Improving attributional life cycle assessment for decision support: The case of local food in sustainable design

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ABSTRACT

Life cycle assessment (LCA) has become widely used to evaluate the environmental sustainability of products. It has been increasingly realized, however, that the conventional framework, attributional LCA (ALCA), may be inadequate for steering decision making. Here we show how ALCA can be improved for decision support if we recognize its limitations. Using local food production in the U.S. as a case study, we show that ALCA can be enhanced by relaxing some of the restrictive assumptions (e.g., static, aggregate, site-generic, linear), by evaluating the situation in question from a more dynamic and prospective angle, and by accounting for the important role of decision makers to introduce innovative systems that reshape the status quo. For local food, studies of food miles have shown that transportation is a minor source of carbon emission, with an implication that local food is not an effective means of helping the environment. But these studies fail to realize other potential benefits which food localization may uniquely enable including recycling of energy, water, and nutrients. These benefits cannot be derived from a simple presentation of the status quo as often done in ALCA studies. Our results show that for some crops, irrigation could contribute up to 50% of the cradle-to-gate carbon emissions, thus they may benefit from food localization making use of water from wastewater treatment plants. Our results also show that local food could reduce the water footprint of lettuce by 50%. Our study suggests that exploring future scenarios, beyond assessing historical outcomes, is critical if ALCA is to support sustainable decision making.

1. Introduction

Paper towels or hand dryers, which one is more environmentally friendly? Do all electric cars really have lower emissions than internal combustion vehicles? Perhaps there are no tailpipe emissions, but what about electricity generation and production of batteries? When we waste food and it ends up in a landfill, are methane emissions from anaerobic decomposition the only consequence of our wasteful behavior? What about refrigeration and transportation of the food, as well as farming, processes that also generate emissions, which could have been avoided or reduced had we not wasted as much food?

Addressing the questions above requires a systems approach that goes beyond what we see around us. Life cycle assessment (LCA) has emerged as a popular systems approach to environmental sustainability. It investigates the whole life cycle of a product from resource extraction, manufacturing, transportation, to use and disposal (Guinee et al., 2002). In the case of electric cars, for example, LCA quantifies emissions not only from electricity generation but also from production of batteries, cars, and their supply chains such as mining and refining of iron and steel (Hawkins et al., 2013). In addition, LCA covers a wide range of environmental issues from global warming, acid rain, smog, to ecological and human toxicity (Pennington et al., 2004). The comprehensiveness of LCA is aimed at preventing or minimizing burden shifting across life cycle stages (e.g., from use to production), regions (e.g., from urban to rural), and impact categories (e.g., from global warming to water stress) (Finnveden et al., 2009).

Over the past decades, LCA has become widely applied in academic research (Guinee et al., 2011). It is, for example, a primary approach to determining the environmental benefits of renewable energy (Cherubini and Strømman, 2011; Hertwich et al., 2015),
estimating consumption-based emissions (Peters, 2008; Wiedmann, 2009), and measuring the sustainability of agricultural and food products (Roy et al., 2009; Tilman and Clark, 2014; Yang and Suh, 2015a). LCA has also played an increasingly important role in the policy arena around the world, as reflected in a number of policy directives in Europe including the Integrated Product Policy (Recchioni et al., 2015). In the U.S., life cycle thinking was the core principle behind the Renewable Fuel Standard and the Sustainable Materials Management program implemented by the U.S. Environmental Protection Agency (EPA, 2016; Schnepf and Yacobucci, 2010). Recently, the Ministry of Industry and Information Technology in China has put forth an LCA-based eco-design guidance to be applied in a select group of corporations, with the aim of leading industries towards a path of green, low-carbon development.

With growing popularity and continuous expansion, the LCA methodology itself has been developing and strengthening. In particular, the inadequacy of attributional LCA (ALCA) for decision making has been increasingly recognized (Geyer et al., 2015; Plevin et al., 2014; Weidema, 2003; Yang, 2016). A shift seems to be underway toward a prospective, dynamic LCA framework that more broadly takes into account market mechanisms and human behaviors (McManus and Taylor, 2015). This change, also known as retrospective or accounting-style LCA, is equivalent to taking a snapshot of an existing system and analyzing it with a set of attributional rules (Weidema, 2003). For example, a typical ALCA comparing corn ethanol and gasoline would compile emissions along their life cycle based mostly on existing technologies such as how corn is currently produced (Yang et al., 2012). If corn ethanol were found to have lower total or life-cycle emissions than gasoline, then ALCA would suggest that corn ethanol is better for the environment and worth promoting (Farrell et al., 2006). However, evidence that product A has lower life-cycle emissions than product B does not necessarily mean that additional production of A would maintain that advantage (Plevin et al., 2014). Indeed, it has been shown that corn ethanol expansion could result in loss of natural habitats and worsen climate change through market-mediated effects such as land-use change (Fargione et al., 2008; Searchinger et al., 2008). In turn, the understanding of land-use change effects has inspired solutions such as the use of marginal croplands for bioenergy production (Zumkehr and Campbell, 2013).

