A MARKET-BASED FRAMEWORK FOR QUANTIFYING DISPLACED PRODUCTION FROM RECYCLING OR REUSE

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ABSTRACT

The most significant environmental benefit of recycling or reusing a wide range of products and materials is typically the potential to displace primary material production; lack of displacement significantly reduces the environmental benefits of these activities. As no consensus method to estimate displacement rate has emerged, environmental assessments have tended to assume displacement occurs on a one-to-one basis. However, displaced production is a complex phenomenon governed primarily by market mechanisms rather than physical relationships. This paper advances the understanding of displacement by presenting a market-based framework describing the displacement relationship and a methodology for quantifying displacement rate based on partial equilibrium modeling. Using this methodology, a general symbolic equation for displacement rate following an increase in recycling is derived. The model highlights the market mechanisms that govern displaced production and identifies five price response parameters that affect displacement rate. Results suggest that one-to-one displacement occurs only under specific parameter restrictions that are unlikely in competitive commodity markets, but zero displacement is possible if secondary materials are poor substitutes for primary materials; displacement is likely to be reduced if secondary materials have inferior technical properties. The presented methodology can be generally applied to any system in which recycled or reused materials are substitutes or complements for primary materials. Implications for improving recycling and reuse efficacy and environmental assessment methodology are discussed, and suggestions are presented for expanding the displacement methodology in future research.

KEYWORDS

Displaced production; avoided burden; life cycle assessment; recycling; partial equilibrium analysis

INTRODUCTION

At the heart of the industrial ecology metaphor is the idea of closing material loops, with the reuse and recycling of end-of-life materials being a central aspect of this concept. Despite the prominence of reuse and recycling in environmental research over the past decades, properly accounting for the benefits of these activities in quantitative environmental assessments remains a significant obstacle (Johnson, McMillan, & Keoleian, 2013). One popular methodology in Life Cycle Assessment (LCA), called the 'avoided burden method,' is to credit a product system that includes recycling or reuse with the avoided, or 'displaced,' production of comparable primary materials (Guinée et al., 2002; Weidema, 2000). The assumption underlying this approach is that secondary material from increased recycling or reuse displaces equivalent primary production, which often has larger impacts. The avoided burden method is illustrated in Figure 1.

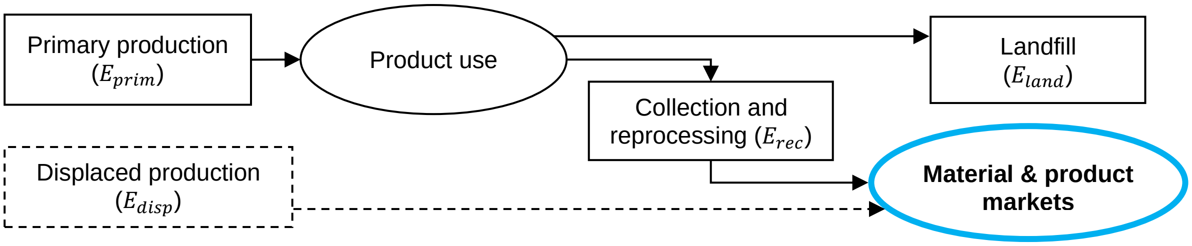

Figure 1: Life cycle impacts of a generic recycled product under the avoided burden method

In this system, a product is produced from virgin materials, which creates environmental impacts E_{prim}. After the product is used, the material is either landfilled or reprocessed. Reprocessing requires energy and material inputs, creating environmental impacts E_{rec}. Although the possibility of avoiding landfill potentially creates some benefits, the most significant environmental benefit of reuse or recycling is typically the potential to prevent the production of equivalent primary materials. Under the avoided burden method, life cycle impacts for the product are calculated by summing the incurred impacts and subtracting the avoided impacts (without loss of generality, in the present discussion we ignore landfill impacts; see the section SI-1 of the online Supplemental Information):

$$E_{net} = E_{prim} + E_{rec} - E_{disp} \tag{1}$$

If the impacts of primary production are larger than the impacts of secondary processing (as is the case with nearly all highly recycled materials), recycling or reuse result in environmental benefit.

