Title

A Heuristic Screening Aid for Consequential Life Cycle Assessment

Journal
Journal of Industrial Ecology, 22(6)

ISSN
1088-1980

Author
Rajagopal, Deepak

Publication Date
2018-12-01

DOI
10.1111/jiec.12699

Peer reviewed

A Heuristic Screening Aid for Consequential Life Cycle Assessment

Deepak Rajagopal

Institute of Environment and Sustainability, University of California–Los Angeles (UCLA), Los Angeles, CA, USA

Keywords:

bioenergy
climate change
environmental policy
life cycle assessment (LCA)
life cycle inventory (LCI)
market-mediated effects

Supporting information is linked to this article on the *JIE* website

Summary

Consequential life cycle assessment (CLCA) is envisioned as a framework that combines the technological richness of attributional life cycle assessment (ALCA) with basic economic intuition to assess the potential environmental impact of an innovation. However, despite a growing literature, CLCA still lacks general guidelines for system boundary definition. Toward filling this gap, this article invents a new index of vulnerability of the life cycle impact of a product (or activity) to emissions arising from the impact of its large-scale adoption on market prices. Using corn ethanol as an example, it is illustrated how such an index might aid in the selection of a small set of affected activities for formal consideration in a CLCA. The application to corn ethanol reveals that in addition to land-cover change, there exist other sources of vulnerability that have not received attention in the context of biofuels. A general procedure for utilizing the vulnerability index as a screening aid for CLCA is outlined. The utility of the vulnerability index is independent of the type of modeling framework (such as multimarket partial equilibrium or computable general equilibrium) that might be employed for a formal CLCA. Finally, this work illustrates how the vulnerability index approach bridges ALCA and CLCA.

Introduction

The environmental impact of an innovation[1] manifests through two different yet interlinked channels. One channel results from differences in the physical-engineered characteristics of the innovation and its supporting infrastructure relative to those for a functional substitute. For instance, electric propulsion technology is more energy efficient relative to internal combustion engines. As a result, the life cycle energy input, as well certain types of air emissions, tend to be lower for electric vehicles while certain other burdens, such as throughput of toxic substances, tend to be higher. This is the life cycle channel. Moreover, this channel is concerned with the effects of simply replacing one unit of an existing product with one unit of a new product, holding all else fixed (Matthews et al. 2016). Attributional LCA (ALCA) is concerned with this channel of impact.

The second channel of impacts is behavioral-economic in origin. Increasing the consumption of a new product, all else fixed, reduces the demand for certain types of scarce resources while simultaneously increasing the demand for certain others. The price of the former types of resources will decline, in turn causing their consumption to rebound while the price for the latter will increase causing an expansion of their supply. For instance, growth in the electric car industry would lower the price of gasoline whose consumption will rebound. It will increase the price of electricity whose supply will increase. This is the price channel of impacts.[2] The need to analyze both these channels justifies the development of consequential LCA (CLCA).

Conflict of interest statement: The authors have no conflict to declare.

Address correspondence to: Deepak Rajagopal, Institute of Environment and Sustainability, UCLA, 300 La Kretz Hall, Box 951496, Los Angeles, CA 90095, USA. *Email:* rdeepak@ioes.ucla.edu; *Web*: http://environment.ucla.edu/rajagopal

DOI: 10.1111/jiec.12699

Editor managing review: Miguel Brandão

Volume 00, Number 0

When impacts via the life cycle channel dominate those via the price channel, linear extrapolation of the per-unit difference in the footprint of two technologies is a reasonable approximation of the actual environmental impact of technology adoption. This might be the case when the context is such that price effects are negligible. For instance, a ban on plastic bags in one city might have little impact on the price of commodities associated with the life cycle of plastic bags or its substitutes. In this case, policies could simply focus on impacts via the life cycle channel, but not otherwise. Biofuels exemplify the risk in relying exclusively on ALCA when adopting public policies supporting (or even discouraging) specific technologies. ALCAs suggest that while the greenhouse gas (GHG) footprint of biofuel is variable, there exist biofuel pathways, including corn ethanol, with a smaller GHG footprint relative to oil products (MacLean and Lave 2003; Farrell et al. 2006; Spatari et al. 2005; Miller et al. 2007; Hill et al. 2009). However, crop-based biofuels increase demand for, and therefore the price of agricultural goods, most notably farmland, whose supply will increase at the expense of nonfarmland. Such a shift could entail sizeable additional GHG emissions (Fargione et al. 2008; Gibbs et al. 2008). However, deriving a reliable estimate of land-use emissions intensity of biofuels is controversial (Kim et al. 2009; Khanna and Zilberman 2012).

CLCA is discussed as a framework to understand the potential actual environmental consequences of adopting a new innovation (Ekvall and Wiedema 2004; Finnveden et al. 2009; Rajagopal 2014). An ideal CLCA would be one that combines the technical richness of ALCA with an explicit representation of economic behavior, market conditions, and the policy context within which an innovation is adopted. There exist a number of economic modeling frameworks, such as multimarket partial equilibrium (PE) and computable general equilibrium (CGE) that have a rich history of use as policy aids that might be integrated with ALCA (Rajagopal 2017). Figure 1 is an attempt to depict graphically the difference in the scope of ALCA and CLCA. Despite its conceptual appeal relative to ALCA, CLCAs raise several new concerns (Suh and Yang 2014). See Anex and Lifset (2014) and the references therein for different visions of CLCA and their strengths and weakness vis-à-vis ALCA.[3] The focus here is on one specific current issue with CLCA: Unlike ALCA, there does not exist any general principles or procedures for defining the system boundary for CLCA (Curran 2013; Zamagni et al. 2012; Hertwich 2014). To the applied researcher or practitioner of CLCA, it is not clear what is that set of commodities whose markets need to be part of a CLCA (or any other systems analytic framework) and which are those that might be excluded, especially given that time and resources for such assessments are often limited (Rajagopal 2017). This is akin to the decision of which material requirements to include and exclude when generating the life cycle inventory (LCI) for which alternative heuristic options exist (see Curran 2006, 29–30). Of course, the economic input-output–based life cycle assessment (LCA) approach obviates this problem in an ALCA context.

Of course, one option is to construct a global CGE model that is technologically as rich as any LCA, behaviorally as rich as possible, and contains a fine spatial and sectoral disaggregation of the global economy. Such a model is likely to account for most, if not all, the intended and unintended impacts on technology adoption. However, this is easier said than done because data on technological and behavioral parameters are typically lacking on such a fine scale, thus necessitating assumptions, which lack empirical basis (Scrieciu 2007; Nassar et al. 2011). Moreover, experience from diverse modeling arenas suggests that typically a few "key" factors generate almost all the uncertainty in any model-based prediction (Saltelli et al. 2008). Building on this argument, once the key economic sectors for market-mediated emissions have been identified, adding further detail might have little effect on the uncertainty in predicted outcomes, which is a major concern for public policy. If this is the case, then a simpler multimarket PE model might suffice (Rajagopal 2014). This motivates the development of a simple approach to identify those key sectors with the potential for large market-mediated emissions (or emissions reductions) so that CLCAs are transparent, useful, and not too costly.

To this end, the next section introduces a simple new index of vulnerability to market-mediated emissions. The utility of the index is subsequently illustrated through an application to biofuels, specifically corn ethanol. Last, but not least, in light of an ongoing debate about the strengths of CLCA vis-à-vis ALCA for decision making, the work presented here illustrates how the vulnerability index bridges ALCA and CLCA, and also shows that the two visions for LCA complement each another as decision aids.

