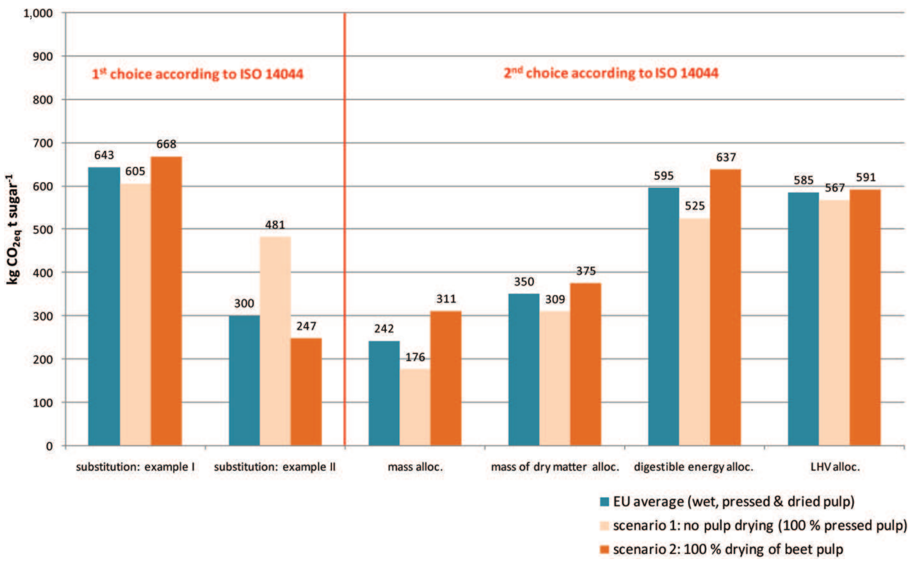

Fig. 6: PCF of white sugar from beet (EU average and 2 different beet pulp drying scenarios) according to the substitution and physical allocation methods (the details of the background data used are provided in Tables 12 and 13).

4.2 PCF of EU beet sugar

Based on the various GHG accounting methods, about a dozen different PCFs for white sugar under each of the beet pulp drying scenarios considered were obtained. Roughly half of the PCFs obtained corresponded to substitution and physical allocation methods as shown in Figure 6.

The large difference observed between the two substitution examples was mainly linked to the choice of different substitute products for dried beet pulp and the amount of GHG credits associated with that choice. Hence, assuming fodder barley as a substitute (example I) this resulted in a GHG credit of 151 kg CO_{2eq}/t sugar, whilst assuming that the substitute was dried lucerne (alfalfa) (example II) this resulted in a GHG credit of 434,3 kg CO_{2eq}/t sugar. Among the various physical allocation methods, the allocation based on (wet) mass systematically resulted in the lowest PCF for white sugar (followed closely by allocation based on dry matter) whereas energy allocation methods provided the highest PCF range based on physical allocation methods.

Economic allocation, on the other hand, resulted in no less than 5 different PCFs for each scenario according to the different prices for sugar chosen. Economic allocation methods resulted, in general, in the highest average ranges of PCFs for white sugar. That is explained by the generally larger share of value captured by sugar compared to the other co-products of the analysed system. The details of each of the fifteen combinations found are shown in Figure 7.

Table 14 summarises the range of PCF results for EU beet sugar obtained across all the methods analysed including both the EU average case and the two alternative scenarios considered for the handling of beet pulp.

Table 11: System GHG emissions of sugar beet cultivation and beet sugar production in kg CO_{2eq} t^{-1} sugar (before GHG credits/allocation of emissions)

	EU average	Scenario no drying of beet pulp	Scenario full drying of beet pulp
Beet cultivation	279.8	279.8	279.8
Beet transport	31.7	31.7	31.7
Sugar factory			
– process steam production	435.5	435.5	435.5
– lime kiln operation	36.6	36.6	36.6
– drying of sugar beet pulp	101.1		163.0
Total	884.5	783.5	946.5

5 Discussion of beet sugar results and comparison with other products and production systems

Using the preferred methodology of ISO EN 14044:2006 for co-product accounting (substitution) requires making some assumptions about the products replaced on the market by the co-products. It is not unusual

Table 14: Ranges of PCF results for EU beet sugar obtained across all methods

	PCF range white sugar in kg CO_{2eq} t^{-1} sugar
EU average case	242–748
Scenario 1 ('no pulp drying')	176–681
Scenario 2 ('all pulp dried')	311–789

Table 12: GHG credits and allocation factors (for physical allocation) resulting from calculation