An exceedingly common assumption in environmental assessments is that primary materials are displaced by secondary materials on a one-to-one basis (e.g., Atherton, 2007). However, the extent to which this displacement actually occurs, if at all, is not a given. Assuming one-to-one, or 'full' displacement is only valid if "the demand for [the good] is not changed and that increased recycling does not affect recycling in other parts of the system" (Merrild, Damgaard, & Christensen, 2008, p. 2). In reality, displacement may not occur or may be incomplete. Displaced production is primarily governed by market mechanisms (McMillan, Skerlos, & Keoleian, 2012)—the interactions of economic agents in the materials and product markets shown in Figure 1. Increasing recycling or reuse can influence prices of both primary and secondary material, affecting overall material demand and therefore displacement rate. Depending on these complex market effects, secondary products and materials may displace primary production of a different kind, or may simply lower overall prices, increase aggregate demand and displace less material than is recycled, leading to incomplete displacement (Ekvall, 2000). It has also been suggested that some secondary goods may actually be complements for primary goods (Thomas, 2003)—that is, sales of used goods may actually increase sales of new goods—leading to negative displacement.

The effect of incomplete displacement can be modeled by including a term d, for displacement rate, in the calculation of net environmental impact in eq. (1):

$$E_{net} = E_{prim} + E_{rec} - d \cdot E_{disp} \tag{2}$$

where d is defined as the change in primary production quantity (ΔQ_p) caused by a change in secondary production quantity (ΔQ_s), multiplied by -1 so that d is positive under the expected outcome that Q_p decreases in response to an increase in Q_s:[1]

$$d = \frac{-\Delta Q_p}{\Delta Q_s} \tag{3}$$

If $d = 1$ (the full displacement assumption) the result is the same as shown in eq. (1). However, if $d < 1$, the benefits of reuse or recycling are diminished.

Although the reality of incomplete displacement has been recognized in the literature (Ekvall, 2000; Frees, 2007; Johnson et al., 2013; McMillan et al., 2012; Thomas, 2003; Weidema, 2003), a complete understanding of the drivers of displacement and a methodology for accurately estimating displacement rate is lacking. Because no method for estimating displacement rate exists, environmental assessments have typically rested on the "inaccurate assumption" (Ekvall, 2000) of one-to-one, or full displacement (Thomas, 2003). In some cases heuristics have been used, such as assuming 0% or 50% displacement (Ekvall & Weidema, 2004; Klöpffer, 1996).

Yet, it has been shown that the displacement rate parameter is extremely important: Different assumptions about displacement rate can frequently reverse the results or preference

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[1] Q_{sec} refers to the quantity of material leaving the reprocessing stage and entering the material market after accounting for recycling rate and yield loss. In this discussion we are primarily concerned with economic drivers of displacement; physical factors such as collection rates and recycling yields have received thorough treatment elsewhere (Davis et al., 2007; Geyer & Jackson, 2004; Kuczenski, Geyer, Zink, & Henderson, 2014; Kuczenski & Geyer, 2010, 2012). See the Supplemental Information (section SI-2) for further discussion on the difference between recycling rate, recycling yield, and displacement rate.

order of an environmental assessment (Geyer & Doctori Blass, 2009; Heijungs & Guinée, 2007; Zink, Maker, Geyer, Amirtharajah, & Akella, 2014). Thus, developing a robust methodology for estimating displacement rate so that we can move beyond assumptions and heuristics is of prime importance to LCA and industrial ecology in general.

Therefore, it is the goal of this paper to improve the understanding of displaced production by exploring the underlying market mechanisms and developing a general methodology for estimating displacement rate following an increase in recycling. With that goal in mind, and in order to maximize expositional clarity, we use a model that is as simple as possible. To use the presented modeling methodology to estimate displacement in an actual materials market, one would need to incorporate several layers of additional complexity, which we address in the discussion. A companion article demonstrates the application of this modeling methodology, including these additional layers of complexity, with a case study of aluminum recycling (Zink, Geyer, & Startz, 2015). This case study will be referred to several times in this article as ‘the companion piece’ or the ‘aluminum case study’.

The remainder of the paper is organized as follows: Next, we develop the basic market modeling methodology using partial equilibrium modeling and system dynamics. Then, we use the model to reveal the determinants of displacement rate and derive the conditions for zero and full displacement. Finally, we discuss general lessons for improving recycling and reuse efficacy, improving environmental assessment methodology, limitations of the model, and directions for future research. Additional explanatory information is included in the online Supplemental Information (SI).