A New Index of Vulnerability to Market-Mediated Emissions

The scope of the framework outlined here needs clarification. The motivation for this framework is to assess the "potential" importance of pollution due to the effects a new innovation on total consumption of different commodities. Say we are interested in the effects of a shock, which increases (or decreases) the consumption (or production)[4] of a product M by *x*% per annum. A real example is a renewable fuel mandate that increases biofuel consumption by a fixed proportion (or fixed volume) each year. There is no single unique threshold for *x* below which its effect on commodity prices could be considered small. Depending on the price elasticity of supply and/or demand, even seemingly small values of *x* could lead to large price effects in upstream and downstream markets. This justifies the need for a heuristic approach to selecting a small subset of economic sectors or commodities for detailed investigation of price effects. Last, in this paper, the terms emissions and emissions intensity both refer to any single type of environmental burden, such as GHG emissions, any type of criteria air pollutant or water pollution. When there are multiple types of burdens of interest, the framework outlined here is repeatable for each different type of burden.

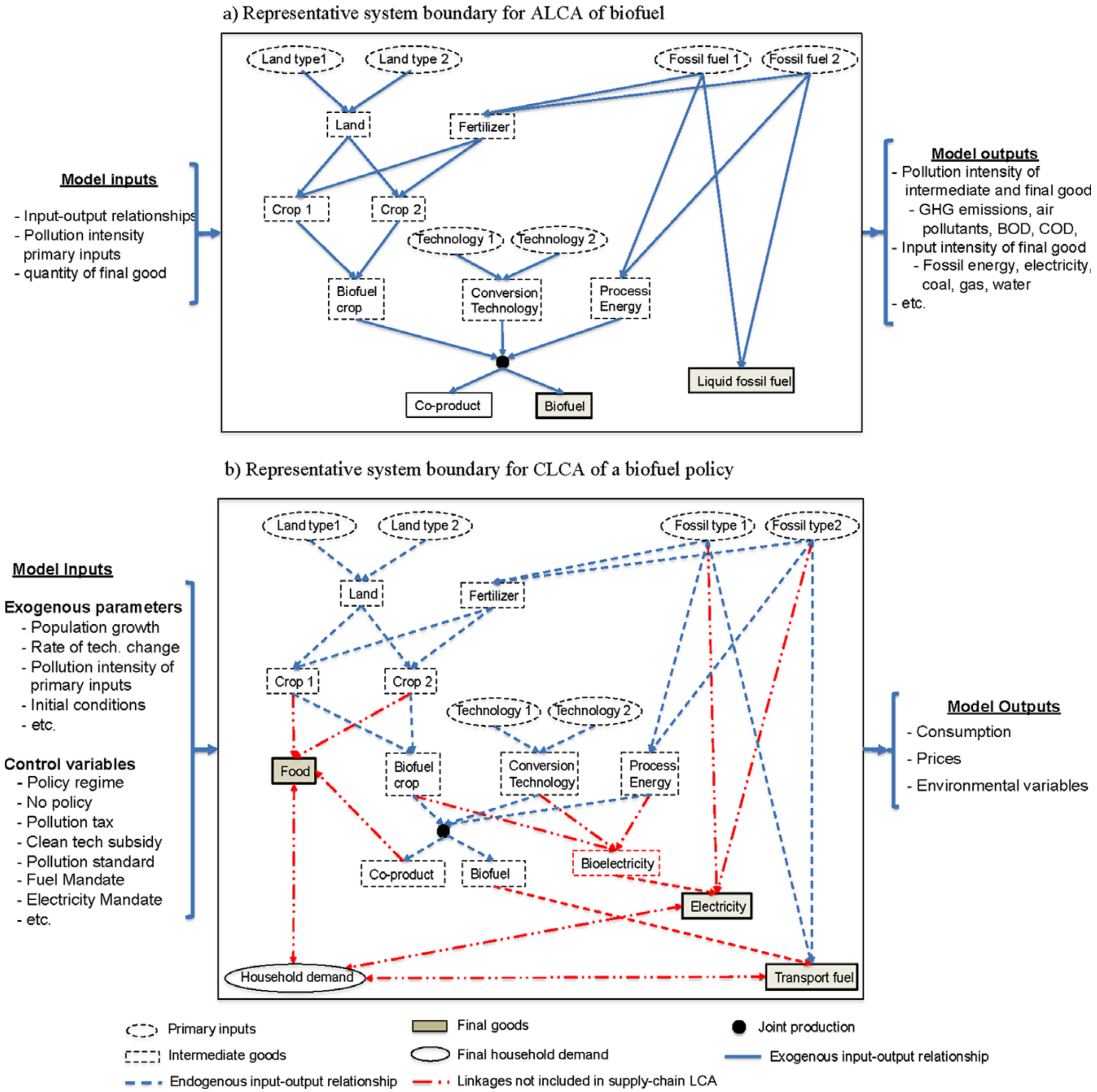


Figure 1 Difference in the system boundary for (a) ALCA and (b) (an ideal) CLCA of biofuel. It depicts two primary inputs, namely, land and fossil fuels, which are combined to produce several intermediate and three final goods that households consume, namely, food, transport fuel, and electricity. Suppose that each of the two primary inputs can be obtained from two different sources that differ in their GHG intensity. Land and fertilizer, an intermediate input, can be utilized to produce two types of crops that can be used for food or biomass for energy production. Biomass can be converted using energy and one of two conversion technologies into biofuel or bioelectricity, which can substitute liquid fossil fuel and fossil-based electricity, respectively. The schematics highlight three differences between ALCA and CLCA: (1) An ideal CLCA would account for the competing uses for each commodity within a life cycle inventory, such as the competition of crops for food and fuel, the competition of fossil fuel for fertilizers, process energy, electricity and transport fuel production, and the competition of biomass for fuel and electricity etc.; (2) whereas ALCA assumes exogenous input-output relationships (shown as solid lines), an ideal CLCA would treat these as endogenous variables (shown as dashed lines); (3) Finally, it is implicit in ALCA that total consumption of each commodity is implicitly fixed. In an ideal CLCA, these would be endogenous and depend on characteristics of the household demand and supply functions. ALCA = attributional life cycle assessment; BOD = biochemical oxygen demand; CLCA = consequential life cycle assessment; COD = chemical oxygen demand; GHG = greenhouse gas.

Let i denote a commodity in the set of all commodities in the LCI of product M; $\bar{\alpha}_i$ and $\overline{\gamma_i}$ represent the average quantity of commodity i needed to produce 1 unit of M and the average emissions intensity of producing commodity i.[5] The difference in life cycle emission intensity (EI) of M and a functionally equivalent unit of substitute S[6] is shown by equation (1):

$$\Delta EI_{\mathrm{ALCA}} = \sum_{i\in\{I_{\mathrm{M}}\}} \overline{\gamma_i}\bar{\alpha}_i - \sum_{i\in\{I_{\mathrm{S}}\}} \overline{\gamma_i}\bar{\alpha}_i \ \ldots \qquad (1)$$

where $\{I_{\mathrm{M}}\}$ and $\{I_{\mathrm{S}}\}$ represent the set of commodities in the LCI of M and S, respectively.