Product	Substitution credit in kg CO_{2eq} t^{-1} sugar		Allocation factor [–]			
	Example I	Example II	Mass	Dry substance mass	Digestible energy	Lower heating value
EU average						
White sugar	n.a.		0.28	0.40	0.68	0.67
Beet soil	Not accounted for		0.30	0.28	0	0
Carbonatation lime	7.4		0.06	0.06	0	0
Molasses	43.6	52.2	0.04	0.05	0.06	0.06
Wet pulp	4.8	11.2	0.06	0.01	0.01	0
Pressed pulp	21.3	49.8	0.15	0.05	0.06	0.03
Dried pulp with molasses	151.0	434.3	0.11	0.15	0.18	0.23
Electricity	13.7	29.5	Substitution method applied			
Steam / heat	Not accounted for		Not accounted for			
Total	**241.8**	**584.5**				
Scenario drying of full amount of beet pulp						
White sugar	n.a.		0.33	0.40	0.68	0.63
Beet soil	Not accounted for		0.36	0.28	0	0
Carbonatation lime	7.4		0.07	0.06	0	0
Molasses	45.5	52.2	0.05	0.05	0.06	0.06
Wet pulp	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Pressed pulp	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Dried pulp with molasses	212	609.9	0.19	0.21	0.25	0.30
Electricity	13.7	29.5	Substitution method applied			
Steam / heat	Not accounted for		Not accounted for			
Total	**278.6**	**699**				
Scenario no drying of beet pulp						
White sugar	n.a.		0.23	0.40	0.68	0.74
Beet soil	Not accounted for		0.25	0.28	0	0
Carbonatation lime	7.4		0.05	0.06	0	0
Molasses	88.2	104.5	0.07	0.10	0.13	0.14
Wet pulp	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Pressed pulp	68.7	160.6	0.16	0.19	0.12	0.16
Dried pulp with molasses	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Electricity	13.7	29.5	Substitution method applied			
Steam / heat	Not accounted for		Not accounted for			
Total	**178**	**302**				

Table 13: Allocation factors (for economic allocation) resulting from calculation

Allocation factor for sugar [–]	EU white reference price	EU quota white sugar	EU industrial sugar	"EU-mix" price	World white price (London #5 ICE)
EU average (total system GHG emission: 885 kg CO_{2eq} t^{-1} sugar)					
Average 2008	0.87	0.87	0.75	0.86	0.73
Average 2009	0.85	0.86	0.78	0.85	0.80
Average 2010	0.78	0.80	0.74	0.80	0.80
Average 2008–10	0.83	0.85	0.76	0.83	0.78
Scenario no drying of beet pulp (total system GHG emission: 783 kg CO_{2eq} t^{-1} sugar)					
Average 2008	0.88	0.87	0.76	0.86	0.74
Average 2009	0.86	0.87	0.79	0.86	0.81
Average 2010	0.84	0.86	0.81	0.86	0.86
Average 2008–10	0.86	0.87	0.79	0.86	0.80
Scenario drying of full amount of beet pulp (total system GHG emission: 946 kg CO_{2eq} t^{-1} sugar)					
Average 2008	0.87	0.86	0.74	0.85	0.72
Average 2009	0.85	0.86	0.77	0.84	0.79
Average 2010	0.75	0.78	0.71	0.78	0.78
Average 2008–10	0.82	0.83	0.74	0.82	0.76

that more than one equivalent product exists, thus allowing for different choices to be made. Within this paper only two examples with sets of possible substitutes were assessed, but this revealed that the result was extremely sensitive to those choices. For the substitution examples calculated, the PCF of white sugar from sugar beet (EU average case) ranged from 300 to 643 kg CO_{2eq}/t sugar. It has to be assumed that with different assumptions different results would also be obtained. Switching to physical allocation methods also provided a large and similar range of results (242–595 kg CO_{2eq}/t sugar for the EU average case). However, it was observed that for each physical allocation method (based on mass or energy) there were

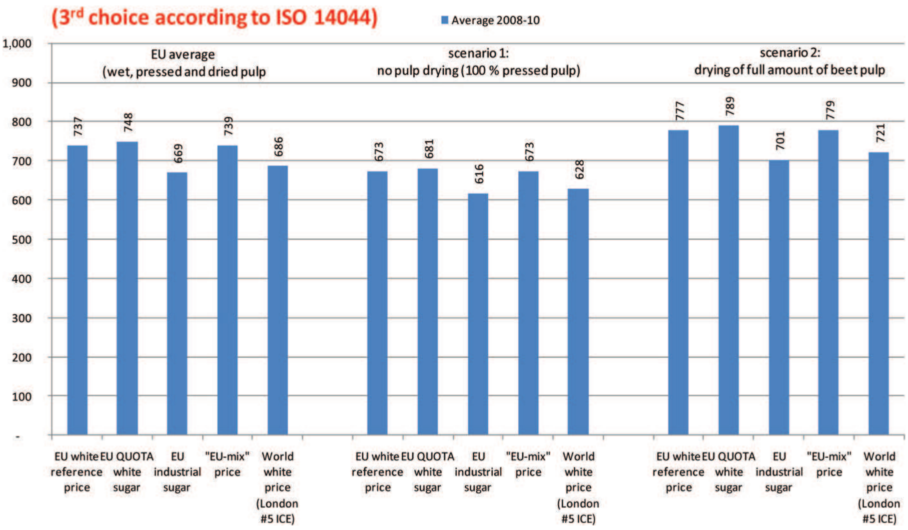

Fig. 7: PCF of white sugar from beet (EU average and 2 different beet pulp drying scenarios) according to the economic value allocation method (based on three-year average prices between 2008 and 2010). For a breakdown of results per year, please refer to Figure 8.

