Construction cost of plant compounds provides a physical relationship for co-product allocation in life cycle assessment

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ABSTRACT

Although, according to the ISO 14044 standard, economic allocation should be the solution of last resort, it is frequently used in LCA studies of agri-food systems because of the inadequacy of solutions preferred by ISO. We calculated allocation factors for a range of plant co-products used as feed ingredients according to three methods: energy allocation (En), economic allocation (Ec) and allocation based on plant physiological construction cost of plant compounds (Cc). Compared to En and Ec, Cc yields higher allocation factors for protein-rich co-products and lower factors for lipids. Whereas the difference between En and Cc is modest (up to 5 percentage points), the difference between Ec and Cc is more variable and can be large (up to 18 percentage points). For plant co-products, Cc is an attractive option, as it is based on the physiological mechanisms involved in plant growth rather than on a common property of the co-products.

Keywords: economic allocation, energy allocation, plant co-products, (biophysical mechanism)

1. Introduction

For a long time, the topic of allocation has been the subject of methodological debate in Life Cycle Assessment (LCA) studies. The International Organisation for Standardisation (ISO) 14044 standard (ISO 2006) for LCA defines allocation as “partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems”. Allocation is about attributing the relative shares of responsibility for environmental impacts to several co-products (Suh et al. 2010; Pelletier and Tyedmers 2011).

The ISO 14044 standard defines the following procedure for allocation:

1. Wherever possible, allocation should be avoided by
   a) dividing the unit process to be allocated into two or more sub-processes and collecting the input and output data related to these sub-processes, or
   b) expanding the product system to include the additional functions related to the co-products.
2. Where allocation cannot be avoided, 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.
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 (ISO 2006).

Agri-food systems contain many multiple output processes, e.g. the transformation of soybeans yielding meal and oil, or the production of milk, calves and cull cows by a herd of dairy cows. How to best allocate impacts to co-products has been the subject of much debate (Suh et al. 2010; Ardente and Cellura 2011; Pelletier and Tyedmers, 2011). Although, according to ISO guidelines, economic allocation should be the solution of last resort, it is frequently used in LCA studies of agri-food systems because of the inadequacy of the solutions that should be preferred according to the ISO decision hierarchy.

Avoiding allocation by dividing the unit process often is not possible, as for instance in the case of the transformation of soybeans in meal and oil. Avoiding allocation by expanding the system is feasible for those co-products that can be produced by other processes. However, for agricultural products this approach is often problematic. For instance, in the case of a dairy herd producing milk, cull cows and calves, we may want to identify a process that yields a product similar to cull cows, i.e. animals that can be transformed into beef. One can identify a suckler cow herd as an alternative producer of animals that can yield beef. However, on close examination this is not satisfactory, as beef from a suckler system is of a different (better) quality than beef from culled dairy cows. Finding an alternative production process for cow milk is even more difficult. One might turn to processes producing goat milk or soy “milk”, but these are obviously very different products. As a consequence, as system expansion applied to LCAs of agricultural products often fails to identify alternative processes producing the same products; it generally resorts to choosing alternative processes yielding products used for the same purpose, i.e. insuring functional equivalence. LCA studies will for instance consider that suckler cow beef can be considered equivalent to dairy cow beef (Nguyen et al. 2013), or that pork is equivalent to beef (Thomassen et al. 2008a). Considering that low and high quality beef are equivalent, or that pork is equivalent to beef may, for a variety of reasons, not only seem quite far-fetched to most people, it also introduces major arbitrariness and additional uncertainty in the LCA study. Last but not least, the system expansion approach causes the LCA model to get larger and more complicated, requiring the collection of more data (Curran 2013).

