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Two sides of the same coin: consequential life cycle assessment based on the attributional framework

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ABSTRACT

Process and Input–Output based methods are standard models used in attributional life cycle assessment (ALCA). These are linear models that, when used to estimate environmental consequences of a decision that involves changes, rely on linear extrapolation to approximate the changes. Behind this linearity are several assumptions such as fixed input/output relationships and unlimited supply of inputs. These assumptions expose the limitations of the attributional framework when used for consequential modeling. For example, if a product system faces supply constraints and an additional output would induce input substitution, a simple linear extrapolation from existing situations would fall short of estimating the environmental consequences of the additional output. These assumptions, however, can be relaxed to better reflect reality and the attributional framework can provide more relevant and accurate estimates for consequential modeling and decision making. Drawing insights from LCA studies on biofuels and the rich literature of Input–Output Analysis, this paper presents a two-step approach to consequential life cycle assessment (CLCA) based on the attributional framework. The first step compiles inventories and conducts attributional analysis to evaluate the status quo of the system under study, identify hotspots on which to focus on subsequently, and construct business-as-usual scenarios. The second step introduces the decision in question, evaluates possible changes to take place, builds scenarios representing associated environmental consequences, and modifies the original inventories accordingly. This paper demonstrates that the attributional framework can serve the purpose of addressing change-oriented questions when it is used properly and its assumptions and limitations are recognized.

1. Introduction

A recent study has frustrated those who intend to eat healthier and help save the environment (Tom et al., 2015). The study finds that on a caloric basis vegetables and fruits in the United States – mostly grown in California (CA)– consume much more water than meat over their life cycles. The authors thus conclude that a dietary shift toward more vegetables and fruits and less meat would put further stress on water systems. Granted, if the dietary shift leads to more vegetables and fruits grown in CA, this will exacerbate the water issues there given its ongoing drought. But what if we grow the extra vegetables and fruits in states with abundant rainfall? What if we grow them locally with reclaimed water? What if we grow them in our own gardens? Unfortunately, none of these possible scenarios following a dietary shift are analyzed in the study. Thus their conclusion that a healthier diet would make the environment worse does not necessarily follow from their presentation of the status quo of crop production (Cucurachi et al., 2016).

The study by Tom et al. (2015) is not a special case, but represents the standard way we do Life Cycle Assessment (LCA). We begin by compiling inventories that mostly reflect existing situations, analyze them with a set of *attributional* rules, and then make suggestions or policy implications that involve or lead to changes (Weidema, 2003). Too often, however, the changes to take place are not adequately captured in the initial inventories compiled and analyzed (Cucurachi et al., 2016; Searchinger et al., 2008; Tillman, 2000; Yang and Suh, 2015a). In other words, attributional LCA (ALCA) that describes an existing and presumably static state may fall short of providing relevant and meaningful information for a decision that brings about changes.

Recognizing the problems of ALCA, Weidema (1993) were among the first to introduce what has come to be known as consequential LCA (CLCA). CLCA estimates how relevant flows change in response to a decision (Curran et al., 2005). But for a long time LCA scholars

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were debating over the two approaches without reaching a consensus (Finnveden et al., 2009). Recently there seems to be a growing awareness of the inadequacy of ALCA for decision making, and an evolution toward CLCA has been observed (McManus and Taylor, 2015). Perhaps the most explicit and salient criticisms of ALCA thus far came from Plevin et al. (2014). The authors argued that ALCA is not predictive of real-world impacts and thus should not be used for policy making. They further advised LCA scholars against drawing the conclusion that because the carbon footprint of product A is X % lower than that of product B, producing more of A would result in an X% reduction in carbon emissions. Interestingly, there was a similar realization by Ferng (2009) in Ecological Footprints, who demonstrated that land multipliers – an index similar to carbon footprint – are inadequate to capture the impact on land due to incremental changes in consumption.

In advocating for CLCA, the use of economic methods such as computable general equilibrium (CGE) models are often recommended (Earles and Halog, 2011; Ferng, 2009; Plevin et al., 2014). These nonlinear optimization models are presumably more sophisticated than the linear models that have been used in ALCA, such as process- and Input–Output (IO) based LCA (Heijungs and Suh, 2002). They account for a broader range of market and institutional aspects such as input substitution, factor constraints, and price effects (Lundie et al., 2007; Rose, 1995). On the other hand, they are also grounded on restrictive, unrealistic assumptions (e.g., rational expectation) that undermine the relevance and accuracy of their estimates (see, e.g., (Barker, 2004; DeCanio, 2003; Thaler, 2015) for detailed critique). My focus, however, is not to argue which class of models is superior. A more interesting question I seek to address is how we can better estimate environmental consequences, or do CLCA, based on the more familiar attributional framework that we have been using in LCA (Heijungs and Suh, 2002).