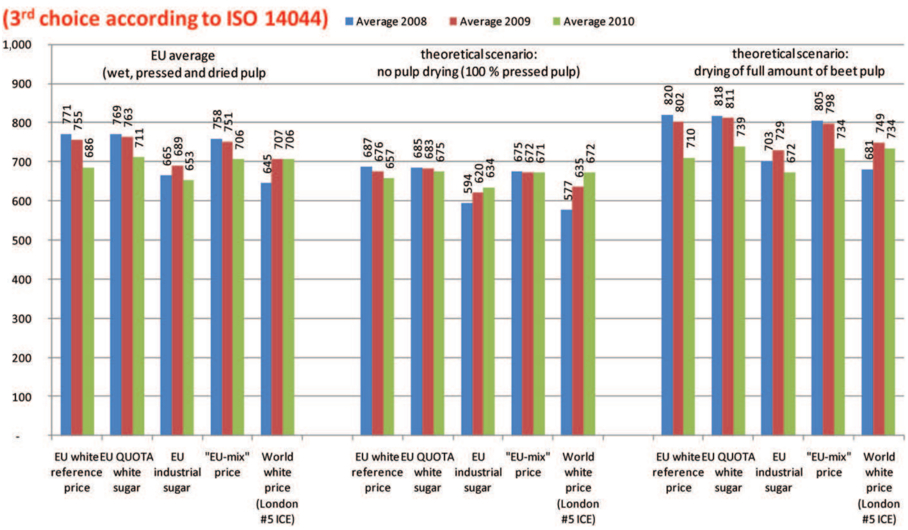

Fig. 8: EU average for PCF for white sugar from beet sugar when using allocation based on economic value of the co-products. Price averages for years 2008, 2009 and 2010

co-products which were not, in principle, allocated any share of GHG emissions (e.g. electricity has no mass or contains no energy expressed as digestible energy or lower heating value; the amount of digestible energy or lower heating value for beet soil or carbonatation lime is zero). This phenomenon was partially solved in the calculations by accounting for surplus electricity via the substitution method. Finally, beet soil was found to have a significant impact on mass-based allocation methods, accounting for about 30% of the total emissions that were allocated to this co-product. Beet soil is, however, a relatively unproductive input that any efficient beet sugar production system should try to minimise to as large an extent as possible. The use of mass-based methods for beet sugar production – where beet soil is accounted for – can thus lead to the paradox that an inefficient soil prevention system will lead to a better performing PCF for sugar.

Economic value allocation, the least preferable option according to EN ISO 14044:2006 – delivered, on the other hand, significantly higher PCF results for white beet sugar than those obtained with the substitution method or by allocation based on physical relationships (range from 645–771 kg CO_{2eq}/t sugar for the EU average case). Economic allocation thus added further complexity as the result was found to vary significantly with time and due to the wide range of sugar prices that can be used (that is especially the case for products which can be equally sold to different markets with different prices as it is the case for the EU sugar market regime). Finally, this method requires some caution, in particular when information is communicated to third parties in a detailed and transparent manner, because it may allow the calculation of average company prices for sugar backwards from the communicated figures.

5.1 Comparison of EU beet sugar PCFs with competing products

5.1.1 Cane sugar

The GHG emissions from cane cultivation and raw cane sugar production of 307 kg CO_{2eq}/t raw sugar published by *Rein* (2010) were used as a basis for the estimated PCF of raw cane sugar for refining in the EU before transport to the EU. After adjusting that figure to account for transport and refining in Europe, the resulting PCFs were 760 kg CO_{2eq}/t white sugar (example I: sugar from Centre-South Brazil) and 642 kg CO_{2eq}/t white sugar (example II: sugar from South-East Africa). This means, in practice, that raw sugar transport to the EU and the refining of cane raw sugar have a significant impact on the PCF of imported cane sugar refined in the EU. The refining emissions represent the main addition (+243 kg CO_{2eq}/t white sugar), although the overseas transport also adds a significant amount of emissions, between 14 and 23% of the total PCF (+88 to +176 kg CO_{2eq}/t white sugar) depending on the distance.[14] Although these PCF-figures reflect just two representative examples, it can be concluded that cane sugar refined within the EU has a PCF range (642–760 kg CO_{2eq}/t sugar) which is on average higher than the total PCF range for EU beet sugar (242–771 kg CO_{2eq}/t sugar) but otherwise, it is equivalent to the highest estimated range for beet sugar (645–771 kg CO_{2eq}/t sugar) based on economic value allocation.

On the other hand, it should be recalled that there are indications that the PCF for cane sugar calculated by *Rein* (2010) is, at least with regard to some aspects, not a conservative estimate but representative of some of the best practices in

[14] For further background data see Table 16.

the production of cane sugar. It was also observed that the estimated emissions value for refining emissions used in this article corresponds to the lower end of the refining emissions range found in the literature (–7% versus *Fereday* et al, 2010; –23% versus *Hattori* et al., 2008).

It should also be noted that direct land use changes were not accounted for in the PCF of cane sugar estimated in this study whereas for EU beet sugar the impact is estimated to be neutral. In fact due to the reform of the EU sugar market regime, the EU turned, during the last decade, from being a net exporter to being a net importer of sugar. Accordingly, during the same period, the cultivation area for sugar beet has been reduced by around 0.5 mn ha, about 25% of the total, letting that area free for other uses, be it cultivation of other crops or nature conservation purposes (CIBE/CEFS, 2010). In the case of imported cane sugar, *Plassmann* et al. (2010) showed that LUC can be an issue for cane sugar cultivation where it can have an enormous impact on the resulting PCF of cane sugar (e.g. for Zambian sugar, 400 kg CO_{2eq}/t sugar without LUC, and 2100 kg CO_{2eq}/t sugar including land use change). Based on that example it is obvious that the actual PCF of imported cane sugar can be significantly higher than the PCF of domestic sugar produced from EU sugar beet.