METHOD

Basic modeling approach

We model market interactions using partial equilibrium analysis (PEA). Following standard approaches used by authors in microeconomics and industrial organization (Blomberg & Hellmer, 2000; Fisher, Cootner, & Baily, 1972; Foley & Clark, 1981; Gilbert, 1995; Gomez, Guzman, & Tilton, 2007; Hojman, 1981; Slade, 1980; US EPA, 1998) we employ PEA to describe market interactions of producers and consumers of primary and secondary material. We make typical assumptions of a reasonably competitive market, including that suppliers are price-takers who choose production levels based on selling prices, and buyers are downstream producers or final goods consumers who choose consumption quantities of all goods based on prices. Buyers can choose between their usual material or substitute materials based on relative prices, technical substitution constraints, and preferences. These assumptions are typical of econometric market models (Blomberg & Hellmer, 2000; Blomberg & Söderholm, 2009; Gilbert, 1995; Slade, 1980), yet there may exist certain markets with strong oligopolistic behavior for which they do not hold.

In PEA, markets are modeled using structural equations describing the behavior of economic agents. We use a basic market model for substitutable primary and secondary materials, described by the following system of simultaneous equations:

$$\begin{aligned}
S_{sec} &= \alpha_1 P_{sec} + \alpha_0 \\
S_{prim} &= \beta_1 P_{prim} \\
D_{sec} &= \gamma_1 P_{sec} + \gamma_2 (P_{prim} - P_{sec}) \\
D_{prim} &= \lambda_1 P_{prim} + \lambda_2 (P_{sec} - P_{prim}) \\
S_{sec} &\equiv D_{sec} \\
S_{prim} &\equiv D_{prim}
\end{aligned} \tag{4}$$

where S_i, D_i, and P_i represent the supply, demand, and price of material i, respectively. The first four equations are linked through shared price variables and therefore react simultaneously to a perturbation introduced to any of them. The last two equations state that in market-clearing equilibrium, supply of each material is equal to demand. The coefficients on the price variables represent the sensitivity of the left-hand side variable to changes in prices.[2] We refer to α_1, β_1, λ_1, and γ_1 as own-price responses and to λ_2 and γ_2 as cross-price responses. The cross-price responses reflect buyers' ability and willingness to switch from their usual material to the competing material as a function of the price differential between the two materials.[3] The cross-price responses reflect a variety of information about the substitutability of the two materials, including metallurgical properties such as strength, purity, etc. Economic theory predicts that α_1 and β_1 should be positive and that λ_1 and γ_1 should be negative. If the two goods are substitutes, we expect λ_2 and γ_2 to be positive; however, relaxing this requirement also leads to interesting results, which we will discuss later. The coefficient α_0 is an intercept on secondary supply, which will be manipulated to shock the system, in this case simulating an increase in recycling.

LCA and other environmental assessments of recycling assume that increases in secondary supply and demand have equal-sized but opposite effects. This assumption can be

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[2] For a step-by-step development of a market model such as this, see Blomberg and Hellmer (2000) and Blomberg (2007).

[3] Another way to model cross-price responses would be to use the absolute price of the competing material instead of the price differential between the two materials. Results for this specification are shown in the SI (section SI-4); the results are qualitatively unchanged under either specification.

tested theoretically by moving α_0 to the secondary demand equation and comparing a secondary demand shock with a secondary supply shock. Such a comparison is out of scope for this initial exposition of the market-based framework shown in eq. 4 and has to be left for future research.

Market dynamics: Understanding price responses

The simultaneous equations in eq. (4) do not necessarily provide an intuition for causality or interconnections in the system. The methodology of system dynamics, which is an approach for understanding the behavior of complex systems such as markets (Morecroft, 2007), can be useful to develop this intuition.

