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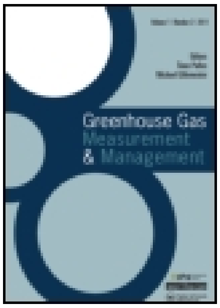

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The use of substitution in attributional life cycle assessment

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Substitution is used within attributional life cycle assessments (LCAs) as a means of avoiding allocation between co-products, and a number of existing standards and guidance documents permit its use in this way. This article discusses the appropriateness of substitution for attributional LCA, and suggests that the use of substitution introduces consequential elements into attributional analysis and that attributional assessments that use substitution will not be appropriate for consumption-based carbon accounting or corporate greenhouse gas reporting. This article suggests that, as a methodological principle, attributional LCA should only include actual physical burdens and should not include values for burdens that are avoided (i.e. do not physically occur). We also suggest that existing standards and guidance should be amended so that substitution is not permitted as a method within attributional LCA and that substitution should be clearly distinguished from expanding the function studied by an assessment. This article focuses on greenhouse gas LCA, but the discussion and conclusions apply to attributional LCA generally.

Keywords: corporate inventory; GHG accounting; GHG inventories; protocols and standards; supply chain

1. Introduction

When a process has more than one useful output or function, the environmental burdens associated with the process, and the inventory of upstream burdens, need to be apportioned between the co-products or multiple functions. One approach for avoiding allocation is the substitution method, which involves identifying the products that are substituted by the co-product(s) of the product that is studied and quantifying the environmental burdens associated with those products. The avoidance of these burdens is then credited to the product that is studied. This method is also known as the 'avoided burden' approach or 'system expansion', although it should be noted that the term 'system expansion' is also used to describe an alternative method for dealing with multi-functionality.

Substitution is generally recognized as a valid method within attributional life cycle assessment (LCA) (Curran, 2007; Thomassen et al., 2008), and its use is sanctioned by a number of attributional LCA standards such as the PAS 2050 (BSI, 2011) and the WBCSD/WRI Product Accounting and Reporting Standard (WBCSD/WRI, 2011a) and guidance documents such as the ILCD Handbook (JRC, 2010). Attributional LCA aims to account for the processes, as well as the associated environmental burdens, that are used in the production (and other life cycle stages) of the product studied. In contrast, consequential LCA aims to account for the total change in environmental burdens caused by a change in demand or the level of output of a product, including changes in environmental burdens associated with processes not directly used in the life cycle of the product studied (i.e. processes that are directly associated with the life cycle of other products).

A worked example is introduced in this article to explore the nature of the substitution method, the way in which it differs from other methods for either avoiding or undertaking allocation, and the implications of substitution for the way in which attributional LCA can be used. The article suggests that because substitution involves the inclusion of a credit for environmental burdens that do not occur, attributional LCA that uses this method will not be appropriate for consumption-based carbon accounting or for life cycle emissions reporting in corporate greenhouse gas (GHG) accounting, as these forms of accounting are inventories of actual physical burdens. We also suggest that, as a methodological principle, attributional LCA should only include actual physical

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burdens and should not include values for burdens that are avoided (i.e. do not physically occur). Although this article focuses on GHG LCA, the conclusions about the appropriateness of substitution in attributional LCA apply generally.

2. Worked example – wheat ethanol and dried distiller grains with solubles

The following example of wheat ethanol is used to explore the conceptual nature of the substitution method and the way in which it differs from the other available methods for dealing with multi-functional processes. A co-product obtained from the production of wheat ethanol is dried distillers grains with solubles (DDGS), which can be used as animal feed and can act as a substitute for soy meal. For the purposes of this example it is assumed that the CO_2 produced during fermentation is released to the atmosphere, and is not captured and used as an additional co-product from the process. The following methods for either avoiding or performing allocation are illustrated in the example: (i) avoiding allocation by using the substitution method; (ii) avoiding allocation by expanding the function studied to include the co-product (the distinction between this method and substitution is discussed in more detail below); (iii) allocation by economic value; (iv) allocation by energy content; and (v) allocation by mass. The emission factors, substitution ratio between DDGS and soy meal, and the allocation ratios used in the worked example are set out in Table 1, and full details of the data used to derive the ratios are presented in the Appendix.