The problems with ALCA have led researchers to suggest that this tool is misleading for policy making (Plevin et al., 2014). This is because using ALCA to estimate changes associated with a decision amounts to a simple linear extrapolation based on such assumptions as fixed input/output relationships and unlimited supply of inputs (Yang, 2016). When these assumptions are severely violated, ALCA falls short of assisting decision making, as in the case of corn ethanol. On the other hand, when the limitations of ALCA are recognized with unrealistic assumptions relaxed, the framework can provide estimates that are more relevant to decision making (Yang, 2016). The consideration of land use change in corn ethanol expansion, for example, significantly improved our understanding of its environmental impacts (Fargione et al., 2008; Searchinger et al., 2008).

The problems with ALCA have also led to new models being developed or more sophisticated models from other disciplines being incorporated into LCA, including system dynamics (Stasinopoulos et al., 2012); partial and general equilibriums models (Hertel et al., 2010; Zink et al., 2016); and integrated assessment models (Plevin et al., 2016). However, these models have their own limitations (Pindyck, 2013; Yang and Heijungs, 2016). Here, we take the approach as proposed in our previous study (Yang, 2016) that while ALCA in its standard form may fall short, it can be modified and improved to provide more relevant and accurate estimates for decision making. Building on our previous study (Yang, 2016), we further demonstrate how ALCA can be enhanced for decision support by analyzing two subjects related to local food in the U.S., namely, food miles and dietary change. We begin with briefly reviewing previous ALCA studies of food miles and dietary change, and then discuss why they may fall short for decision making. Next, we show what the literature has missed with respect to the environmental benefits of local food. In so doing, we demonstrate how ALCA can be improved for decision making, by relaxing restrictive assumptions (e.g., static, aggregate, site-generic, linear), by thinking from a more dynamic and prospective angle, and by recognizing the important role we as decision makers can play in terms of coming up with innovative ideas, setting targets, making changes, and reshaping the status quo. The last point on the role of decision maker constitutes a major contribution of our study to the LCA literature.

2. Environmental benefits of local food

Local food consumption, which is characterized by foodsheds with small distances between production and consumption, is projected to double to $20 billion during this decade in the U.S. (Low et al., 2015). This growth is consistent with a recent study of the geophysical potential of local food that found an unexpectedly large upper limit for local systems to support as much as 90% of U.S. food demand (Zumkehr and Campbell, 2015). There are many drivers behind this local movement. Some consumers perceive local food as fresher and better in taste or nutritional content; some value the knowledge of where foods come from; while others believe local food supports local economies (Schnell, 2013). Still, some consumers believe that local food is more environmentally sustainable than long-distance foods (Schnell, 2013).

2.1. Food miles

However, research of food miles shows that transportation in general is a minor contributor to the life-cycle energy and greenhouse gas (GHG) emissions of foods, suggesting that localization may not be an effective means of reducing environmental impacts (Cleveland et al., 2011; Garnett, 2011; Wakeiland et al., 2012; Weber and Matthews, 2008). Weber and Matthews, for example, studied how long foods travelled in the U.S. and found that final delivery of foods from producer to retail accounted for only 4% of life-cycle GHG emissions and transportation throughout the life cycle contributes 11% (Weber and Matthews, 2008).

A commonly used method in food miles and life-cycle GHG emissions is the Input-Output LCA (IO-LCA) (Cleveland et al., 2011; Rocco and Colombo, 2016; Weber and Matthews, 2008), which often relies on a national model based on average industrial transaction and emission data without regional characteristics (Hendrickson et al., 2006). Such nationally averaged data, however, may be inadequate for assessing the environmental sustainability of food production (Avetisyan et al., 2014; Edwards-Jones et al., 2008). This is mainly because agricultural systems are highly variable in terms of yield and input use across regions due to weather, soil, and geography (Miller et al., 2006; Yang et al., 2012). Additionally, IO-LCA is a highly-aggregated model with hundreds of food items represented by several sectors. Even if transportation is insignificant for food on average, it may be a large source of emissions for certain food products.