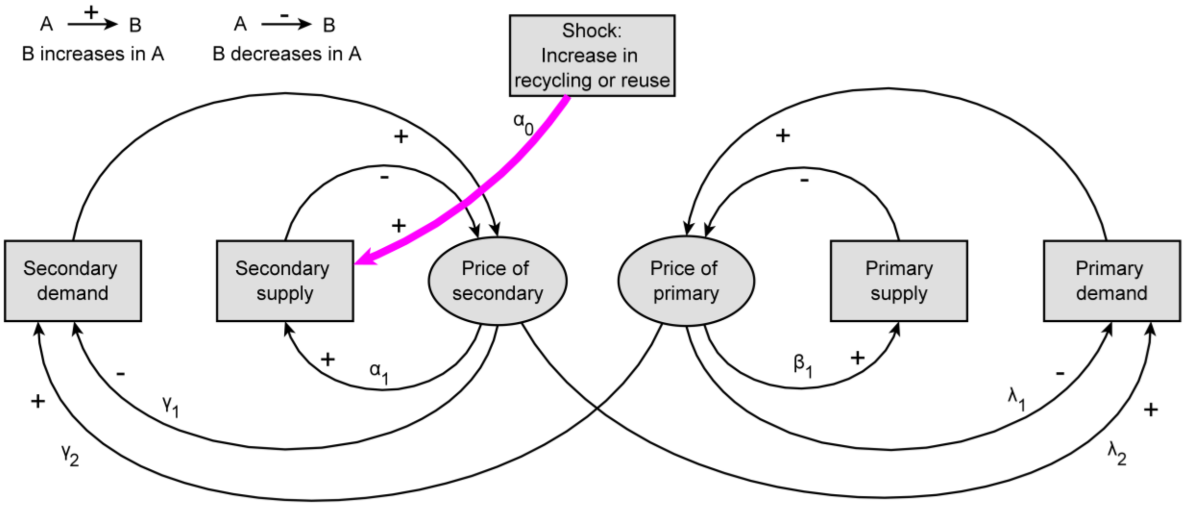

Figure 2: System dynamics diagram showing the flow of causality through the market model. Signs next to each arrow indicate whether the direction of the relationship is positive (+) or negative (-).

Figure 2 is a system dynamics representation of the PEA model in eq. (4). Boxes represent physical processes; ovals represent information; arrows represent causal relationships, where the positive or negative sign on the arrow indicates whether the relationship is positive or negative. The entire system adjusts simultaneously and, before any intervention, is assumed to be at equilibrium (i.e., all arrows initially have a magnitude of zero).

Our approach to estimating displacement is to simulate a shock to secondary supply, which is designed to model the avoided burden approach, shown in Figure 2 with a bold arrow. Following the effects of this shock through the system provides a qualitative understanding of how the components are interconnected. For a step-by-step walkthrough of the figure, see the SI (section SI-3).

Figure 2 highlights that the model is entirely driven by price changes and responses to these changes. The logic behind the price effects is simple, and is in fact intuitive when placed in the context of more familiar goods. For instance, consider two standard substitute goods, sausages and hamburgers. If a government subsidy were to increase pig production, we would expect sausage prices to fall. In response, people would tend to shift their consumption from hamburgers to sausages, causing hamburger prices to fall. This, correspondingly, would induce more hamburger consumption. When this simple system finally came to a new equilibrium, we should not be surprised to find that the increase in sausage consumption was not exactly offset by an equivalent decrease in hamburger consumption—it could be that lowered prices for *both* goods may have increased *overall* consumption.

Of course, the human stomach can only hold so many sausages and hamburgers, so demand is somewhat fixed. In the context of industrial goods, the expectation that changes in production of substitute goods will not exactly offset one another ought to be even stronger, since these goods have many possible uses and are therefore not subject to demand constraints. In our model, an outside shock (analogous to the pig subsidy) artificially increases supply of secondary materials, inducing the same kind of sausage-hamburger price changes to occur with primary and secondary material. In this context, just as with sausages and hamburgers, displacement less than 100% occurs when increased secondary supply decreases prices of *both* materials such that *overall* demand and supply increase.