5.1.2 Glucose and fructose syrups derived from starch (isoglucose / HFCS)

The only PCFs for glucose and fructose syrups that could be obtained from publicly available sources are "cradle to gate" figures using German wheat and US corn as feedstocks to produce isoglucose (*Setzer*, 2005). The resulting PCFs have a range of 640 to 1100 kg CO_{2eq}/t sugar equivalent. Due to the restricted information available about the methodology used to obtain those PCFs it is even more difficult to infer a valid conclusion when comparing these figures with the PCF for beet sugar than when doing so with imported cane sugar. At this stage, it can only be observed that the average PCF range for those syrups indicates significantly higher carbon footprint figures than the calculated range of PCFs for EU beet sugar, with only a partial common zone around the extremes of each PCF range (the highest part of the PCF range for beet sugar and the lowest one for starch syrups).

5.2 Comparison of GHG and land use efficiencies of beet and cane sugar production systems

Based on an initial plot of land of 1 ha it was estimated an identical production of 8.8 t of sugar from either beet or cane. This was done only for the purpose of having a balanced comparison between two theoretical beet and cane systems. Actual average EU beet sugar extraction yields are in reality far better than the hypothesis used here.[15] Different co-products are created in different amounts in both cane and beet sugar production systems (e.g. more molasses and electricity in the cane system and more animal feed and lime fertilizer in the beet system). In order to make a valid comparison, two equivalent production systems were re-created by compensating (in terms of land and GHG emissions) for those outputs produced in greater amounts by one system or the other. The products taken into consideration as well as the results of that comparison of equivalent systems are provided in Table 15.

From the above analysis it appears that the total direct emissions of both cane and beet sugar systems are similar and comparable but a very significant amount of additional land (51% more) is required for cane production systems to fully replace beet sugar ones, in particular due to the need for cane production systems to compensate for the animal feed (beet pulp) produced in the beet sugar system (see Fig. 9).

Currently about 85% of EU sugar needs (~16 mn t) are covered by locally produced beet sugar and the balance is supplied

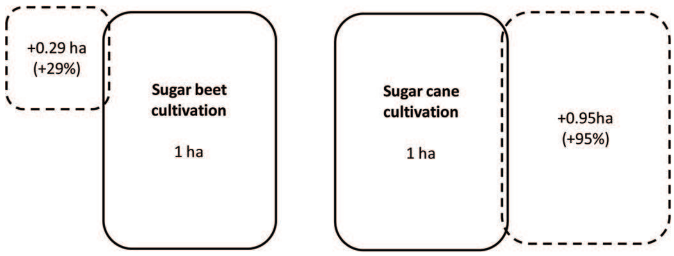

Fig. 9: A comparison of the land use efficiency of two equivalent beet and cane systems

15 The actual yield for the EU is about 10.6 t sugar/ha (5-year average for the period 2006–2011. Source: CEFS, 2011)

Table 15: Products taken into consideration as well as the results of that comparison of equivalent systems

	Beet (EU average case)	Cane (*Rein*, 2010)	Additional land required / CO_{2eq} emitted (beet)	Additional land required / CO_{2eq} emitted (cane)
Sugar yield	8.8 t/ha	8.8 t/ha	–	–
Animal feed	1.9 t (wet pulp) 4.9 t (pressed) 3.5 t (dried and molassed)	–	–	0.9 – 1 ha 1556 – 4355 kg CO_{2eq}
Electricity	259 kWh	3465 kWh	1491 kg CO_{2eq} (EU-electricity mix)	–
Liming fertilizer	1.9 t	Not leaving system	–	65 kg CO_{2eq}
Molasses	1.4 t	2.8 t	0.3 ha of barley 464 kg CO_{2eq}	–
Total system (equivalent) emissions			9731 kg CO_{2eq}	10,236 kgCO_{2eq} (average) [range: 8323 – 12150 kg CO_{2eq}]
Total system (equivalent) land use			1.29 ha	1.95 ha (average) [range: 1.9 – 2.0 ha]

Table 16: GHG emission for provision of cane sugar to EU in kg CO_{2eq} t^{-1} refined cane sugar

	Example I	Example II
Cane cultivation	222	222
Cane transport	16	16
Cane sugar factory	70	70
Road transport to harbour	33	4
Ship transport to EU	176	88
Road transport to refinery	0	0
Refining	243	243
Total	760	642

from imports of cane sugar. The above findings therefore suggest that, in the future, an eventual shift towards a larger substitution of EU beet sugar production with cane sugar imports into the EU will put further pressure on the global demand for arable land. That increased demand could, in addition, increase the risk of land use change emissions since most uncultivated land types, be it grassland, savannah or forest land have a much higher carbon stock than agricultural land. On the other hand, an increased supply of EU beet sugar in the EU market would decrease the pressure on the global demand for land and liberate land to supply the increasing demand for food and feed linked to the rising global population.