Without a net change in the economy-wide consumption of each of the different commodities in the LCI of M and S, the emissions (E) reduction from increasing consumption of M by Q_{M} units (or, equivalently, by x% relative to current consumption M_0 i.e., $Q_{\mathrm{M}} = x\mathrm{M}_0$) would be (equation 2):

$$\Delta E_{\mathrm{ALCA}} = Q_{\mathrm{M}} * \Delta EI_{\mathrm{ALCA}} \ldots \qquad (2)$$

However, if the economy-wide consumption of any of the different commodities were to change as a consequence of the increase in consumption of M, then both additional emissions or emissions reductions would be result from the commodities whose consumption changes. Using a basic microeconomic concept called the price elasticity (denoted ε) of supply and demand, we can, to a first degree of approximation, derive an expression for the effect of producing Q_{M} units of M on the change in price and total consumption of each commodity in the LCI of M and S. The price elasticity of demand (supply) measures the ratio of the percentage change in quantity of demanded (supplied) of a commodity the ratio of the percentage change in price (Ekvall and Weidema 2004). The mathematical expression for elasticity and a more detailed derivation of all the expressions that follow is at the end as part of the Supporting Information available on the Journal's website. The phrase "to a first degree of approximation" is used because we will analyze the equilibrium one sector at time and ignore intersector linkages. In other words, we will assume that the supply and demand for a commodity is a function only of its own price and ignore cross-price elasticities.

Let p denote the price, q denote the quantity, superscript 0 denote the initial state, ε denote the elasticity, α_i represent the input of commodity i per unit of M for the marginal facility, superscripts S and D denote supply and demand, respectively, and Δ denote the change in a variable. The percentage change in the price of commodity i in response to an increase in demand for i by an amount $\alpha_i\ Q_{\mathrm{M}}$(equation 3):

$$\frac{\Delta p_i}{p_i^0} = \frac{\alpha_i Q_{\mathrm{M}}}{\left(\varepsilon_i^s - \varepsilon_i^D\right) q_i^0} \ldots \qquad (3)$$

The percentage change in the quantity of commodity i consumed in equilibrium in response to a change in price is related to the elasticity of supply as shown by equation (4):

$$\frac{\Delta q_i}{q_i^0} = \varepsilon_i^s \frac{\Delta p_i}{p_i^0} \ldots \qquad (4)$$

Substituting equation (3) in equation (4) we get equation (5):

$$\Delta q_i = \frac{\alpha_i Q_{\mathrm{M}}}{\left(1 - \frac{\varepsilon_i^D}{\varepsilon_i^S}\right)} \ \ldots \qquad (5)$$

Let γ_i represent marginal emissions intensity of producing commodity i. The emissions (ΔE_i), associated with the change in production of quantity Δq_i of commodity i is shown by equation (6):

$$\Delta E_i = \gamma_i \Delta q_i = \frac{\gamma_i \alpha_i Q_{\mathrm{M}}}{\left(1 - \frac{\varepsilon_i^D}{\varepsilon_i^S}\right)} \ldots \qquad (6)$$

We are now ready to define a dimensionless vulnerability index, V, for each distinct commodity or sector featuring in the LCI of M, as the ratio of the potential emissions via the price channel from commodity or sector i (ΔE_i) to the emissions benefits via the life cycle channel (ΔE_{ALCA}) (equation 7).

$$V_i = \frac{\Delta E_i}{\Delta E_{ALCA}} \ldots \qquad (7)$$

Note that ΔE_i and ΔE_{ALCA} could have opposite signs. For an innovation that is considered environmentally benign, ΔE_{ALCA} would be a negative quantity. However, ΔE_i could either be positive or negative. It could be negative (positive), when total economy-wide consumption of a commodity decreases (increases). Our concern is with the magnitude of V_i. The larger the $|V_i|$, the greater is the potential for additional emissions or emissions reduction due to price effects from the market for i. Additional discussion on the interpretation of the magnitude of V follows in the section on *Cut-Off Rules*.

Substituting the expressions for ΔE_{ALCA} and ΔE_i from equations (1), (2), and (6) into equation (7) is shown by equation (8):

$$V_i = \frac{1}{\left(1 - \frac{\varepsilon_i^D}{\varepsilon_i^S}\right)} \left[\frac{\gamma_i \alpha_i}{\Delta EI_{\mathrm{ALCA}}}\right] \text{ for } i \in \{I_{\mathrm{M}}\} \ldots \qquad (8)$$

Likewise, for commodities in the LCI of substitute S is shown by equation (9):

$$V_i = \frac{1}{\left(1 - \frac{\varepsilon_i^D}{\varepsilon_i^S}\right)} \left[\frac{-\gamma_i \alpha_i}{\Delta EI_{\mathrm{ALCA}}}\right] \text{ for } i \in \{I_{\mathrm{S}}\} \ldots \qquad (9)$$

The negative sign on the right-hand side of equation (9) represents the fact that demand for the commodities in the LCI of the substitute S decreases unlike demand for commodities in the LCI of the main product M.

Qualitative Significance of the Parameters in the Vulnerability Index

The vulnerability index is a function of four basic parameters—the price elasticity of demand (ε_i^D), price elasticity of supply for a commodity (ε_i^S), the emissions intensity of the marginal unit of i (γ_i), and the input-output ratio for input i with respect to final good (α_i). A fifth entity in the vulnerability index is the difference in the ALCA emissions intensities of the main product and its substitute, ΔEI_{ALCA}. This is, however, a linear combination of the average emissions intensity $\overline{\gamma_i}$ and α_i. Let us analyze, qualitatively, the sensitivity of the vulnerability index to the different parameters in the expression above (equations 8 and 9), while holding the other parameters fixed. A quantitative analysis of sensitivity is presented in the illustration section below.

1. The price elasticity of demand for a commodity (ε_i^D)

Note that this is a negative number. When demand elasticity increases, all else fixed, the denominator increases, and so the vulnerability decreases. The intuition is explained with the aid of Figure 2. The panel on the left and right depict elastic and inelastic demand situations, respectively. Consider the panel on the left. An elastic demand means that the demand function (the downward sloping solid red line, D) is flatter relative to that for inelastic demand. A positive demand shock (solid green arrow) pushes the demand functions to the right (i.e., solid red line, D, shifts outward to the dashed red line, D'). The length of the solid green arrow represents the size of the shock. The intersection of each of the two red lines with the upward sloping black line, which represents supply (S), identifies the initial and final total consumption of the commodity.

We can see that the net increase in consumption of commodity i in equilibrium, Δq_i, is smaller than the size of the shock, that is, the dotted green arrow is smaller in length than the solid green arrow, that is, total consumption of i does not increase as much. Conversely, for a negative demand shock, an inelastic demand would mean that total consumption of i would not increase as much. The panel on the right shows that as demand becomes more inelastic, the total increase (decrease) in consumption approaches the size of the positive (negative) shock. In the extreme, when ε_i^D is perfectly inelastic ($\varepsilon_i^D = 0$, i.e., quantity consumed does not respond to price) the net equilibrium change in consumption of commodity i equals the size of the quantity shock and when ε_i^D is perfectly elastic ($\varepsilon_i^D = \infty$), there is no net change in consumption of commodity i.

Therefore, for commodities that are inputs to the life cycle of the substitute good(s), which would experience a negative demand, shock would not decline 1:1, which needs to be accounted for in CLCA. To give a specific example, consider the demand for corn for food production. The more elastic this demand, diverting corn to ethanol would require replacing less corn for food. Therefore, total corn production will have to increase by a smaller amount relative to that diverted to ethanol production, which in turn means smaller indirect land-use change. On the other hand, gasoline is a substitute to ethanol. An ethanol mandate reduces the demand for gasoline, which in turn reduces the demand for crude oil, the input to gasoline production. The more elastic the demand for crude oil, a fall in the price of crude oil due to a fall in gasoline demand will lead to larger rebound in oil consumption. Therefore, total crude oil production will decrease by a smaller amount.