Besides the problems above, however, estimates of the food miles studies were derived from analysis of the status quo, which is typical of attributional LCA (ALCA) (Weidema, 2003). As discussed above, ALCA studies how a set of processes are interconnected with one another through economic and technological relationships. It
provides a static view of how a world works and as it is or more precisely as it was because inventory data used in LCA are often outdated (Yang and Suh, 2015a). The question then arises, is a simple presentation of, at the best, the status quo sufficient in the conclusion that local food is not worth the endeavor?

Undoubtedly, a good understanding of the status quo provides valuable information for the decision in question. In some cases, such information may be sufficient to inform decision making, but in others it may fall far short as it fails to capture the dynamics of decision making and neglects the role and power of decision makers. We as decision makers can actively engage ourselves, reevaluate the status quo, and revise our (tentative) decisions or goals put forth in the first place. We can reinforce the positive aspects in the status quo and alleviate the negative aspects. We can think creatively and innovatively to come up with ideas not at all captured in the status quo. The point is that the status quo, although offering valuable insights into the future, does not determine it; we as decision makers are capable of shifting the trajectory from initial assessments. So for local food, if we think from a more dynamic and prospective angle, what other benefits could localization of production potentially provide besides transportation?

Short distances between food production on farms and food consumption in cities may provide unique pathways to the sustainable management of wastewater, water storage and solid waste. Treated wastewater is a source of recycled water that could offer unique opportunities for local food to mitigate stresses on water, energy, and food for four reasons. First, the close spatial proximity of the farms to cities reduces pumping energy needed to distribute recycled urban water for irrigation. Second, recycled water is a surface water resource that may be a low-energy alternative to pumping groundwater, which can be a significant source of carbon emissions in food production (Khan et al., 2009). Third, the application of recycled water to croplands can reduce the need for energy-intensive nutrient removal at the wastewater plant. Fourth, when farms use recycled water, they provide an opportunity for farms and cities to share rather than compete for water. Fig. 1 shows a list of crops we compiled that may benefit from local production. They are produced in different states and rely heavily on underground irrigation, which accounts for 10%–50% of the cradle-to-farmland energy use and GHG emissions. Estimates are partly from the literature and partly from our own calculation (see the supporting information (SI)).

Also, management of water storage may also benefit from local farms, which can provide infiltration basins for replenishing urban groundwater reservoirs using treated urban wastewater and diverted stormwater. Severe overdraft of aquifers has increased pumping energy costs and accelerated seawater intrusion rates into coastal aquifers with peak vulnerabilities in drought years (CA DWR, 2003). The use of local croplands as infiltration basins could provide a low-energy alternative to hard engineering approaches to protect both water quality and quantity in aquifers (Bachand et al., 2014). Local food also shortens the distances required for economic and energy-efficient recycling of nutrients between farms and cities. The recycling of urban organic waste as a compost fertilizer can mitigate the need for synthetic fertilizers (Dawson and Hilton, 2011), which is typically a large component of the energy footprint of food and can reduce solid waste accumulation and associated emissions in landfills (Morris et al., 2013).

In addition, local irrigated farms around a city could result in atmosphere-biosphere interactions that cause regional cooling that is similar in magnitude but opposite in sign to urban heat islands and global climate warming. This potential climate benefit is based on recent evidence that irrigated croplands can significantly reduce local temperatures (Bonfils and Lobell, 2007; Kueppers et al., 2007). Irrigation can also reduce the frequency, duration and intensity of heat waves (Lu and Kueppers, 2015). Even agriculture that is not irrigated can affect surface energy fluxes by partitioning absorbed energy to latent heat flux during transpiration, a process strongly influenced by leaf area index and the timing of crop growth (Williams and Torn, 2015). Harnessing these climate regulation effects closer to cities may be particularly important in light of recent evidence that urban heat islands can drive regional warming that extends beyond urban boundaries (Georgescu et al., 2014).