6 Conclusions

The calculations made to obtain the PCF of white sugar from sugar beet have revealed that the results are extremely sensitive to methodological choices and therefore it may be difficult to compare the actual performance of sugar products with regard to GHG emissions via a direct comparison of published PCFs.

The PCF range for beet white sugar (based on the EU average case) was 300–643 kg CO_{2eq}/t sugar when using the substitution method, which is the preferred method for co-product accounting according to ISO EN 14044:2006. The second preference according to this standard (allocation based on physical relationship) delivered a similar range of 242–595 kg CO_{2eq}/t sugar whilst the least preferred option according to the ISO hierarchy (economic value allocation) delivered a range of 645–771 kg CO_{2eq}/t sugar. The total PCF range across all methods was therefore 242 to 771 kg CO_{2eq}/t sugar from sugar beet. The results for substitution and economic value allocation shown in this study reflect only some of the possible examples of PCFs that can be calculated for EU beet sugar. Using the substitution approach required making assumptions about the most suitable substitute products. The wide difference in results observed from the two analysed examples of substitution indicates that different operator's choices and assumptions will have a significant impact on the results. This in turn, can lead to differences in PCFs for beet sugar producers not reflecting the actual improvements in product performance but simply different substitution choices. When calculating PCFs for the EU average case, economic allocation was found to be the allocation methodology more open to a multiplicity of results (from the same dataset) due only to different choices being made by different operators. The latter also raised other issues such as the complexity of its implementation (multiplicity of markets/prices for EU sugar, asymmetrical changes in the prices of sugar and co-products) and the confidentiality of companies' price data when PCFs are conducted at company level.

Physical allocation methods were found to be more constant and limited in number although some other challenges had to be overcome. Indeed, since physical allocation methods cannot be applied to some beet sugar co-products (notably surplus electricity/heat and 'sugar factory lime') they need to be combined with the substitution method (in a similar way as done in the EU Renewable Energy Directive). A method leading to conservative estimates of the PCF of beet sugar would be to use substitution with exactly defined substitutes for surplus electricity (e.g. national/regional grid GHG intensity), surplus heat/steam (e.g. heat/steam related emissions from a natural gas boiler) and 'sugar factory lime'/carbonatation lime (e.g. mineral lime fertilizer of equivalent grade and quality). Due to the presence of wet products among the range of possible co-products, mass allocation (on wet basis) was found to distort the obtained results significantly and would not be recommended to calculate the PCF of beet sugar. Beet soil was found to have a significant impact on mass-based allocation methods, accounting for about 30% of the total emissions that were allocated to this co-product. Beet soil is, however, a relatively unproductive input that any efficient beet sugar production system should try to minimise to the largest extent possible. The use of mass-based allocation methods to calculate PCFs for beet sugar production – when beet soil is accounted for as a co-product – can thus lead to the paradox that an inefficient soil prevention system will lead to a better performing PCF for sugar. For that reason mass allocation methods would not be recommended in those circumstances where beet soil is also accounted for. Allocation methods based on energy (digestible energy or lower heating value) seemed to be, under the scope of present analysis, adequate candidate methodologies to account for the emissions of EU beet sugar production systems, such as the one considered in the present study.

Finally it should be recalled that data used for beet sugar factories represent the EU situation in 2005–2008. Meanwhile – due to the reform of the EU sugar market regime – many of the least efficient factories have been closed down, whereas beet cultivation and beet sugar production have been concentrated in the most productive sites and regions. Therefore it has to be assumed that the current EU average PCF range for EU beet sugar would be lower than the one calculated in this study.

For cane raw sugar imported and refined in the EU it was found that the PCF range (642–760 kg CO_{2eq}/t sugar) is generally higher than the PCF range for EU beet sugar (242–771 kg CO_{2eq}/t sugar) if not equivalent to the highest estimated range for beet sugar (645–771 kg CO_{2eq}/t sugar, based on economic allocation). The estimated range for cane sugar does not account however, for direct LUC effects, which can have a significant impact by increasing the PCF figures for sugarcane. According to the available data, the PCF range of glucose and fructose starch syrups, based on a study of isoglucose produced either from European wheat or US corn (640 to 1100 kg CO_{2eq}/t sugar equivalent), appeared to be higher than the PCF range of EU beet sugar.

7 Beyond PCFs

PCFs are not necessarily indicators of overall environmental sustainability of a product. This is based on the fact that carbon footprints focus on one sole ecological impact: climate impact. Water requirements for example, although not dealt with in this article, also vary strikingly between crops, with sugar beet requiring, for example, half the water needed to grow sugarcane (*Gerbens-Leenes* et al., 2006). Other relevant (agro-)ecological aspects are not reflected at all in carbon footprint figures. Sugar beet, for example, is a key rotational crop for farmers in the EU. Grown in the same field only every three to five years, it breaks up the common cereal-based crop-rotations. The resulting cereal yield after beet is 10–20% higher than after two successive years of cereals (CIBE/CEFS, 2010). Because sugar beet is not a host to pests or diseases which generally affect combinable crops, the cultivation of sugar beet as a break crop also reduces the level of weeds, diseases and pests on a given land and therefore reduces the overall amount of pesticides applied on the farm.