Table 1 Emission factors, substitution ratio and allocation ratios

Description	Value	Unit	Source
Emissions from the production of wheat ethanol	2.18	tCO_2e/t ethanol produced	Derived from RFA (2010)
Quantity of DDGS produced per tonne of ethanol	1.03	t DDGS/t ethanol	Derived from Warwick Lywood (pers. commun.)
Emissions from the production of soy meal	5.78	tCO_2e/t soy meal	Derived from Weightman et al. (2010)
Substitution ratio between DDGS and soy meal	0.59	t soy meal/ t DDGS	Lywood et al. (2009)
Economic value of ethanol as percent of total value of co-products	74%	percentage	Derived from Warwick Lywood (pers. commun.)
Energy content of ethanol as percent of total energy of co-products	59%	percentage	Derived from Warwick Lywood (pers. commun.)
Mass of ethanol as percent of total mass of co-products	49%	percentage	Derived from Warwick Lywood (pers. commun.)

The total emissions from producing ethanol and DDGS are 2.18 tCO_2e per 1 t ethanol and 1.03 t of DDGS produced, and either these emissions need to be allocated between the co-products or allocation needs to be avoided. As described above, the substitution method can be used to avoid allocation by identifying the products that are substituted by the co-product, that is, soy meal, quantifying the environmental burden associated with that product (in this case 5.78 tCO_2e/t soy meal) and crediting the product studied for the avoided burden.

It is worth highlighting at this point that substitution has been distinguished from the alternative method of expanding the function studied by the assessment, which also avoids the need for allocation by including the function provided by the co-product(s). In the case of this example, the product studied becomes '1 t of ethanol and 1.03 t of animal feed'.

Confusingly, these distinct methods are often both referred to as 'system expansion' in the literature, and tend not to be clearly distinguished. For example, ISO 14044 states that allocation should be avoided by 'expanding the product system to include the additional functions related to the co-products' (ISO, 2006, section 4.3.4.2), which can be interpreted as referring to either method. The example of expansion of system boundaries in ISO 14049 (ISO, 2000) suggests that ISO 14044 is referring to expanding the function studied by the assessment rather than substitution, but this is not explicitly stated, and it is still possible to interpret ISO 14044 as referring to both methods for avoiding allocation. That the ISO publications are open to interpretation is evidenced by Heijungs and Guinée's (2007) comment that ISO 14001 'implicitly' supports the substitution method and by the way in which practitioners, for example, Cederberg and Stadig (2003), cite the ISO standards when applying the substitution method.

Finnveden et al. (2009) describe the substitution method as a variant of expanding the system boundary, but do not state that the two are distinct methods, which have implications for how the results of an LCA can be used. As shown by the worked example, the use of these different approaches gives fundamentally different results, and the two methods are not equivalent. In addition, as discussed below, substitution is not appropriate for attributional LCA, whereas expanding the function studied by the assessment is.

Table 2 The results from using different methods of treating co-products

Method	Result/allocation to ethanol (tCO_2e/t ethanol)	Result/allocation to DDGS (tCO_2e/t DDGS)
Substitution method	−1.35	Not applicable (substitution avoids allocation)
Expanding the scope of the assessment to include the co-product	2.18	Not applicable (system expansion avoids allocation)
Allocation by economic value	1.62	0.56
Allocation by energy content	1.29	0.89
Allocation by mass	1.07	1.11

The results obtained by employing the substitution method, by expanding the function that is studied, and by allocating emissions by economic value, energy content and mass are shown in Table 2.

3. Discussion

The results from using the substitution method are negative and are notably different from the results of the other methods, which are all positive. It is well known that different methods for dealing with co-product allocation can provide divergent results (Guinée and Heijungs, 2007; Kaufman et al., 2010); however, the difference in sign suggests that the substitution method is doing something radically different from the other methods. For the other methods, the results from treating co-product allocation *cannot* be negative if the emissions from the multi-functional process (including upstream emissions) are positive; that is, the results for an LCA will only be negative if physical removals of GHGs from the atmosphere are greater than physical emissions. The substitution method is unique in creating negative results for an LCA even when the physical removals associated with the product's life cycle are not greater than physical emissions.

The reason for this difference is that substitution involves a credit for emissions that have not happened. In the case of the ethanol example, the avoided emissions are those associated with the production of the soy meal that is *not* produced because its function is fulfilled by the DDGS. It is worth noting that quantifying all changes in emissions, including the change in emissions due to reduced soy meal production, is properly the aim of consequential LCA (which uses substitution in order to show the consequences that flow from the production of co-products).