I begin with a brief review of corn ethanol LCA studies to further illustrate the inadequacy of ALCA for estimating consequences of decision making when the methodology is used without recognizing its limitations. The reason I single out corn ethanol is that biofuels have played a key role in the debate between ALCA and CLCA (McManus and Taylor, 2015; Plevin et al., 2014), and corn ethanol is arguably the most contentious part of the discourse as reflected in multiple debates (Anex and Lifset, 2009; Babcock, 2009; Mathews and Tan, 2009; Searchinger et al., 2008). It is also an interesting case that, besides revealing many of the limitations of ALCA, casts light on how we can better conduct LCA to address change-oriented questions and support decision making. Then, from a methodological point of view, I analyze the assumptions involved in using ALCA to estimate changes.

Next, I present a two-step approach to CLCA based on the attributional framework. As to be shown, the approach treats attributional analysis as an important and indispensable part of the overall consequential modeling for purposes of, e.g., evaluating the status quo of the system under study and identifying hotspots on which to focus on subsequently. For this, the approach differs from much of the CLCA literature that view themselves in stark contrast to ALCA (Ekvall and Weidema, 2004; Plevin et al., 2014; Suh and Yang, 2014; Weidema, 2003). I conclude with discussions on issues like development of marginal coefficients. This paper demonstrates that the attributional framework can serve our purpose of addressing change-oriented questions when we use it properly and recognize its assumptions and limitations.

2. A brief history of corn ethanol LCA and some reflections

Driven by policies in the United States (Runge and Johnson, 2008), corn ethanol has become a major source of biofuels worldwide (Fig. 1). Its use was partly justified by the potential to reduce greenhouse gas (GHG) emissions by displacing gasoline (Keeney, 2008). Whether corn ethanol generates lower GHG emissions than gasoline, however, has to be evaluated on a system wide, or life cycle, basis. This means emissions from vehicle operation, fuel refining, feedstock production, and fuel transportation and distribution, as well as emissions from supply chains such as fertilizer production.

A typical LCA study would sum emissions across all life cycle stages and then compare the totals. Early LCA estimates differed as to which fuel performed better (Farrell et al., 2006). Notably, research by Pimentel and colleagues was all-negative for corn ethanol (Pimentel, 2003; Pimentel and Patzek, 2005). The results, together with concern over soil, air, and water pollution associated with corn production, led them to strongly oppose the use of corn ethanol (Pimentel et al.,, 2008). But subsequent studies, with updated data and ethanol coproducts accounted for, converged on that corn ethanol had moderately lower life cycle GHG emissions than gasoline (about 70 versus 90 g CO_2e MJ^{-1}) (Farrell et al., 2006; Hill et al., 2006; Kim and Dale, 2008; Wang et al., 2007). It was then concluded that corn ethanol could reduce about 20% GHG emissions, or 20 g CO_2e MJ^{-1}, by displacing gasoline (Farrell et al., 2006).

Next came the two game-changing articles published in *Science* (Fargione et al., 2008; Searchinger et al., 2008). Fargione et al. (2008) used process-based LCA to investigate the direct land use change (LUC) effects of biofuels expansion; e.g., farmers in the US clear grassland to grow corn for ethanol use. Searchinger et al. (2008), by contrast, explored the indirect LUC effects using process-based LCA together with partial equilibrium analysis (PEA) (see (Marvuglia et al., 2013; Vázquez-Rowe et al., 2013) for more discussion of the methodology). For example, in response to increasing corn demand from ethanol industry, US farmers could reallocate their land to produce more corn at the expense of reduced soybean production. This could drive up global soybean prices and lead farmers across the world to produce more soybeans by clearing forest and grassland. In both direct and indirect LUC, large amounts of carbon would be released from land conversion, offsetting any carbon benefits that corn ethanol may provide for decades to come. Indeed, over the past few years we have observed significant corn expansion into grassland and cropland like cotton (Johnston, 2013; Wallander et al., 2011; Wright and Wimberly, 2013; Yang and Suh, 2015b). Since publication, the two studies have changed the discourse of bioenergy LCA research, culminating in amendments to biofuels policies that took land use change effects into consideration (Farber, 2011).

Why were LUC effects systematically neglected in previous LCA studies? In hindsight, it was mainly because they used the attributional LCA (ALCA) approach without realizing its limitations. What

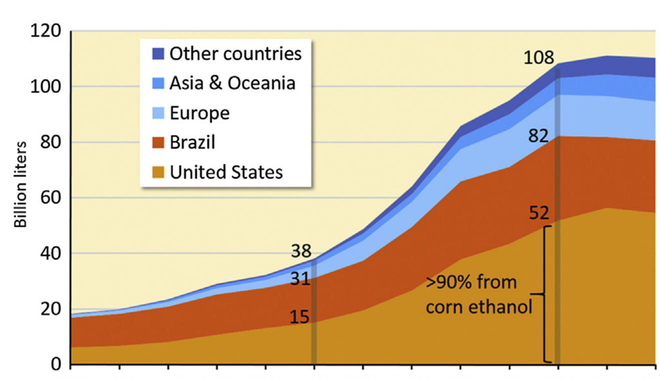

Fig. 1. Global biofuels production between 2000 and 2012 (US Energy Information Administration).