2. The price elasticity of supply of a commodity (ε_i^S)

Note that this is a positive number. As the elasticity of supply increases, V increases. When supply elasticity increases, the denominator decreases, and so the vulnerability increases as well. The intuition is similar to that for demand elasticity and is explained with the aid of figure 3. The panel on the left and right depict elastic and inelastic supply situations, respectively. Consider the panel on the left. An elastic supply means that the supply function (the upward sloping solid black line, S) is flatter relative to that for inelastic supply (panel on the right). With elastic supply (and somewhat inelastic demand), the net increase in consumption of commodity i in equilibrium, Δq_i, approaches the size of the shock (the dotted green arrow is about the same length as the solid green arrow). To give a specific example, consider the supply of land for crop production. The more elastic its supply, an increase in ethanol demand will lead to a greater increase in the supply of farmland, which means greater land-use change emissions. On the other hand, the more elastic the supply of crude oil, a fall in the price of crude oil due to a fall in gasoline demand will lead to larger reduction in oil consumption. Therefore, total crude oil production will decrease by a larger amount.

The panel on the right shows that as supply becomes more inelastic, the total increase (decrease) in consumption becomes smaller relative to the size of the positive (negative) shock. In the extreme, when ε_i^S is perfectly inelastic ($\varepsilon_i^S = 0$), there is no net change in consumption of commodity I, and when ε_i^D is perfectly elastic ($\varepsilon_i^D = \infty$), there is no net change in consumption of commodity i.

3. The marginal emissions intensity of a commodity (γ_i)

Recall that the ALCA emissions intensity could be computed using average or marginal emissions factors. In the case of the former, γ_i appears only in the numerator of the vulnerability expression (equations 8 and 9), and therefore vulnerability is in direct proportion to the marginal emissions intensity, which is intuitive. However, if the ALCA emissions intensity is computed using marginal emissions factors, then γ_i appears both in the numerator and the denominator of V as the emissions intensity variable, ΔEI_{ALCA} is a linear function in γ_i (see equation 1). Therefore, one needs to analyze the derivative of V with respect to γ_i to understand the effect of a change in γ_i on the direction of change in V. Differentiating equations (8) and (9) with respect to γ_i is shown by equations (10) and (11):

$$\text{For } i \in \{I_M\} : \frac{dV_i}{d\gamma_i} = \frac{1}{\left(1 - \frac{\varepsilon_i^D}{\varepsilon_i^S}\right)} \left[\frac{\alpha_i (\Delta EI_{ALCA} - \gamma_i \alpha_i)}{\Delta EI_{ALCA}^2} \right] \ldots (10)$$

$$\text{For } i \in \{I_S\} : \frac{dV_i}{d\gamma_i} = \frac{-1}{\left(1 - \frac{\varepsilon_i^D}{\varepsilon_i^S}\right)} \left[\frac{\alpha_i (\Delta EI_{ALCA} - \gamma_i \alpha_i)}{\Delta EI_{ALCA}^2} \right] \ldots (11)$$

For $i \in \{I_M\}$, $\frac{dV_i}{d\gamma_i} < 0 \; if \; \Delta EI_{ALCA} < 0$, otherwise it is ambiguous. For $i \in \{I_S\}$, $\frac{dV_i}{d\gamma_i}$ *is* > 0 if $\Delta EI_{ALCA} < 0$, otherwise it is ambiguous. Since one is likely interested in a CLCA of a new

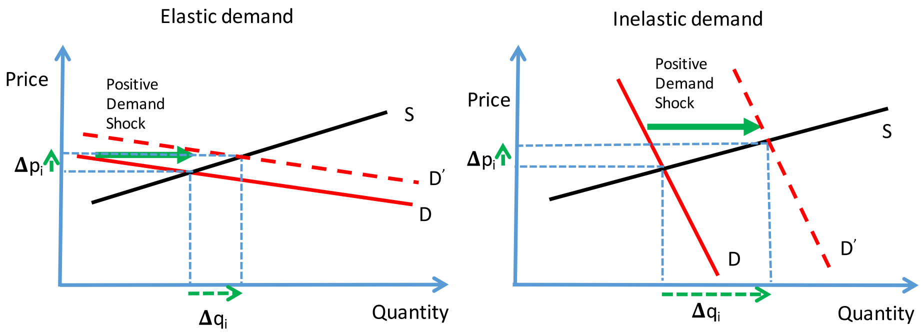


Figure 2 Illustration of the role of demand elasticity. Solid red line = demand function (*D*); solid green arrow = positive demand shock; the dashed green arrow shows the change in price or quantity $\Delta \boldsymbol{q}_i$; black line = supply (*S*); dashed red line = new demand function post demand shock.

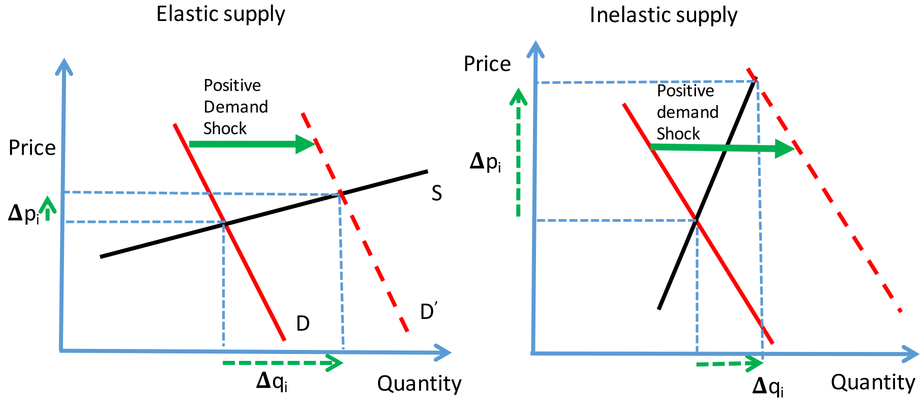


Figure 3 Illustration of the role of supply elasticity. Solid red line = demand function (*D*); solid green arrow = positive demand shock; the dashed green arrow shows change in price or quantity; black line = supply (*S*); dashed red line = new demand function post demand shock.

product because it has a lower life cycle emissions intensity, that is, $\Delta EI_{ALCA} < 0$, it is plausible that $\frac{dV_i}{d\gamma_i} < 0$ for commodities that are only part of the LCI of the new technology. If a commodity features in the LCI of both the new technology and substitutes, then the sign of the derivative of V is ambiguous.

4. The input-output ratio(α_i)

This parameter enters in an identical manner to γ_i in the expression for V_i and in the expression for ΔEI_{ALCA}. Therefore, it has the same qualitative effect as a change in γ_i. Please refer to the discussion above.

Cut-Off Rules

Analyzing the market for each and every commodity in the LCI, however small its vulnerability index as part of a formal CLCA, negates the purpose of developing the vulnerability index. But then how does one determine the threshold above which a commodity sector is deemed vulnerable enough to market-mediated emissions that it merits inclusion within a formal CLCA? This question is analogous to the decision of which raw materials and intermediate requirements to include when performing an LCI assessment during traditional LCA (Curran 2006). There is no unique cut-off value or rule. It is, however, possible to develop some general strategies similar to those for system boundary definition under International Organization for Standardization (ISO) 14044 for LCA.