Supply shock experiment

The model presented in eq. (4) exists in equilibrium until an exogenous shock is introduced. Since the system of equations is simultaneous, a shock to one exogenous variable will affect the entire system. To see this explicitly, eq. (5) shows the system solved to the reduced form, in which each endogenous variable is expressed as a function of the exogenous variables:

$$\begin{aligned}
P_{prim} &= \frac{\alpha_0\lambda_2}{-\alpha_1\beta_1+\beta_1\gamma_1-\beta_1\gamma_2+\alpha_1\lambda_1-\alpha_1\lambda_2-\gamma_1\lambda_1+\gamma_1\lambda_2+\gamma_2\lambda_1} \\
P_{sec} &= \frac{\alpha_0(\beta_1-\lambda_1+\lambda_2)}{-\alpha_1\beta_1+\beta_1\gamma_1-\beta_1\gamma_2+\alpha_1\lambda_1-\alpha_1\lambda_2-\gamma_1\lambda_1+\gamma_1\lambda_2+\gamma_2\lambda_1} \\
S_{prim} = D_{prim} &= \frac{\alpha_0\beta_1\lambda_2}{-\alpha_1\beta_1+\beta_1\gamma_1-\beta_1\gamma_2+\alpha_1\lambda_1-\alpha_1\lambda_2-\gamma_1\lambda_1+\gamma_1\lambda_2+\gamma_2\lambda_1} \\
S_{sec} = D_{sec} &= \frac{\alpha_0(\beta_1\gamma_1-\beta_1\gamma_2-\gamma_1\lambda_1+\gamma_1\lambda_2+\gamma_2\lambda_1)}{-\alpha_1\beta_1+\beta_1\gamma_1-\beta_1\gamma_2+\alpha_1\lambda_1-\alpha_1\lambda_2-\gamma_1\lambda_1+\gamma_1\lambda_2+\gamma_2\lambda_1}
\end{aligned} \tag{5}$$

From eq. (5) it can be seen that the equilibrium price and quantity of both materials are a function of all the price response coefficients and the secondary supply intercept, α_0. The extent to which each endogenous variable is affected by a change in α_0 is determined by the functional form and the values of the coefficients.[4] Thus, displacement can be measured by introducing a shock to the supply intercept and observing how both primary and secondary supply are affected. Specifically, following a shock, displacement can be calculated by first computing the difference between supply of each material before and after the shock, and then by taking the ratio of the change in primary supply to the change in secondary supply, in accordance with eq. (3). For

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[4] The ability of the model to produce reliable results rests on the accuracy of both of these aspects. For this reason we have made the basic model as simple and general as possible; the model presented assumes only linearity and fundamental economic theories of supply and demand. For discussion of how the results differ when using log-log form or an alternate cross-price response specification, see the SI (sections SI-4 and SI-5).

instance, suppose we introduce a shock to α_0 in eq. (5), and label the ‘before’ intercept α_{0B} and the ‘after’ intercept α_{0A}. We can then compute d by dividing the difference between primary supply before and after the shock by the difference in secondary supply before and after the shock, as shown in eq. (6):

$$\begin{aligned}
\Delta S_p = \Delta D_p &= \frac{(\alpha_{0A} - \alpha_{0B})\beta_1\lambda_2}{-\alpha_1\beta_1 + \beta_1\gamma_1 - \beta_1\gamma_2 + \alpha_1\lambda_1 - \alpha_1\lambda_2 - \gamma_1\lambda_1 + \gamma_1\lambda_2 + \gamma_2\lambda_1} \\
\Delta S_s = \Delta D_s &= \frac{(\alpha_{0\mathrm{A}} - \alpha_{0B})(\beta_1\gamma_1 - \beta_1\gamma_2 - \gamma_1\lambda_1 + \gamma_1\lambda_2 + \gamma_2\lambda_1)}{-\alpha_1\beta_1 + \beta_1\gamma_1 - \beta_1\gamma_2 + \alpha_1\lambda_1 - \alpha_1\lambda_2 - \gamma_1\lambda_1 + \gamma_1\lambda_2 + \gamma_2\lambda_1} \\
d = \frac{-\Delta S_p}{\Delta S_s} &= \frac{-(\alpha_{0\mathrm{A}} - \alpha_{0B})\beta_1\lambda_2}{(\alpha_{0\mathrm{A}} - \alpha_{0B})(\beta_1\gamma_1 - \beta_1\gamma_2 - \gamma_1\lambda_1 + \gamma_1\lambda_2 + \gamma_2\lambda_1)} \\
d &= \frac{-\beta_1\lambda_2}{\beta_1\gamma_1 - \beta_1\gamma_2 - \gamma_1\lambda_1 + \gamma_1\lambda_2 + \gamma_2\lambda_1} \qquad (6)
\end{aligned}$$

Eq. (6) calculates the displacement rate caused by an increase in secondary material supply as a function of the relevant price responses and market structure shown in eq. (4). For a demand-side shock, the constant α_0 would appear in the secondary demand equation in (4). It turns out that the model would solve to different reduced-form equations in (5), and therefore the final equation for displacement would also be different in (6). To fully explore the differences between a secondary supply-shock and demand-shock (as well as shocks to primary supply and demand) is worthwhile, but out of scope for this initial methodological exposition.