When allocation can not be avoided either by dividing the unit process or by expanding the product system, then the next best option, according to ISO 14044, is to allocate the inputs and outputs between the products in a way that reflects the underlying physical relationships between the products. In their eloquent but in parts hard-to-understand paper "An ecological economic critique of the use of market information in life cycle assessment research" Pelletier and Tyedmers (2011) critique the use of economic allocation and plead for the use of physical or biophysical properties of products in allocation. They admit however that biophysical allocation is harder to justify when it is necessary to allocate burdens between co-products with divergent functions, for example when soy processing co-products are used as meal for animal nutrition and as oil for biodiesel. In such a case, finding a common physical or biophysical property adequate for both functions is difficult. Furthermore, even when one can find such a property, one may wonder to what extent the identification of a common physical or chemical property of the co-products can be equated to the existence of an underlying physical relationship between the co-products as mentioned in the ISO 14044 standard. Although this seems to have been accepted as a common interpretation of the ISO standard in many published papers on the subject, it remains quite a puzzling assumption to the authors of this paper.

So, since both avoiding allocation as well as allocating according to a physical relationship rarely seem to work satisfactorily for agri-food multi-output systems, it should not come as a surprise that many LCA studies of such systems end up allocating inputs and outputs to co-products in proportion to their economic value (Ardente and Cellura 2011; Brankatschk and Finkbeiner 2014). For many authors, economic allocation is attractive as it is the value created that causes the process. However, economic allocation is not without difficulties. It is based on the one hand on the relative masses of the co-products produced and on the other hand on the relative economic values of these co-products. While the former are generally quite stable, the latter tend to fluctuate with time and place in response to changes in supply, demand, regulation, subsidies, culture (Pelletier and Tyedmers 2011) and technological developments. As a result allocation factors will fluctuate, affecting the credibility of the results of the LCA. This problem can be reduced by averaging product prices over several years which will smooth short-term variations

In this paper we want to contribute to this debate. We first present an inventory of the use of methods to attribute impacts to plant co-products used as animal feed in recent LCA studies to quantify the relative importance of these methods as they are actually used in studies published in peer-reviewed publications. Secondly we propose a new way of allocating impacts to plant co-products according to the underlying physical relationships between the co-products. We compare this method to two current allocation methods.

2. Methods

2.1. Attribution of impacts to plant co-product in LCA studies

We found 24 LCA studies from peer-reviewed scientific journals and scientific reports for the 2000-2013 period that attributed impacts to plant co-products used as animal feed. These studies used either system expansion or allocation according to co-product mass, energy content, nitrogen content or economic value, or several of these methods. This allowed us to establish the relative share of co-product handling methods used in "real life", so to say.

2.2. Comparison of three allocation methods

This case study focused on plant co-products used as ingredients for animal feed. We compared three methods for the allocation of impacts to plant co-products: energy allocation, economic allocation and the new allocation method (presented in this paper) according to the construction cost of plant compounds.

Energy allocation is often used to allocate impacts when one or more of the co-products are used as biofuels (ADEME 2010). Energy allocation is generally based on the lower heating value (LHV) of the co-products. For some plant co-products not associated with biofuel production (e.g. wheat middlings) LHV data are not available in the literature. Furthermore, in many biofuel studies, LHV values used for the various co-products are taken from several literature sources, introducing methodological heterogeneity for these data. In order to obtain a coherent set of LHV values for the co-products we studied we estimated their LHV values from their gross energy values taken according to INRA (2004; 2007). Gross energy is defined as the heat produced during the complete combustion of an organic component in a calorimeter in the presence of oxygen (INRA 2007). Given this definition, a gross energy value therefore corresponds to a higher heating value (HHV). It has been observed that the LHV of co-products used as animal feed is 6 to 7% lower that their HHV (Hofstrand 2008). We assumed a 6% difference to estimate LHV from gross energy values, as we thus obtained LHV values that were closest to those found in literature sources.