When $|V_i| > 1$, then it means that the magnitude of emissions due to price effects exceed the magnitude of emissions changes due solely to difference in ALCA emissions intensity. Clearly, the markets for such commodities or inputs need to be part of a formal CLCA. If $|V_i| \in (0, 1)$ then one needs to exercise some additional judgment. One strategy would be to sort the various commodities in the LCI based on their vulnerability and choose a fixed number of vulnerable sectors say, the top three or five. If there are a large number of sectors that exceed the value 1, then each is a candidate for CLCA. Another strategy could be to choose all sectors above a fixed vulnerability index, say, 0.25. With any specific cut-off strategy, it is desirable to adopt an iterative approach wherein the cut-off rule becomes gradually more conservative. With the first strategy above, this would mean beginning by cutting off all but the top three most vulnerable commodities and performing a CLCA followed by cutting off all but the top five most commodities and so on.

Data Requirements and Uncertainty

The vulnerability index does not increase data requirements relative to what would be required for a CLCA in the absence of the index. The four basic parameters comprising the vulnerability index (α_i, γ_i, ε_i^D, and ε_i^S) would each be needed for a CLCA using a partial equilibrium or CGE approach.[7] An ideal CLCA would involve a richer specification of the economic system that gives rise to market-mediated emissions and hence involve a larger set of economic parameters. The richer specification could take the form of nonlinear functional forms for production or demand, imperfectly competitive market structure, and cross-price elasticity between different pairs of commodities. The utility of the vulnerability index results from its role in reducing the number of commodity markets for which such data are to be collected for CLCA.

Since the empirical parameters constituting the index are uncertain,[8] so is the vulnerability score. When data are rich enough that uncertainty can be characterized in probabilistic terms, then one could use tools such as Monte Carlo analysis to derive a distribution of the vulnerability index for each commodity sector from which an expected value or any other statistic could be computed (Huijbregts et al. 2001; Morgan et al. 1990). With less rich data, scenario analysis involving guesses for a high, medium, and low value of each uncertain parameter could be employed. Of course, since the number of combinations of high, medium, and low scenarios increase exponentially with the number of uncertain parameters, this approach can quickly become unwieldy. But then, in the absence of a measure such as the vulnerability, a CLCA model is likely to contain even larger set of uncertain inputs to be analyzed.

Illustration: Corn Ethanol

The utility of the vulnerability measure is illustrated through an application to corn ethanol and its comparison to conventional gasoline. To account for the difference in the energy density on a per-volume basis between the two fuels, the comparison is done for a functional unit of 1 megajoule (MJ) contained in each fuel.[9] The illustrations focus only on the computation and interpretation of the vulnerability index. The LCI for corn ethanol reported in Farrell and colleagues (2006) is used as the reference for an ALCA-based comparison of corn ethanol and conventional gasoline. For the sake of brevity, the life cycle emissions intensity of conventional gasoline is not disaggregated into its constituent entities.

Table 1 shows the average emissions intensity ($\bar{\gamma}_i$), the input per unit of output (α_i), and GHG emissions ($\bar{\gamma}_i\alpha_i$) for each item in the LCI of corn ethanol. The table is sorted in descending order of contribution of each commodity or activity to the emission intensity of the average corn ethanol. Three inputs—coal and natural gas for biorefining and nitrogen fertilizers—account for 80% of the emissions per unit of producing ethanol (prior to application of the co-product credit). Production of corn ethanol also yields distiller's grains (DG), which is itself a substitute for corn grain in animal feed operations. The co-production of DG effectively therefore reduces the amount of corn that needs to be produced for animal feed. According to Farrell and colleagues (2006), application of an emissions credit for co-production of DG reduces the emissions intensity of corn ethanol by 25%. Each of the rest of inputs contributes a small portion to the ALCA emissions intensity.

Next, let us compute the vulnerability index for each input in the LCI of corn ethanol and the life cycle emissions intensity of gasoline. As the reference or base case, the following assumptions are used. For each input in the LCI: (1) the marginal emissions intensity is the same as average emissions intensity, which is reported in table 1. The one exception is land conversion, whose marginal emissions intensity is assumed to be 292,000 kilograms carbon dioxide equivalent per hectare (kg CO_2-eq/ha)[10]; (2) the input per unit output ratio is as shown in table 1; and (3) the ratio of the elasticity of demand and supply, $\varepsilon_i^D/\varepsilon_i^S$, $= -1$ for each input.[11] In a real application, one would first try to obtain actual estimates of this parameter from the literature or alternatively assume a reasonable value. The discussion in endnote 11 shows why the absolute value of this ratio is likely to lie within a narrow range for any arbitrary input.

The vulnerability index thus computed using equation (8) is shown in figure 4. The table of values underlying this figure is in the Supporting Information on the Web. First, land conversion stands out as the single largest source of vulnerability, which suggests that the marginal emissions intensity factor for land conversion is a major driver of vulnerability in the GHG benefits of corn ethanol. The next major source of vulnerability is the life cycle of gasoline, which is the substitute for ethanol. This is followed by coal, whose vulnerability index is much lower compared to that for the previous two factors but still greater than unity. This is followed by co-product emissions credit, natural gas for biorefining, and nitrogen fertilizers, whose index is less than unity but greater than 0.5. The vulnerability index for each of the other inputs is even smaller (<0.1).

The vulnerability index reinforces the importance of understanding the risk of biofuels on account of conversion of nonfarmland to farmland. However, it also shows that the gasoline life cycle and gasoline market effects represent substantial vulnerability, a fact that has not received much attention in the literature.

Next, let us analyze the sensitivity of the index to each of the parameters one at a time. Due to space constraints, let us focus on the top six inputs in figure 4. We vary each of the three parameters $\varepsilon_i^D/\varepsilon_i^S$, γ_i, and α_i by $\pm 50\%$. In other words, each parameter is assigned a value of either zero or twice its base-case value, while holding all the other parameters at their base case values. The results are shown in figure 5. First, varying either the marginal emissions intensity or the input per unit output by a given proportion relative to the base value has the same effect on the vulnerability. This is intuitive as these two terms enter the vulnerability expression in an identical fashion and in a proportional manner. Second, the sensitivity to elasticity ratio is different from the other two parameters given its nonlinear and inverse relationship to vulnerability.