2.2. Dietary change

LCA has been increasingly applied to investigate the environmental implications of dietary change (Tilman and Clark, 2014). For example, Vanham and coauthors evaluated the water footprint of different diets in Europe and found a change toward vegetarian diets could contribute the most to water footprint reduction (Vanham et al., 2013b, 2013a). Consistent with those findings, a study of diets in Germany estimated that a shift toward healthier diets recommended by the German Nutrition Society could reduce water use by 26% and GHG emissions by 11% (Meier and Christen, 2013). Marlow and coauthors also found that a vegetarian diet in California poses a much smaller threat to the environment on various indicators including water and pesticide use as compared with a non-vegetarian diet (Marlow et al., 2009). Studies of the U.S. on a national scale, however, seem to be largely negative. Heller and Keoleian (2015) estimated that a shift to the U.S. Department of Agriculture (USDA) dietary recommendations could increase GHG emissions by 12%, and only when caloric intake is reduced could reduce GHG emissions (but by merely 1%). Similarly, Tom and coauthors (2015) found that a shift to USDA recommended diets could increase the water footprint, GHG emissions, and energy use by various degrees.

The methodology of the studies above can be summarized by the following equation (Cucurachi et al., 2016):

$$ e_i = a_1x_{i1} + a_2x_{i2} + \cdots + a_nx_{in}, $$

where $a_{1,2,..,n}$ represents the life-cycle emissions or resource use of foods and $x$ represents their proportions, on a caloric or protein basis, in a specific diet choice $i$. By varying the proportions ($x$), the

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**Fig. 1.** Ratio of GHG emissions from irrigation to the cradle-to-farmland GHG emissions for various crops in locations relying heavily on groundwater pumping. For example, irrigation could contribute up to 50% to the cradle-to-farmland GHG emissions in spinach production (see SI for details).
studies discussed above compare the life cycle emissions or resource use of different diets. As with food mile studies, however, $d_{1,2...n}$ represents, at best, the status quo of crop production. While the studies above claimed to evaluate dietary change, the only parameters changed in the equation are the proportions ($x$). But dietary change, by definition, involves increased output of certain produce such as vegetables and decreased output of others such as red meat. By keeping a constant, the studies implicitly assumed that, for example, additional vegetables will have the same life-cycle emissions or resource use as existing vegetables, equivalent to a simple linear extrapolation as discussed above (Yang, 2016).

Linear extrapolation is not necessarily an unrealistic assumption (Yang, 2016). For a small country that is largely self-sufficient and highly homogeneous in agricultural practices, such an assumption that additional crops would generate similar emissions as existing ones may be reasonable. For a large country like the U.S. with many different agroecological regions, however, the assumption may be highly problematic. For example, life-cycle impacts of staple crops such as corn could vary by a factor of 2–4 across states for various issues such as smog formation and eutrophication due to differences in nutrient use and runoff, and could vary by an order of magnitude for ecological toxicity due to differences in pesticide use and emissions (Xue et al., 2015; Yang and Suh, 2015b). The variability is even more dramatic for the blue water footprint, which is dominated by irrigation water use. In the case of lettuce, irrigation water use per kg of lettuce produced in 2013 ranges from a few liters in Kansas and Rhode Island to 130 L in California, and 270 L in Arizona (USDA, 2015). Because today California and Arizona produce the vast majority of lettuce consumed in the U.S., the average irrigation water use of lettuce in the U.S. is relatively high, resulting in a higher blue water footprint than most types of meat (Tom et al., 2015).

A high blue water footprint for existing lettuce today, however, by no means indicates it will remain high for additional lettuce to be produced tomorrow as a result of dietary change. Hidden opportunities, for example, can be dug out from the wide regional variability of irrigation water use. As a proof of concept, we compute a local-food scenario assuming that a dietary shift took place across the country and additional lettuce in each state would be grown in state (Fig. 2). As Fig. 2 demonstrates, we have the potential to reduce the blue water footprint of lettuce by nearly 50% if we localize lettuce production.

Fig. 2 is not meant to provide a realistic estimate of what will happen tomorrow if we start to eat more lettuce. More realistic estimates may not be as low as 86 L/kg considering factors including cost, land availability, economies of scale, and marginal yield. On the other hand, we should not neglect, again, our active role as decision makers and our ability to set goals and make changes (Sachs, 2015). We can, for example, implement policy interventions that incentivize lettuce production in states with suitable soil and abundant rain. We can facilitate technological advances that can vastly improve upon current irrigation efficiencies. And we can also invest in what used to be futuristic technologies such as vertical farming but are now on the horizon (Diamandis and Kotler, 2012). The point is that a simple presentation of the status quo using ALCA should not be interpreted as offering definitive answers to our decisions in question, but rather provides a playground for our imagination. Without imagination, we cannot expect to solve the complex and pressing environmental problems that society faces.