For economic allocation we used average annual prices for the 2005-2009 period. These were world market prices for oils and meals from soybean, rapeseed, sunflower, linseed, oil palm, and for corn oil (ISTA 2009; 2011); for wheat and maize co-products other than corn oil these were prices for the United States of America (USDA 2012), for sugar beet co-products these were prices for France (AGRI C5 2013; I. Bouvarel pers. Comm. 2013). These prices were used to calculate so-called “Olympic averages” i.e. for each co-product we took the five annual average values for the 2005-2009 period, eliminated the highest and lowest values, and averaged the values for the remaining three years.

We propose a new allocation method for plant co-products based on physiological mechanisms involved in plant growth rather than on physical or chemical characteristics of the co-products. Plant biomass results from photosynthesis. Plants convert glucose, the prime product of photosynthesis, into other plant compounds such as carbohydrates, proteins, lipids, lignin and organic acids. These groups of compounds differ in their construction costs, i.e. g of glucose/g of compound (Poorter, 1994). Plant co-products (e.g. soybean meal and soybean oil) differ in their contents of these compounds and consequently have different construction costs. We propose biomass construction cost as a characteristic for physical allocation.

Construction cost was estimated according to Poorter (1994) using the following equation:

$$CC = (-1.041 + 5.077 * C_{om}) * (1-M) + (5.325 * Norg)$$

Where:
CC: the total cost to produce one gram of plant biomass (g glucose/g dry weight)
C_{om}: the carbon content of the biomass (g/g dry matter)
M: the mineral content of the biomass (g/g dry matter)
N_{org}: the organic nitrogen content of the biomass (g/g dry matter)

The carbon content of the biomass was estimated according to Vertregt and Penning de Vries (1987) using the following equation (ignoring organic anions):

$$C_{om} = 0{,}444 * carbohydrates + 0{,}535 * protein + 0{,}774 * lipids + 0{,}667 * lignin$$

All components as well as C_{om} are expressed as g/g dry matter (DM). Carbohydrate, protein, lipids, lignin and mineral contents of co-products were taken from INRA (2004; 2007), from the Feedipedia (2013) website and from ANSES (2013).

The calculation of allocation coefficients for the three methods requires extraction rates (the proportion of the processed product obtained from the parent product). Extraction rates for soybean, rapeseed and sugar beet were from Jungbluth et al. (2007), for sunflower from FAO (2002), for linseed from unpublished INRA data, for oil palm from Schmidt (2007), for wheat and maize from Würdinger et al. (2002).

3. Results

3.1. Attribution of impacts to plant co-product in LCA studies

In the studies surveyed, economic allocation was used in 19 out of 24 cases (Table 1). Energy allocation was used in three studies, system expansion and mass allocation were used in two studies, while nitrogen content was used in one study. This illustrates the popularity of economic allocation among scientists dealing with LCAs involving plant co-products, in spite of ISO 14044 recommending economic allocation as a last resort.

Table 1. The use of methods to attribute impacts to co-products used as animal feed in LCA studies published in peer-reviewed journals in the 2000 – 2013 period.

Study reference	Main product studied	System expansion	Allocation method			
			Mass	Energy (gross energy)	Nitrogen content	Economic
Cederberg and Mattsson 2000	Milk					X
Haas et al. 2001	Milk					X
Cederberg and Stadig 2003	Milk					X
Casey and Holden 2005	Milk					X
Basset-Mens and van der Werf 2005	Pig					X
Casey and Holden 2006	Beef cattle					X
Mollenhorst et al. 2006	Eggs					X
Williams et al. 2006	Milk, meat, eggs					X
Katajajuuri 2008	Chicken					X
Pelletier 2008	Chicken			X		
Thomassen et al. 2008a	Milk	X	X			X
Thomassen et al. 2008b	Milk					X
Van der Werf et al. 2009	Milk					X
Pelletier et al. 2010a	Pig			X		
Pelletier et al. 2010b	Beef cattle			X		
Nguyen et al. 2010	Beef cattle	X				
Gerber et al. 2010	Milk					X
Cederberg et al. 2013	Milk, meat, eggs					X
O'Brien et al. 2012	Milk		X			X
Weiss and Leip 2012	Milk, meat, eggs				X	
Nguyen et al. 2012a	Chicken					X
Nguyen et al. 2012b	Beef cattle					X
Ripoll-Bosch et al. 2013	Sheep					X
Nguyen et al. 2013	Milk					X
Total	**24**	**2**	**2**	**3**	**1**	**19**