The application to corn ethanol illustrates as to how the index might aid in selecting a small set of commodities for

Table 1 LCI for corn ethanol (based on work by Farrell et al. 2006)

Input/activity	*Average GHG emissions intensity* ($\bar{\gamma}_i$)	*Units*	*Average input per unit output* ($\bar{\alpha}_i$)	*Units*	*GHG emissions (units: kg CO_2-eq/MJ)*
Coal (for biorefining)	0.107	kg CO_2-eq/MJ	0.396	MJ/MJ Eth.	0.0422
Nitrogen fertilizer	10.945	kg CO_2-eq/kg	2.06E-03	kg/MJ Eth.	0.0225
Natural gas (NG) (for biorefining)	0.066	kg CO_2-eq/MJ	0.264	MJ/MJ Eth.	0.0174
Diesel (on farm)	0.091	kg CO_2-eq/MJ	0.037	MJ/MJ Eth.	0.0034
Lime fertilizer	0.509	kg CO_2-eq/kg	6.16E-03	kg/MJ Eth.	0.0031
Feedstock transport to biorefinery	0.020	kg CO_2-eq/kg	0.028	MJ/MJ Eth.	0.0024
Transport (to farm)	0.050	kg CO_2-eq/kg	8.80E-06	MJ/MJ Eth.	0.0023
Gasoline (on farm)	0.094	kg CO_2-eq/MJ	0.018	MJ/MJ Eth.	0.0016
Phosphate fertilizer	1.608	kg CO_2-eq/kg	8.75E-04	kg/MJ Eth.	0.0014
Process water for biorefining	0.065	kg CO_2-eq/MJ	0.018	MJ/MJ Eth.	0.0012
Potash fertilizer	0.712	kg CO_2-eq/kg	1.36E-03	kg/MJ Eth.	0.0010
Herbicide	25.078	kg CO_2-eq/kg	3.81E-05	kg/MJ Eth.	0.0010
Liquefied petroleum gas	0.080	kg CO_2-eq/MJ	0.011	MJ/MJ Eth.	0.0008
Electricity	0.069	kg CO_2-eq/MJ	0.011	MJ/MJ Eth.	0.0008
Natural gas (farm phase)	0.069	kg CO_2-eq/MJ	0.009	MJ/MJ Eth.	0.0006
Capital equipment (for biorefining)	0.065	kg CO_2-eq/MJ	0.006	MJ/MJ Eth.	0.0004
Insecticide	26.012	kg CO_2-eq/kg	2.87E-06	kg/MJ Eth.	0.0001
Irrigation energy	0.074	kg CO_2-eq/MJ	0.001	MJ/MJ Eth.	0.0001
Co-product (DG) emissions credit	0.102	kg CO_2-eq/MJ	−0.246	kg/kg	−0.025
Land conversion[a]	0	kg CO_2-eq/ha	4.58E-07	ha/MJ Eth.	0.0000
Effective ALCA emissions intensity of corn ethanol (kgCO_2-eq/MJ)					0.078
ALCA emissions intensity of conventional gasoline (kgCO_2-eq/MJ)[b]					0.094
Difference in ALCA GHG intensity of corn ethanol and conventional gasoline					**−0.016**

[a] The assumption for ALCA is that corn for ethanol is derived from existing farm land. This restriction is relaxed when computing the vulnerability index. Refer to table S1 in the supporting information on the Web for the assumptions about the marginal emissions intensity of land conversions.

[b] Farrell and colleagues (2006) use the Argonne National Laboratory Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model Version 1.6 for calculating the life cycle emission intensity of conventional gasoline.

LCI = life cycle inventory; ALCA = attributional life cycle assessment; CO_2-eq = carbon dioxide equivalent; GHG = greenhouse gas; ha = hectare; kg = kilogram; MJ = megajoule; Eth. = ethanol; DG = distiller grains.

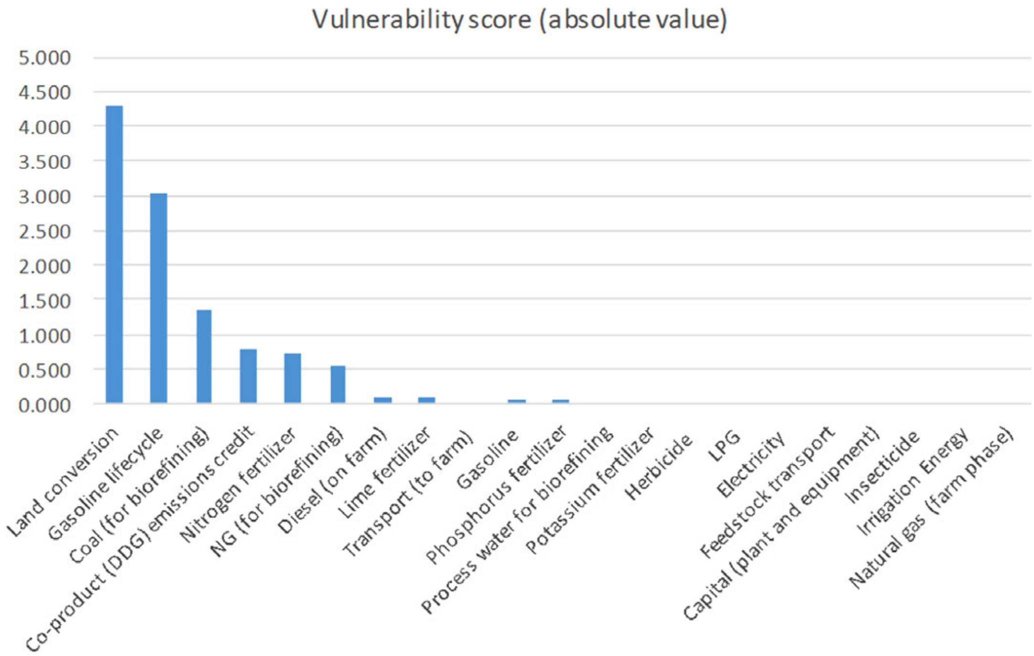


Figure 4 Vulnerability index for corn ethanol. Computed using equation (8) and parameter values reported in table S1 in the supporting information on the Web. DDG = dry distillers grains; LPG = liquid petroleum gas; NG = natural gas.

a full and formal CLCA. Specifically, it reveals that in addition to land-cover change, there exist several other sources of vulnerability that have not received attention in the context of biofuels.

A General Procedure for Utilizing the Vulnerability Index

Based on the discussion above, the following procedure could be employed to screen or select a small subset of product markets for CLCA.

1. Obtain an LCI of the main product M and a substitute product S.
2. Collect data on the four parameters comprising the vulnerability index for each item in the LCI of M and S.
3. For each item in the LCI of the main product and its substitute compute the vulnerability index V.[12]
4. Choose a cut-off value for tolerable level of vulnerability and include all commodities whose V exceeds the cutoff within a formal CLCA. Since V is uncertain, one would need to select a statistic for V such as its expected value.
5. Conduct a CLCA using a formal multimarket PE or CGE framework.
6. Assess whether the contribution of each sector to total emissions predicted by CLCA correlates with the vulnerability index for each sector.
7. Depending on the findings from step 6, and the time and resources available return to step 4 and choose a more conservative cutoff (i.e., include more commodities and activities from LCI into formal CLCA) and repeat step 5.