Besides methodological challenges for the calculation of PCFs for beet sugar, further year-on-year variability of results is to be expected due to single external factors (e.g. weather conditions) affecting the PCFs' values independently of actual changes in the relative environmental performance of specific farmers or raw material processors. The use of PCFs at consumer level – as a tool to guide consumers' purchase decisions towards more environmentally sustainable choices within the sugars category of products – appears, in the light of the above findings with regard to the uncertainty and variability of calculations, to be a significant challenge.

Furthermore, although greenhouse gas (GHG) accounting using a life-cycle approach is useful for understanding the impact of a product or a service with respect to climate change, the suitability of PCFs for comparing the climate performance of different products is questionable in particular, in light of the results obtained with the comparison of entire productions systems for beet and cane sugar consumed in the EU.

Indeed, the comparison of production systems for beet and cane sugar revealed, that PCFs alone do not provide the full GHG and land use efficiency picture. The ecological impact indicator "land use (efficiency)" is typically assessed separately from the indicator "GHG emission / PCF". However, not accounting for land use efficiency (i.e. the amount of land needed to provide a certain amount of goods) when deciding if a product is more climate-friendly than another (i.e. just doing so based on PCFs) could push for greater consumption of certain products while leading to an increased global demand for land. This in turn would increase the pressure to change the land use of previously non-cultivated land with the result of increased global GHG emissions.

In particular, the comparison of beet and cane sugar production systems showed that, in order to supply the EU market with sugar and its related co-products (notably animal feed), the demand for land would be significantly greater in the case of increased supplies from cane sugar whereas direct GHG emissions would remain similar for both cane and beet sugar production systems.

Acknowledgements

The authors would like to thank *A. Papagrigoraki* for her support in the preparation and editing of this article.

References

BIOGRACE (2011): List of standard values. Version 4 and Excel Greenhouse gas emission calculation tool. Available online at http://www.biograce.net/ (accessed 22 September 2011)

Brenton, P.; Edwards-Jones, G.; Jensen, M.F. (2010): Carbon Footprints and Food Systems: Do Current Accounting Methodologies Disadvantage Developing Countries? The World Bank, ISBN 978-0-8213-8539-5; available online at: http://www.worldbank.org (Last accessed 1 June 2011)

Bürcky, K.; Märländer, B. (2000): Untersuchungen zum Nährstoffgehalt von Carbokalk während dessen Lagerung im Feld. Zuckerind. 125, 169–174

CEFS (2010): CEFS Sugar statistics 2010. Covering data for the previous 10 campaigns. Available online at www.cefs.org (Last accessed 6.12.2011)

CEFS (2011): CEFS Sugar statistics 2011. Available online at www.cefs.org (Last accessed 6.12.2011)

Chappert, A.; Toury, J.-C. (2011), Evaluation des impacts environnementaux de la production de sucre de betterave sur les sites de Cristal Union par une analyse du cycle de vie. Industries Alimentaires et Agricoles July / August, 46–48

CIBE/CEFS (2010): Sustainable Environmental Report: The EU Beet and Sugar Sector: A model of Environmental Sustainability. Available online at www.cefs.org and www.cibe-europe.eu.

Clarke, M.A.; Roberts, E. J.; Godshall, M.A. (1999): Acid Beverage Floc from Sugar Beets. Journal of Sugar Beet Research 36 (No. 3, July–September), 15–27

Climatop (2010a): CO_2 Balance: Sugar, fact sheet, validity: 1.9.2009 – 30.8.2010, 18.3.2010. Available online from http://www.climatop.ch/downloads/E-Fact_Sheet_Pronatec_Sugar_v3.pdf (Last accessed 23.9.2011)

Climatop (2010b): CO_2 Balance: Sugar, fact sheet, validity: 1.10.2010 – 30.9.2010 (renewed calculation), 20.10.2010. Available online from http://www.climatop.ch/downloads/E-Fact_Sheet_Migros_Sugar_b1.pdf (Last accessed 23.9.2011)

COPA / COGECA, C.I.D.E., Confederation Internationale de l'industrie et du commerce des Paille, Fourrage, tourbe et dérivés (2007): Die Luzerne, ein Trumpf für die Umwelt. / La Luzerne un atout pour l'Environnement. Available online from http://www.luzernes.org/docs/2007_CIDE_La%20luzerne-atout-environnement.pdf (last accessed 11.12.2011)

Denmead, O.T.; Macdonald, B.C.T.; Bryant, G.; Naylor, T.; Wilson, S.; Griffith, D.W.T.; Wang, W.J.; Salter, B.; White, I.; Moody, P.W. (2010); Emissions of methane and nitrous oxide from Australian sugarcane soils. Agricultural and Forest Meteorology (No. 150), 748–756

DLG (1997): Futterwerttabellen Wiederkäuer. Universität Hohenheim (Ed.), Dokumentationsstelle. Unter Mitw. des Ausschusses für Bedarfsnormen der Gesellschaft für Ernährungsphysiologie und der Bundesanstalt für Alpenländische Landwirtschaft Gumpenstein; 7. erw. und überarb. Aufl.; DLG-Verlag, Frankfurt am Main 1997, ISBN 3-7690-0547-3

EN ISO 14044:2006 (2006): Environmental management – Life cycle assessment – requirements and guidelines. Available from http://www.iso.org/iso/iso_catalogue.htm

ENTEC (2010): EU ETS Phase III Benchmarking Project for CEFS. Unpublished.