3. Discussion

Using studies of food miles and dietary change, we have shown that ALCA in its standard form may fall short of steering decision making. For example, it may be insufficient to support the conclusion that because A has a lower footprint than B, then A is better and worth promoting (Plevin et al., 2014). First, this is because the assumptions behind ALCA, such as linearity, may be severely violated, rendering the conclusion questionable. Second, ALCA is often applied in a retrospective manner based on data reflecting the past. It may be unable to capture the dynamics of decision making, e.g., new things which appear as a result of the decision in question but which are not captured in the original inventories compiled. Third, ALCA studies often neglects the important role that decision makers can play upon receiving new information. For example, the suggestion against eating more vegetables for the environment because they consume more water than meat fails to recognize the fact that we can produce vegetables in less water-intensive ways.

However, recognizing these limitations of ALCA, we can harness the tool to better assist decision making. We can use more detailed, process-based and site-dependent data rather than rely on aggregate data (Geyer et al., 2013). We can capture marginal changes (Weidema et al., 1999). We can evaluate the situation from a more dynamic and prospective angle, instead of retrospectively. And we as decision makers can think creatively and innovatively, reinforcing the positive aspects and alleviating the negative aspects in the preliminary results so as to make changes toward (larger) environmental benefits. In the case of local food, even though transportation is in general a minor source of GHG emissions, food localization may bring about other benefits, such as reducing the use of irrigation energy and commercial fertilizers. In the case of dietary change, although some of the healthy foods produced today are estimated to have a large footprint, this does not mean the estimates will be the same for additional production. We as decision makers can intervene, grow them where arable land is available, weather is suited, and water is abundant, and thus significantly lower the footprint of the additional healthy food.

On the role of decision makers, we further emphasize the use of scenario analysis for understanding environmental consequences of decision making. This is partly to capture the high uncertainty associated with studying how a complex system may respond to a decision in question, and partly to reflect the complexity of the process of decision making, including the reaction of decision makers themselves upon receiving new information. More importantly, scenario analysis can also open the door to innovative thinking that may identify more improvement opportunities, to strategies that cope with negative aspects in the status quo, and to policy interventions that can further facilitate positive developments. The dietary shift question, for example, could be
addressed by developing a number of possible scenarios, such as what if additional healthy foods following a dietary change are continually produced by states producing them today (i.e., business as usual); what if they are produced by regions with the least cost; what if they are produced locally; and, what if they are produced by technologies around the corner such as vertical farming (Qin et al.). If, for example, the local-food scenario is found to be the best, we can devise policies such as local food subsidies to facilitate the movement. If certain regions are found to be much more suited than other regions to grow the additional foods, favorable policies can be implemented in those regions only.

Last, our indication that local food may provide potential environmental benefits not captured by previous studies should not be interpreted as that local food is overall green or it is better than imported food everywhere. Our analysis was to primarily demonstrate a methodological point, that is, how ALCA can be improved for decision support. Given the geographical variability of crop production, local food needs to be examined on a location-by-location basis, taking account of input use and emissions at the local or regional level. Our suggestion of irrigating local food with reclaimed water also should take geography into consideration, such as the location of wastewater treatment plants and energy needed to transport water to local croplands. Future studies can further investigate the ideas discussed here.

4. Conclusions

Limitations of attributional LCA (LCA), often relying on a simple presentation of the status quo using average and aggregate data, have been increasingly recognized. Using local food as a case study, we demonstrate that the framework can be enhanced by relaxing some of the restrictive assumptions (e.g., static, aggregate, site-generic, linear), by evaluating the situation in question from a more dynamic and prospective angle, and by accounting for the important role of decision makers to introduce innovative systems that reshape the status quo. In so doing, we show that studies of food miles are inadequate to conclude whether local food is effective for the environment. There are many potential benefits which food localization may uniquely enable including recycling of energy, water, and nutrients. The main implication of our study is that exploring future scenarios, beyond assessing historical outcomes, is critical for ALCA to support sustainable decision making.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2017.01.020.

References