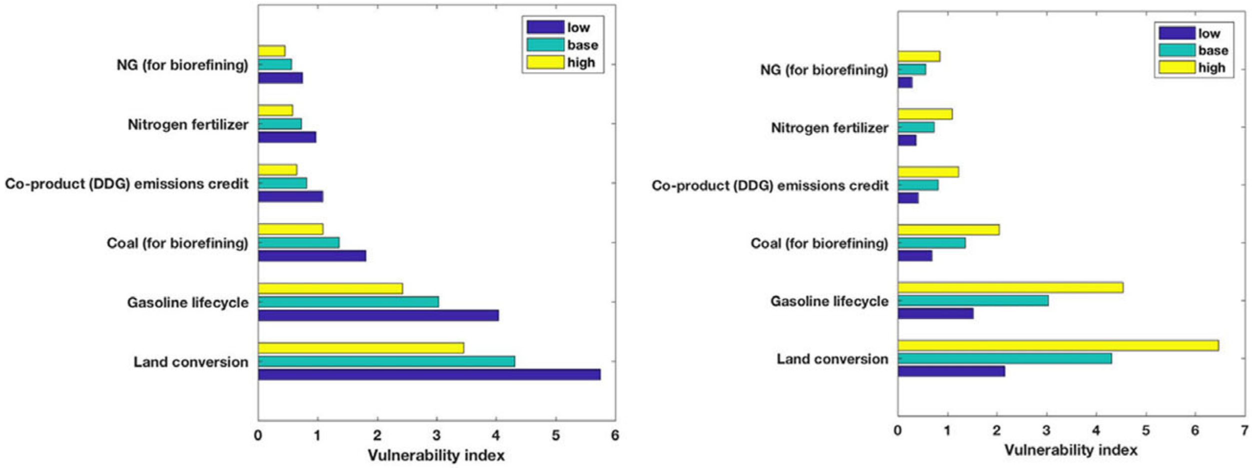
Discussion

A CLCA has two basic features. One is the use of marginal emissions factors as opposed to average emissions factors. The second is that in addition to a product's own life cycle emissions, it would account for emissions (or emissions reductions) arising from the effect of a product's wider adoption on prices and consumption of commodities economywide. While an ALCA might be undertaken with marginal emissions factors, the second feature is salient to CLCA. However, since, in theory, price effects could manifest in each and every distinct economic sector, and potentially, on a global scale, defining the system boundary for CLCA is challenging. To reiterate, there still do not exist any general principles or procedures for system boundary definition for CLCA.

To this end, a simple new index of vulnerability to market-mediated emissions has been introduced. This index can be used to infer which among the activities connected to the life cycle of a new product might be a source of vulnerability in terms of additional pollution. Its utility was illustrated through an application to biofuels, specifically corn ethanol. The usefulness of this heuristic is independent of the type of modeling framework (multimarket partial equilibrium, computable general equilibrium, or any other) that might be employed for a formal CLCA. It is worth emphasizing that what is presented here is a practical, but not theoretically foolproof, measure and is best understood as a heuristic. Application to other products and services will help further refine this heuristic approach.

a) Sensitivity with respect to elasticity ratio

b) Sensitivity with respect to marginal emissions intensity



c) Sensitivity with respect to Input-to-output coeff.

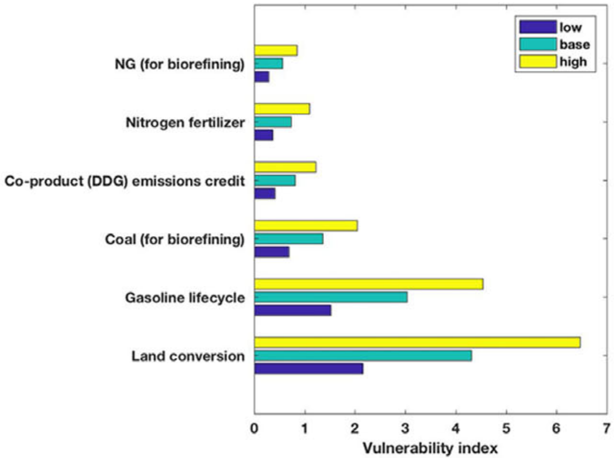


Figure 5 Sensitivity analysis of the vulnerability index. For each of several activities listed in table 1, three parameters are given, indicating sensitivity with respect to: (a) ratio of price elasticity of demand to supply; (b) marginal emissions intensity; and (c) input per unit output. Price elasticity was first increased (yellow bars) and then decreased (blue bars) by 50% relative to its base value (green bars), while holding the other two parameters fixed at their base values, which is listed in table S1 in the supporting information on the Web. The sensitivity charts for marginal emissions intensity (subfigure (b)) and input-to-output coefficient (panel (c)) are identical, as one would expect from the expression for the Vulnerability index (see equations 8 and 9). DDG = dry distillers grains; NG = natural gas.

Among the four different parameters that constitute the vulnerability index two parameters—input per unit output and marginal emissions per unit output are physical-technical in nature, while the other remaining two—the price elasticity of supply and demand for a commodity are behavioral-economic in nature. Furthermore, effective use of the vulnerability index relies on ALCA to provide a detailed LCI for the main product in question as well as its substitutes. In this way, the vulnerability index approach also bridges ALCA and CLCA.

Acknowledgments

The author is grateful to three anonymous referees whose comments helped substantially improve the clarity of the paper. The author is also grateful to Richard Plevin and Mark Delucchi for their insights and suggestions.

Notes

1. The term innovation is used broadly to refer to, and interchangeably with, a commodity (e.g., ethanol), consumer good (e.g., electric vehicle), an activity (such as ride-hailing), or a service (e.g., air-conditioning).
2. There might result other behavioral responses, which are independent of price effects and that these could have substantial environment implications relative to impacts via the life cycle channel. This is beyond the scope of this work.
3. There are other approaches that do not fall strictly under the rubric of CLCA, but are also aimed at addressing limitations of traditional

LCA such as scenario analysis (Guinee et al. 2010) and integrated modeling systems and scenario analysis (Delucchi 2011), to name a few.

4. The quantities produced and quantities consumed are used interchangeably here because their distinction is not central to the discussion here. Therefore, the term mandate can be interpreted as a production or consumption mandate. However, they need to be differentiated in the context of international or inter-regional trade. Alternatively, they need to be distinguished in an intertemporal context when there is a market for storage.
5. In principle, the LCA may be carried out using input-output ratios and emissions intensity associated for the average industry output or the marginal facility producing commodity *i*.
6. The importance of the phrase "functionally equivalent unit of substitute" is worth reiterating. Only then is equation (2) meaningful. Alternatively, if equation (1) is not set up in terms of functional equivalents, equation (2) needs modification. For instance, when comparing corn ethanol and gasoline, if *Q* refers to gallons of ethanol, then functional equivalent unit if gasoline is two thirds of a gallon of gasoline. Alternatively, *Q* could be measured in gallons of gasoline equivalent in which case the functional equivalent unit if gasoline is simply a gallon of gasoline. A third intuitive option is to denote *Q* in megajoules of ethanol in which case the functional equivalent unit is a megajoule from gasoline.
7. An ALCA could, in principle, use emissions factors for either the average or the marginal facility producing a given good, although typically it is the former that is used. If the latter is the case, then one would need to collect data on marginal emissions intensities for the vulnerability index. Using average emissions intensities is less meaningful for vulnerability index.
8. For a discussion of various types of uncertainty relevant to LCA, see Huijbregts (1998a, 1998b).
9. This functional unit requires that there is no significant difference in the efficiency of combustion of a megajoule contained in the two different fuels, which is not an unreasonable assumption.
10. This value is a simple mean of the emissions factors used in the California LCFS regulation for land conversion from forestry to annual crops across the 18 different agro-ecological zones into which global land cover is divided (see Plevin et al. 2014).
11. The explanation for the choice of –1 for the ratio of elasticity of demand to supply is as follows. Although, in theory, the absolute value of price elasticity has a range $[0, \infty)$, the empirically observed range is much narrower across a wide range of commodities. In the short run or over small time horizons, the price elasticity of supply and demand for any commodity or activity tends to be close to zero and typically less than 0.5. Over longer time horizons of, say, 5 years or more, price elasticity of supply and demand both tend to be larger. But since the vulnerability index is a function only of the ratio of these two parameters, it tends to vary over a much narrower range. Please refer table S2 in the supporting information on the Web, which lists econometric estimates of own price elasticity of demand and supply for select major commodities reported in the literature, which suggests that range of variability across the different inputs is plausibly within 1 order of magnitude. From a search of the literature, it appears that econometric estimates of elasticity are relatively more easily found for certain commodities, such as gasoline, electricity, and major food crops, but is harder to locate for others, such as land, fertilizers, and specific chemicals. Furthermore, empirical estimates of price elasticity of demand for commodities by households (electricity, gasoline, and food) is available relatively more easily when compared to price elasticity of supply.
12. When there is more than one substitute to the main good, there exist a few possibilities. One is to compute an LCI market-share–weighted average of the LCI of each substitute. Another possibility is to identify one product or process as the marginal output and do the comparison of M relative to this product. Yet another option is to repeat the algorithm for each pair of M and S.