3.2. Lower heating value, average price and construction cost for the co-products

The lower heating values (in MJ/kg DM) that we calculated from gross energy values were 36.9 for oils and fat, for oilseed meals they ranged from 18.1 for rapeseed meal to 18.5 for soybean meal; for the other co-products they ranged from 14.5 for beet molasses to 18.9 for palm kernel (Table 2). Prices for oils (in $/t gross product) ranged from 626 for palm oil to 1028 for linseed oil; for oilseed meals they ranged from 178 for sunflower meal to 321 for soybean meal; for the other co-products they ranged from 69 for corn gluten feed to 585 (Euros) for beet sugar. Construction costs (in glucose/kg DM) were 2.89 for oils and fat, for oilseed meals they ranged from 1.54 for sunflower meal to 1.67 for soybean meal; for the other co-products they ranged from 0.99 for beet molasses to 2.20 for palm kernel.

Table 2. Lower Heating Value (LHV), Olympic average price for 2005-2009 and construction cost of plant co-products used for animal feed

Co-product	LHV (MJ/kg DM[1])	Price 05-09 ($/t gross product[2])	Construction cost (kg glucose/kg DM)
Soybean oil	36.9	694	2.89
Soybean meal	18.5	321	1.67
Ratio oil/meal	1.99	2.16	1.73
Rapeseed oil	36.9	874	2.89
Rapeseed meal	18.1	184	1.59
Ratio oil/meal	2.04	4.75	1.82
Sunflower oil	36.9	851	2.89
Sunflower meal	18.2	178	1.54
Ratio oil/meal	2.03	4.78	1.88
Linseed oil	36.9	1028	2.89
Linseed meal	18.2	293	1.58
Ratio oil/meal	2.03	3.51	1.83
Refined palm oil	36.9	626	2.89
Palm kernel	18.9	-	2.20
Fodder fat	36.9	-	2.89
Wheat flour	15.4	313	1.42
Wheat bran	17.8	82	1.34
Wheat middlings	17.9	82	1.39
Feed grade wheat flour	17.8	82	1.40
Maize starch	16.5	319	1.22
Corn gluten feed	17.6	69	1.32
Corn oil	36.9	760	2.89
Corn gluten meal	21.7	370	2.07
Beet sugar	15.7	585[3]	1.21
Pressed sugar beet pulp	16.0	134[3]	1.13
Beet molasses	14.5	160[3]	0.99

[1] Dry Matter
[2] Product at its reference humidity content
[3]€/t gross product

For LHV oil/meal ratios for the four oilseeds (soybean, rapeseed, sunflower and linseed) varied little and ranged from 1.99 for soybean to 2.04 for sunflower (Table 2). For prices the ratio varied widely, ranging from 2.16 for soybean to 4.78 for sunflower. For construction cost the ratio varied moderately, ranging from 1.73 for soybean to 1.88 for sunflower. For soybean oil/meal ratios varied least across the three methods (1.73 to 2.16), whereas for the other three oilseeds these ratios varied much more across methods: rapeseed: 1.82 to 4.75, sunflower 1.88 to 4.78 and linseed 1.83 to 3.51.

Construction cost was strongly correlated with LHV, price was correlated with both LHV and construction cost, but the correlation was weaker (Table 3).