To obtain an actual estimate of the displacement rate following an increase in recycling for a specific product system, one would simply need to populate the price responses in eq. (6) with appropriate values; the aforementioned companion piece to this article demonstrates this process in the context of U.S. aluminum recycling (Zink et al., 2015).

RESULTS AND DISCUSSION

Although the basic model is simplified compared to a full market model, it is useful because it is simple enough to be solved symbolically. This allows us to see the general structure and behavior of the model without introducing complexities and uncertainties associated with parameter estimation or nonlinearity. The basic market model results in a symbolic equation for displacement, which leads to several results: The significant price response parameters and their direction of influence, the conditions necessary for zero displacement to occur, and the conditions for full displacement to occur.

Determinants of displacement

According to eq. (6), displacement due to an increase in secondary supply is determined by five price response parameters: The own-price response of primary supply (β_1), the own-price responses of demand for both materials (λ_1, γ_1) and cross-price responses of demand for both materials (λ_2, γ_2). Thus, accurately estimating these parameters is critical, and these response parameters should be the focus of future market models that seek to estimate displacement.

Taking the derivative of d with respect to each parameter reveals the direction of influence that each price response variable has on displacement, summarized in Table 1. It emerges that λ_1, γ_1, and γ_2 have an inverse relationship with displacement (in terms of absolute value) while the own-price response of primary supply (β_1) and the cross-price response of primary demand (λ_2), have a direct relationship with displacement. The net determination of displacement depends on the relative magnitudes of these competing forces. These general facts point to important general lessons for environmental assessment and environmental management, discussed later.

It also emerges that some parameters—the size of the secondary supply shock (α_0) and the own-price response of secondary suppliers (α_1)—do not effect displacement. They affect both primary and secondary supply proportionally and thus cancel out of the displacement equation.[5] Estimating price responses is non-trivial, so narrowing down the important variables is useful.

Variable	Description	Effect on displacement[a]
β_1	Own-price response of supply (primary)	Positive
λ_1	Own-price response of demand (primary)	Negative
λ_2	Cross-price response of demand (primary)	Positive
γ_1	Own-price response of demand (secondary)	Negative
γ_2	Cross-price response of demand (secondary)	Negative

[a] Indicates the relationship with d as the absolute value of the price response increases (i.e. is more elastic).

Table 1: Summary of how displacement following a secondary supply-side shock is affected by relevant price response variables

To explore the sensitivity of displacement rate to the five important parameters, we performed Monte Carlo simulation. To increase the realism of the simulation, we chose representative ranges of parameter values for the U.S. aluminum market. Specifically, we constructed normal distributions for each price response parameter from literature estimates of aluminum price responses, where available, and from our own aluminum model (detailed in the aforementioned companion article) for the cross-price responses, as no literature estimates exist. These cross-price responses in the companion piece were estimated using an aluminum industry model similar in structure to eq. (4), expanded to include temporal dynamics, imports and exports, and various control variables, and expressed in log-log form. This model was estimated using two-stage least squares with instrumental variables on data covering 1970-2012 from the U.S. Geological Survey (USGS), the U.S. Energy Administration, and the U.S. Census. These estimates therefore represent recent U.S. conditions.

The estimates from the literature and our aluminum model are in the form of elasticities; to use them in our linear model we back-transformed the elasticities into linear coefficients using 2012 aluminum price and production data from USGS. We constrained the parameter

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[5] Note that this finding relies on an assumption of linearity in the parameters that may not be valid for large magnitude shocks. Additionally, with a demand-side or other type of shock, a_1 does not necessarily cancel out. This result is valid only for secondary supply-side shocks.

distributions to the domain predicted by standard economic theory ($\beta_1 \geq 0$; $\lambda_1, \gamma_1 \leq 0$). For the initial results, we also assumed that the two goods were substitutes and therefore $\lambda_2, \gamma_2 > 0$, an assumption that we will relax and elaborate on shortly. Table 2 details the parameter estimates used for the simulation.