Eurostat trade database accessed in September 2011. http://epp.eurostat.ec.europa.eu/portal/page/portal/external_trade/data/database).

Fereday, N.; Forber, G.; Powell, N.; Todd, M.; Midgely, C.; Nutt, T.; Girardello, S.; Wagner, O. (2010): Assessing the carbon footprint of cane and beet sugar production. Sugar and Sweeteners, Sweetener Analyses, LMC International Ltd, June issue. Available online at http://www.lmc.co.uk/Articles.aspx?id=1&repID=75 (Last accessed 6.12.2011)

Finkbeiner, M. (2009): Carbon footprinting opportunities and threats. The International Journal of Life Cycle Assessment 14 (No. 2), 91–94; available online at http://www.springerlink.com/content/5106170g43854187/fulltext.pdf (Last accessed 6.12.2011)

FranceAgriMer (2011): L'Economie Sucrière – Campagne 2009/10. Edition June 2011; available on-line at http://www.franceagrimer.fr/Projet-02/08publications/index83.htm (Last accessed 15.12.2011)

Gerbens-Leenes, W.; Hoekstra, A.Y.; Meer, T.H. van der (2009): The water footprint of bioenergy. Proc. National Academy of Sciences 106 (No. 25), 10219–10223; available online at: www.waterfootprint.org (Last accessed 6.12.2011)

Global Emission Modell for Integrated Systems (GEMIS): 2011 Global Emission Model for Intergrated Systems (GEMIS), Version 4.7; available online at http://www.oeko.de/service/gemis/en/index.htm (Last accessed 6.12.2011)

Hanff, H.; Neubert, G.; Brudel, H. (2008): Datensammlung für die Betriebsplanung und die betriebswirtschaftliche Bewertung landwirtschaftlicher Produktionsverfahren im Land Brandenburg – Ackerbau / Grünlandwirtschaft / Tierproduktion. Schriftenreihe des Landesamtes für Verbraucherschutz, Landwirtschaft und Flurneuordnung Abteilung Landwirtschaft und Gartenbau, Teltow, Großbeeren, Groß Kreutz, Güterfelde, Paulinenaue, Wünsdorf; Reihe Landwirtschaft, Band 9, Heft IV. Ed.: Ministerium für Ländliche Entwicklung, Umwelt und Verbraucherschutz des Landes Brandenburg (MLUV) und Landesamt für Verbraucherschutz, Landwirtschaft und Flurneuordnung.

Hattori, K.; Suzuki, A.; Ebashi, T.; Ota, M.; Sato, K. (2008): The calculation of carbon dioxide emission intensity from sugarcane to refined sugar. Proc. Res. Soc. Japan Sugar Refineries Technol. 56, 29–35

IPCC (2006): Guidelines for National Greenhouse Gas Inventories. Chapter 11: N_2O emissions from managed soils, and CO_2 emissions from lime and urea application (pdf); available online at http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_11_Ch11_N2O&CO2.pdf,

IPCC (2007): Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press

Kägi, T.; Wettstein, D. (2008): Ökobilanz von Zucker. Stiftung myclimate – The Climate Protection Partnership, 28.8.2008; available online from http://ch.myclimate.org/fileadmin/documents/cms/Publications/100120_Bilanz_Zucker_public.pdf (Last accessed 23.09.2011)

Kaltschmitt, M.; Reinhardt, G. (Ed.) (1997): Nachwachsende Energieträger – Grundlagen, Verfahren, ökologische Bilanzierung. Vieweg Verlag, ISBN 3-528-06778-0

Mashoko, L.; Mbohwa,C.; Thomas, V.M. (2010): LCA of the South African sugar industry. Journal of Environmental Planning and Management 53 (No. 6), 793–807

Peyker, W.; Degner, J. (1996): Leitlinie zur effizienten und umweltverträglichen Erzeugung von Luzerne und Luzernegras. Thüringer Landesanstalt für Landwirtschaft, 1. Auflage

Plassmann K.; Norton, A.; Attarzadeh, N.; Jensen, M.P.; Brenton, P.; Edwards-Jones, G. (2010): Methodological complexities of product carbon footprinting: a sensitivity analysis of key variables in a developing country context. Environmental Science & Policy 13 (No. 5) 393–404; available online through http://www.sciencedirect.com/science/article/pii/S1462901110000316 (Last accessed 6 December 2011)

Rein, P.W. (2010): The carbon footprint of sugar. Sugar Industry / Zuckerind. 135, 427–434

Rein, P.W. (2011): Sustainable production of raw and refined cane sugar. Sugar Industry / Zuckerind. 136, 734–741

Renouf, M.A.; Wegener, M.K. (2007): Environmental Life Cycle Assessment (LCA) of sugarcane production and processing in Australia. Proc. Aust. Soc. Sugar Cane Technol. 29, 385–400