Because the substitution method includes a credit for emissions that have not happened, the results from an LCA that uses the substitution method will not equal total physical emissions. In contrast, the other methods for dealing with allocation only count physical emissions (and removals) and their results will equal total net physical emissions. For example, the result from expanding the function studied by the assessment is 2.18 tCO_2e, which are the total physical emissions from the production of the ethanol and the DDGS. Similarly, the sum of the allocated emissions will always equal 2.18 tCO_2e. The wheat ethanol example provides an extreme case in order to demonstrate the anomaly created by substitution, but any use of substitution, including the cases where the results are not negative, will be inconsistent with the principle of only counting actual emissions or removals.

It is worth noting that the ILCD guidance (JRC, 2010) suggests that substitution can be appropriate for attributional LCA if the aim of the LCA is to describe the life cycle of an existing or previously existing product system, including its interactions with other systems. However, such 'attributional' assessments are better described as consequential assessments about changes that have already happened, i.e. the question is simply 'What *were* the consequences of producing product A?' rather than 'What *will be* the consequences of producing product A?'. There does not appear to be a credible distinction between consequential LCA and 'attributional' LCA that includes interactions with other systems.

In fact, the methodological integrity of such 'attributional' assessments may be more questionable than simply mischaracterizing consequential assessments as attributional, as typically only *some* consequential elements are picked for inclusion, that is, credits for co-products or recycling through the use of the substitution method, and the results are neither a true inventory of actual emissions, nor do they show the full consequences associated with the product. It is unclear what the results from such 'partially consequential' assessments show.

There are two important implications for the use of attributional LCA if substitution is used. Firstly, the results will not be appropriate for consumption-based carbon accounting, which aims to quantify all the emissions associated with an individual's, organization's or a country's consumption (Larsen and Hertwich, 2009). As with production-based inventories, such as national GHG inventory reporting under the UNFCCC (IPCC, 2006), consumption-based accounting should not double-count emissions and the sum of all inventories should approximate to total global emissions.

Attributional LCA will not be appropriate for consumption-based carbon accounting *if* substitution has been used, as the sum of life cycle emissions will not correspond to actual total emissions. If the other methods for dealing with co-products are used, such as system expansion (in the sense of expanding the function studied by the assessment) or allocation by value, energy or mass, then the LCA results will be suitable for consumption-based carbon accounting.

The second area in which substitution creates problems is when attributional LCA is used within corporate carbon accounting. Corporate carbon accounting aims to quantify the total emissions and removals associated with the activities of businesses and organizations. Current best practice for corporate carbon accounting is provided by the WBCSD/WRI GHG Protocol (WBCSD/WRI, 2004), which categorizes emissions into three scopes. Scope 1 emissions are from sources which are owned or operated by the reporting entity; Scope 2 emissions are those from the generation of imported electricity or other forms of energy; and Scope 3 are all other emissions from sources owned or operated by third parties but which the reporting company also has some influence over, such as business travel in third-party-owned vehicles, or the disposal of the reporting company's waste. Included within Scope 3 are the upstream and downstream emissions associated with the products and services that businesses consume and supply (WBCSD/WRI, 2011b). As with consumption-based carbon accounting, the values included in corporate inventories are for actual physical emissions or actual physical removals, rather than values for emissions which have not happened, and life cycle emissions which are calculated using substitution will not be consistent with the principles of a corporate inventory. Interestingly, the WBCSD/WRI standard for product accounting (WBCSD/WRI, 2011a) allows the use of substitution and is therefore at odds with the aims of WBCSD/WRI standard for corporate value chain emissions (WBCSD/WRI, 2011b) which supports the reporting of Scope 3 life cycle emissions in corporate inventories.

The WBCSD/WRI product accounting standard states that substitution is appropriate for attributional LCA if the *average* emissions associated with substituted products are credited to the product studied, rather than the emissions from the marginal units of production which are substituted. However, using any value within an attributional GHG LCA which is not for an actual physical emission or an actual physical removal, whether average or marginal, means that the results will not equal total physical emissions. To return to the ethanol and DDGS example, the figure of 5.78 tCO_2e/t soy meal is based on average data, but crediting the ethanol with this value means the results of the LCA do not correspond to actual physical emissions and are not appropriate for consumption-based carbon accounting or corporate Scope 3 reporting.