Table 3. Correlation coefficient (r) between lower heating value (LHV), Olympic average price for 2005-2009 and construction cost of plant co-products used for animal feed

	LHV	Price 05-09	Construction cost
LHV	1.0	0.697	0.987
Price 05-09		1.0	0.722
Construction cost			1.0

Table 4. Allocation factors according to energy content, economic value and construction cost for plant co-products used for animal feed

Raw material	Energy content	Economic value	Construction cost
Soybean oil	35.3	34.2	32.1
Soybean meal	64.7	65.8	67.9
Rapeseed oil	60.0	75.6	57.3
Rapeseed meal	40.0	24.4	42.7
Sunflower oil	63.0	78.1	61.2
Sunflower meal	37.0	21.9	38.8
Linseed oil	46.9	57.5	44.3
Linseed meal	53.1	42.5	55.7
Refined palm oil	85.0	81.8	80.5
Palm kernel	11.5	15.0	16.1
Fodder fat	3.6	3.2	3.4
Wheat flour	76.7	93.6	79.8
Wheat bran	13.6	3.8	11.6
Wheat middlings	4.0	1.1	3.5
Feed grade wheat flour	5.7	1.6	5.1
Maize starch	62.5	79.2	61.0
Corn gluten feed	24.9	6.4	24.6
Corn oil	6.4	7.5	6.5
Corn gluten meal	6.3	6.9	7.9
Beet sugar	67.3	72.8	69.4
Pressed sugar beet pulp	22.8	23.0	21.6
Beet molasses	9.9	4.2	9.0

3.3. Allocation factors for the co-products

For soybean, energy (En) and economic (Ec) allocation factors were close (Table 4). For the other oilseeds Ec allocation had higher factors for oil than En allocation, but for oil palm Ec allocation had a lower factor for oil than En allocation. For co-products from wheat, maize and sugar beet Ec allocation had higher factors for the main product (flour, starch and sugar, respectively) than En allocation.

Relative to En allocation, construction cost (Cc) allocation had a lower factor for oil for the four oilseeds as well as for oil palm. For wheat co-products, Cc had a higher allocation factor for flour and a lower allocation factor for bran than En. For maize and sugar beet co-products En and Cc allocation factors were quite close.

4. Discussion

The survey on the application of the different approaches for the attribution of impacts to plant co-products yielded quite sobering results, as it revealed a large gap between the normative propositions on co-product handling in the ISO guidelines and the actual practice by scientists publishing LCA studies. Clearly neither avoiding allocation nor allocation according to a physical relationship proved satisfactory for plant co-products to most LCA practitioners. There may therefore be interest among LCA scientists for a new approach to allocation of plant products.

Allocation according to the underlying physical relationships between the co-products, as recommended in the ISO 14044 standard, is generally done by identifying a common physical chemical property of the co-products such as mass or energy content (Pelletier and Tyedmers 2011). However, the identification of a common property such as mass or energy content does not really establish or reflect a common relationship between co-products. Any two products in the world have a mass and an energy content, but this does not mean they are related. The relationship between co-products is their common origin, so a physical allocation method should not be based on the physical properties of the co-products, but rather on the mechanism reflecting their common origin, as this is the basis of their relationship.

The new method proposed in this paper corresponds in our view to a more appropriate interpretation of the ISO 14044 standard, as it is not based simply on a physical property of the co-products, but on their construction cost, i.e. the common plant physiological mechanism at the origin of the different compounds that make up plant biomass. Although construction cost is strongly correlated with LHV, it is not identical. Whereas for LHV oil/meal ratios for the four oilseeds analyzed in this paper are around 2, these ratios vary between 1.73 and 1.88 for construction cost. As a result, relative to allocation factors based on energy content, allocation factors based on construction costs are higher for meals than for oils

5. Conclusion

Although, according to the ISO 14044 standard, economic allocation should be the solution of last resort, it is frequently used in LCA studies of agri-food systems because of the inadequacy of solutions preferred by ISO. Allocation according to the underlying physical relationships between the co-products is generally done by identifying a common physical chemical property of the co-products, but this does not really reflect a relationship between the co-products. We propose construction cost of plant compounds making up the co-products as an allocation criterion which is truly based on a relationship between the co-products.

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