Parameter	Elasticity form (standard error)	Linear transformation (standard error)	Source
β_1	0.14 (1.84)	130 (1.59×10^6)	Gilbert (1995)
λ_1	-0.127 (2.78)	-118 (2.40×10^6)	Gilbert (1995)
γ_1	-0.34 (0.185)	-461 (3.40×10^6)	EPA (1998)
λ_2	0.269 (0.597)	231 (4.40×10^5)	Authors' aluminum model
γ_2	0.646 (0.844)	948 (1.82×10^6)	Authors' aluminum model

Table 2: Price responses used for the Monte Carlo simulation; distributions were constrained at zero (see text)

For each of 1 million simulations drawn from these distributions, the resulting displacement rate was calculated using eq. (6) and recorded. A histogram of the calculated displacement rates is shown in Figure 3. The analysis showed that coefficient uncertainty can have large impacts on calculated displacement, but the majority of displacement rates were concentrated around zero. Although the model can predict very large values for displacement when the denominator of eq. (6) approaches zero, the majority (60%) of the predicted displacement rates fell between zero and one. Less than 0.2% of the simulated displacement rates fell between 0.98 and 1.02, whereas 46% fell between zero and 0.02.

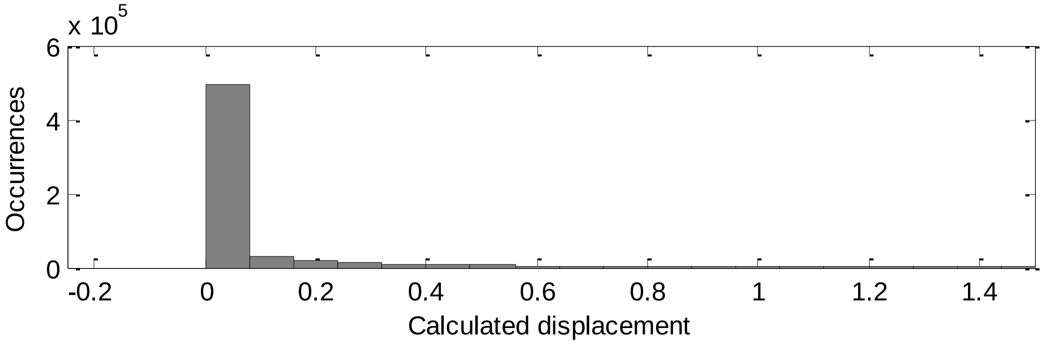

Figure 3: Histogram of Monte Carlo output (1 million iterations)

At this point we would like to highlight an interesting result, which is that the displacement results change depending on assumptions made about the domain of the cross-price responses λ_2 and γ_2. There are two theoretically reasonable domain restrictions: If the two goods are substitutes, the cross-price responses should be restricted to the positive domain—as the price of Good A rises, the demand for substitute Good B also rises; if they are complements, the cross-price responses should be restricted to the negative domain—as the price of Good A rises, the demand for complement Good B falls. Alternatively, if one is unsure whether the two goods are complements or substitutes, no domain restrictions should be placed on these parameters.

These different domain assumptions lead to different displacement results. If the goods are assumed to be substitutes (i.e. the cross-price responses are positive), the model predicts only positive displacement rates, and the Monte Carlo result is that shown in Figure 3. However, if the goods are assumed to be complements, the model predicts only negative displacement (i.e. an increase in recycling *increases* primary production), and the Monte Carlo result is roughly the mirror-image of Figure 3. If no domain restriction is placed on the cross-price responses, the model (unsurprisingly) predicts both positive and negative displacement rates in the Monte Carlo simulation (demonstrated and discussed in the Supplemental Information section SI-6).

Negative displacement has been theoretically predicted to occur. Thomas (2003) demonstrates that it is possible for a secondary good to be a complement for (i.e. increase demand for) a primary good. In these cases, we expect displacement to be negative.