An example of the misapplication of substitution-based LCA values is given by the UK's official guidelines for corporate reporting which provide emission factors for recycled waste which include a credit for avoided emissions caused by the substitution of virgin material (Defra/DECC, 2011). These factors are inconsistent with the other emission factors provided in the guidelines, which are for actual emissions per unit of activity, and the use of the recycled waste factors means that the resulting corporate accounts are not true inventories of actual emissions. The GHG Protocol (WBCSD/WRI, 2004, p.61) rightly recommends that *reductions* caused in other organizations' inventories, such as the reductions caused by displacing virgin production due to recycling, should not be included within the inventory of the organization that caused the reduction, but can be reported separately.

Heijungs and Guinée (2007) also argue that substitution should not be used within attributional LCA; however, their argument focuses on the way in which substitution is speculative and relies on unprovable 'what if' assumptions. The argument presented in this article is that even if the systems that are substituted are known, the inclusion of burdens that are avoided undermines the use of attributional LCA as an inventory of actual burdens.

A final point that is worth discussing is how attributional and consequential LCA fits within the framework of other GHG accounting practices. As has been outlined above, attributional LCA is akin to production-based national inventory accounting, consumption-based accounting, and corporate GHG accounting, which are all inventories of actual physical emissions and removals. In contrast, consequential LCA is akin to project carbon accounting, such as the Clean Development Mechanism methodologies and the WBCSD/WRI GHG Protocol for Project Accounting (WBCSD/WRI, 2005), which aim to quantify the total change in emissions that result from a change in some activity. The credits from emission reduction projects can be used to offset emissions that actually occur, but these are reported separately and are not included *within* inventories of actual emissions. For example, the WBCSD/WRI GHG Protocol (WBCSD/WRI, 2004) states that 'It is important for companies to report their physical inventory emissions for their chosen inventory boundaries separately and independently of any GHG trades they undertake' (p.60).

4. Conclusions

The substitution method for dealing with co-products or multi-functional processes is different from the other methods available as it includes credits for burdens that are avoided, and this creates problems for how attributional life cycle assessment (LCA) results can be used. Substitution is properly suited to the purposes of consequential LCA, which aims to quantify the total change in emissions that result from a change in the level of output of a product, including changes in emissions that are directly associated with the life cycle of other products. Although the discussion presented here has focused on greenhouse gas LCA, the conclusions are relevant to the use of substitution in attributional LCA generally.

We conclude by recommending that the existing standards and guidance that currently permit the use of substitution in attributional LCA should be amended, as should the Defra/DECC waste emission factors for corporate reporting. We suggest that, as a methodological principle, attributional LCA should only count actual physical burdens, and should not count burdens that do not occur. We also recommend that existing standards and guidance should clearly distinguish between substitution and expanding the function studied by the assessment, as these are distinct methods that are appropriate for different kinds of LCA.

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Appendix

Full details of the data used to derive the ratios are presented in Table A1.

Table A1 The data that were used to derive the substitution credit and allocation factors

Description	Value	Unit	Source
Emissions from the production of wheat ethanol	1.623	tCO_2e/t ethanol produced	RFA (2010)
Quantity of DDGS produced and sold as animal feed	1.14	tDDGS/t ethanol	RFA (2010)
Credit for DDGS co-product	491	$kgCO_2e$/t DDGS	RFA (2010)
Substitution ratio between DDGS and soy meal	0.594	t soy meal/t DDGS	Lywood et al. (2009)
Emissions per tonne of soya imported into the EU27 from South America	4.62	tCO_2e/t soy beans	Weightman et al. (2010)
Yield of soy meal from soy beans	0.80	t soy meal/t soy beans	Weightman et al. (2010)
Economic value of ethanol	540	£/t	Warwick Lywood (pers. commun.)
Economic value of DDGS	180	£/t	Warwick Lywood (pers. commun.)
Energy content of ethanol (net calorific value)	26.28	MJ/kg	Defra 2011
Energy content of DDGS (net calorific value)	17.6	MJ/kg	Warwick Lywood (pers. commun.)
Yield of ethanol per tonne of wheat	0.32	t ethanol/t of moist wheat	Warwick Lywood (pers. commun.)
Yield of DDGS per tonne of wheat	0.330	t DDGS/t of moist wheat	Warwick Lywood (pers. commun.)