Seabra, J.E.A.; Macedo, I.C.; Chum, H.L.; Faroni, C.E.; Sarto, C.A. (2011): Life cycle assessment of Brazilian sugarcane products: GHG emissions and energy use. Biofuels, Bioprod. Bioref. 5, 519–532; DOI: 10.1002/bbb.289

Setzer, T. (2005): Ökoeffizienz-Analyse Nachwachsende Rohstoffe zur Chemikalienherstellung am Beispiel Zucker. Masterarbeit im Studiengang Wirtschaftsingenieurwesen der Fachhochschule Mannheim

Poel, P.W. van der; Schiweck, H.; Schwartz, T. (1998): Sugar Technology. Beet and Cane Sugar Manufacture. Verlag Dr. Albert Bartens, Berlin

Wiltshire, J.; Wynn, S.; Clarke, J.; Chambers, B.; Cotrill, B.; Drakes, D.; Gittins, J.; Nicholson, C.; Phillips, K.; Thorman, R.; Tiffin, D.; Walker, O.; Tucker, G.; Thorn, R.; Green, A.; Fendler, A.; Williams, A.; Bellamy, P.; Ausdsley, E.; Chatterton, J.; Chadwick, D., Foster, C. (2009): Scenario building to test and inform the development of a BSI method for assessing greenhouse gas emissions from food. Technical annex to the final report. Report to Defra, Project Reference Number: FO0404, ADAS, UK

Yuttiham, M.; Gheewala, S.H.; Chidthaisong, A. (2011): Carbon footprint of sugar produced from sugarcane in eastern Thailand. Journal of Cleaner Production 19, 2119–2127; available online from http://www.deepdyve.com/lp/elsevier/carbon-footprint-of-sugar-produced-from-sugarcane-in-eastern-thailand-1X16yym4NX (Last accessed 6.12.2011)

L'empreinte carbone du sucre de betterave de l'U.E. (Résumé)

Les calculs effectués pour obtenir le bilan CO_2 (ou le PCF: produits à empreinte Carbone) du sucre blanc de l'U.E. provenant de betteraves ont montré que les résultats sont extrêmement sensibles aux choix méthodologiques. Cet article fournit quelques recommandations à cet égard. Une comparaison entre du sucre de l'U.E. et deux sucres bruts de canne importés et raffinés en U.E. a montré que la gamme de l'empreinte du sucre de canne importé et raffiné est, en moyenne, comparable, si pas plus élevée (642–760 kg CO_{2eq}/t de sucre) que dans la gamme, déterminée par la même méthode dans le sucre de betterave de l'U.E. (242–771 kg CO_{2eq}/t de sucre). Une revue de la littérature publiée a montré, d'une part, que les émissions pour le sucre de canne peuvent être considérables à la suite de changements dans l'utilisation du sol, mais sont rarement prises en considération et, d'autre part, que le transport outre-mer et le raffinage ajoutent une quantité importante d'émissions au PCF du sucre de canne importé dans l'U.E. De la comparaison de l'efficacité de l'utilisation des sols entre les différents systèmes de production, on peut conclure qu'il faut significativement plus de sol (51 %) pour la canne pour obtenir une quantité équivalente de produits (sucre et coproduits) avec une quantité équivalente d'émissions de GES (gaz à effet de serre). Enfin, les limitations de PCFs comme outil pour évaluer pour évaluer la durabilité environnementale globale du sucre de betteraves de l'U.E. ont été aussi analysés.

El balance de los gases de invernadero de azúcar de remolacha de la UE (Resumen)

Cálculos del balance de CO_2 (Product Carbon Footprint, PCF) de azúcar blanco de remolachas de la UE mostraron que el resultado depende extremamente de la metodología seleccionada. Es por esto que en este artículo se presentan varias recomendaciones de metodología. El balance de CO_2 de azúcar de remolacha de la UE (valor medio) se comparó con dos ejemplos de azúcar crudo importado y refinado en la UE. El balance de CO_2 del azúcar importado y refinado, en promedio, fue similar hasta mayor (642–760 kg CO_{2eq}/t azúcar) que el balance de CO_2 del azúcar producido y refinado directamente en la UE (242–771 kg CO_{2eq}/t azúcar). Un análisis de las publicaciones al respecto mostró, por uno, que las emisiones, originadas de cambios del uso de campos, pueden ser considerables pero normalmente no se las toma en cuenta, y, por otro, que el transporte de ultramar y la refinación producen mayores valores de CO_2 del azúcar importado. Una comparación de la eficacia del aprovechamiento de áreas cultivados con caña de azúcar y con remolachas azucareras mostró que para el cultivo de caña de azúcar, la producción de azúcar y de subproductos se requiere un poco más área (51 %), pero se obtiene la misma emisión de gas invernadero como con la producción de remolachas azucareras. Finalmente se estudiaron la limitaciones del balance de CO_2 como instrumento para la determinación de la persistencia ecológica de azúcar de remolacha de la UE.

Author's addresses: *Ingo Klenk*, Südzucker AG, Germany; *Birgit Landquist*, Nordic Sugar, Denmark; *Oscar Ruiz De Imaña*, Deputy Director-General, CEFS (Comité Européen des Fabricants de Sucre), Av. de Tervuren 182, 1150 Brussels, Belgium; e-mail: oscar.ruiz@cefs.org