References

Anex, R. and R. Lifset. 2014. Life cycle assessment. *Journal of Industrial Ecology* 18(3): 321–323.

Curran, M. C. 2006. *Life cycle assessment: Principles and practice*. Technical report number: EPA/600/R-06/060. Milford, OH, USA: National Risk Management Research Laboratory, U.S. Environmental Protection Agency.

Curran, M. C. 2013. Life cycle assessment: A review of the methodology and its application to sustainability. *Current Opinion in Chemical Engineering* 2(3): 273–277.

Delucchi, M. A. 2011. Beyond lifecycle analysis: Developing a better tool for simulating policy impacts. In *Sustainable transportation energy pathways: A research summary for decision makers*, edited by J. Ogden and L. Anderson, 278–295. Davis, CA, USA: Institute of Transportation Studies, University of California, Davis.

Ekvall, T. and B. P. Weidema. 2004. System boundaries and input data in consequential life cycle inventory analysis. *The International Journal of Life Cycle Assessment* 9(3): 161–171.

Fargione, J., J. Hill, D. Tilman, S. Polasky, and P. Hawthorne. 2008. Land clearing and the biofuel carbon debt. *Science* 319(5867): 1235–1238.

Farrell, A. E., R. J. Plevin, B. T. Turner, A. D. Jones, M. O'Hare, and D. M. Kammen. 2006. Ethanol can contribute to energy and environmental goals. *Science* 311(5760): 506–508.

Finnveden, G., M. Z. Hauschild, T. Ekvall, J. Guinee, R. Heijungs, S. Hellweg, A. Koehler, D. Pennington, and S. Suh. 2009. Recent developments in life cycle assessment. *Journal of Environmental Management* 91(1): 1–21.

Gibbs, H. K., M. Johnston, J. A. Foley, T. Holloway, C. Monfreda, N. Ramankutty, and D. Zaks. 2008. Carbon payback times for crop-based biofuel expansion in the tropics: The effects of changing yield and technology. *Environmental Research Letters* 3(3): 034001.

Guinee, J. B., R. Heijungs, G. Huppes, A. Zamagni, P. Masoni, R. Buonamici, T. Ekvall, and T. Rydberg. 2010. Life cycle assessment: Past, present, and future. *Environmental Science & Technology* 45(1): 90–96.

Hertwich, E. 2014. Understanding the climate mitigation benefits of product systems: Comment on using attributional life cycle assessment to estimate climate-change mitigation. *Journal of Industrial Ecology* 18(3): 464–465.

Hill, J., S. Polasky, E. Nelson, D. Tilman, H. Huo, L. Ludwig, J. Neumann, H. Zheng, and D. Bonta. 2009. Climate change and health costs of air emissions from biofuels and gasoline. *Proceedings of the National Academy of Sciences of the United States of America* 106(6): 2077–2082.

Huijbregts, M. A. J. 1998a. A general framework for the analysis of uncertainty and variability in life cycle assessment. *The International Journal of Life Cycle Assessment* 3(5): 273–280.

Huijbregts, M. A. J. 1998b. Dealing with parameter uncertainty and uncertainty due to choices in life cycle assessment. *The International Journal of Life Cycle Assessment* 3(6): 343–351.

Huijbregts, M. A. J., G. Norris, R. Bretz, A. Ciroth, B. Maurice, B. von Bahr, B. Weidema, and A. S. H. de Beaufort. 2001. Framework for modelling data uncertainty in life cycle inventories. *The International Journal of Life Cycle Assessment* 6(3): 127–132.

Kim, H., S. Kim, and B. E. Dale. 2009. Biofuels, land use change, and greenhouse gas emissions: Some unexplored variables. *Environmental Science & Technology* 43(3): 961–967.

Khanna, M. and D. Zilberman. 2012. Modeling the land-use and greenhouse-gas implications of biofuels. *Climate Change Economics* 3(03): 1250016.

MacLean, H. L. and L. B Lave. 2003. Life cycle assessment of automobile/fuel options. *Environmental Science & Technology* 37(23): 5445–5452.

Matthews, H. S., C. T., Hendrickson, and D. Matthews. 2016. *Life cycle assessment: Quantitative approaches for decisions that matter*. www.lcatextbook.com. Accessed 23 October 2017.

Miller, S. A., A. E. Landis, and T. L. Theis. 2007. Environmental tradeoffs of biobased production. *Environmental Science & Technology* 41(15): 5176–5182.

Morgan, G. M., M. Henrion, and M. Small. 1990. *Uncertainty: A guide to dealing with uncertainty in quantitative risk and policy analysis*. Cambridge, UK; New York: Cambridge University Press.

Nassar, A. M., L. Harfuch, L. C. Bachion, and M. R. Moreira. 2011. Biofuels and land-use changes: Searching for the top model. *Interface Focus* 1(2): 224–232.

Plevin, R. J., H. K. Gibbs, J. Duffy, S. Yui, and S. Yeh. 2014. *Agro-ecological zone emission factor (AEZ-EF) model*. Technical report. Sacramento, CA, USA: California Air Resources Board.

Rajagopal, D. 2014. Consequential life cycle assessment of policy vulnerability to price effects. *Journal of Industrial Ecology* 18(2): 164–175.

Rajagopal, D. 2017. A step towards a general framework for consequential life cycle assessment. *Journal of Industrial Ecology* 21(2): 261–271.

Saltelli, M. R., T. Andres, F. Campolongo, J. Cariboni, D. Gatelli, M. Saisana, and S. Tarantola. 2008. *Global sensitivity analysis: The primer*. Chichester, UK; Hoboken, NJ, USA: John Wiley.

Scrieciu, S. S. 2007. The inherent dangers of using computable general equilibrium models as a single integrated modelling framework for sustainability impact assess-ment. A critical note on Bohringer and Loschel (2006). *Ecological Economics* 60(4): 678–684.

Spatari, S., Y. M. Zhang, and H. L. MacLean. 2005. Life cycle assessment of switchgrass- and corn stover-derived ethanol-fueled automobiles. *Environmental Science & Technology* 39(24): 9750–9758.

Suh, S. and Y. Yang. 2014. On the uncanny capabilities of consequential LCA. *The International Journal of Life Cycle Assessment* 19(6): 1179–1184.

Zamagni, A., J. Guinee, R. Heijungs, P. Masoni, and A. Raggi. 2012. Lights and shadows in consequential LCA. *The International Journal of Life Cycle Assessment* 17(7): 904–918.

Supporting Information

Supporting information is linked to this article on the *JIE* website:

Supporting Information S1: This supporting information includes the derivation of the effect of a demand shock to a commodity on the equilibrium price and consumption of that commodity in a single market partial-equilibrium context, base case vulnerability for various activities, and representative econometric estimates of own price elasticity of demand and supply for select major commodities in the short-run and long-run as report in the literature.