Overall, the Monte Carlo simulation suggests that the model's predicted displacement rate is fairly sensitive to assumptions about the five parameters. Parameter distributions with tighter standard errors produce significantly less variation in displacement. Accurately estimating these parameters is therefore very important. When using this methodology with another product, one could conduct a similar Monte Carlo simulation using distributions around estimated price response values to determine the distribution of probable displacement rates.

Conditions for zero displacement

As stated, two commonly assumed values for displacement in the LCA literature are zero and one. In the case of an increase in secondary supply, the symbolic equation for displacement in eq. (6) enables us to evaluate the necessary conditions for each of these extremes and then assess the market conditions under which they are likely to hold.

Zero displacement occurs only when the numerator of eq. (6) is equal to zero and the denominator is not. The conditions for $d = 0$ are shown in eq. (7).

$$\begin{gathered} d = 0 \text{ if either} \\ \beta_1 = 0 \text{ and } \gamma_2\lambda_1 \neq \gamma_1(\lambda_1 + \lambda_2), \\ \text{or} \\ \lambda_2 = 0 \text{ and } (\beta_1 - \lambda_1)(\gamma_1 - \gamma_2) \neq 0 \end{gathered} \tag{7}$$

Thus, displacement is equal to zero when either the own-price response of primary supply (β_1) or the cross-price response of primary demand for secondary material (λ_2) is zero (and the denominator is not zero). To visualize why values of zero for these coefficients lead to zero displacement, refer again to Figure 2 and imagine a break in either the line from 'price of primary' to 'primary supply' (β_1) or the line from 'price of secondary' to 'primary demand' (λ_2).

If either of these pathways are broken (i.e. the corresponding coefficient is zero), changes in the secondary market will not loop back to affect primary supply, primary supply will not change in response to a change in secondary supply, and displacement will be equal to zero.

In terms of real-life markets where these conditions might exist, it is hard to imagine realistic cases in a competitive market where primary producers are completely unresponsive to selling prices (i.e. $\beta_1 = 0$). This condition may be possible for monopolies or in cases where production is intentionally decoupled from prices, such as in the provision of public services, but for commodity goods and materials in reasonably competitive markets, it is very likely that $\beta_1 > 0$.

However, the possibility that primary demand is insensitive to changes in the price of secondary material (i.e. $\lambda_2 = 0$) is more realistic and even likely in certain situations. The parameter λ_2 measures the willingness and ability of buyers of primary material to switch to secondary material. For many materials, these buyers are in fact intermediary producers who transform material inputs into semifabricated goods or final products. Therefore their willingness and ability to switch to secondary material may be limited by technical constraints or quality requirements. If the quality of secondary material is unsuitable for their needs it may be difficult or impossible to substitute, meaning that λ_2 will be close or equal to zero. Thus, real-life situations where displacement rate is equal to or near zero may arise from technical limitations on material substitutability.

Conditions for full displacement

On the other end of the spectrum from zero displacement, the displacement equation can be set equal to one, and conditions for full displacement derived, as shown in eq. (8). Unlike the conditions for $d = 0$, there is an infinite set of solutions that satisfy $d = 1$, which makes it more difficult to draw general conclusions about when full displacement is likely to occur. However, we can narrow the solution set by remembering that the domains of the price responses are bounded by economic theory: β_1 must be positive, while λ_1 and γ_1 must be negative. If we are willing to assume that the two good are substitutes, we can impose the additional constraint $\lambda_2, \gamma_2 > 0$. These bounds allow us to prove the second condition in eq. (8), that $\lambda_2 \geq \gamma_2$, which is demonstrated in the Supplemental Information (section SI-7).

$$\begin{gathered} d = 1 \text{ if and only if} \\ -\beta_1\lambda_2 = \beta_1\gamma_1 - \beta_1\gamma_2 - \gamma_1\lambda_1 + \gamma_1\lambda_2 + \gamma_2\lambda_1, \\ \text{and} \\ \lambda_2 \geq \gamma_2 \\ \text{and either} \\ (\beta_1 - \lambda_1)(\gamma_1 - \gamma_2) \neq 0 \\ \text{or} \\ \gamma_1\lambda_2 \neq 0 \end{gathered} \tag{8}$$

The second condition ($\lambda_2 \geq \gamma_2$) is the most problematic for real-world products or materials. This condition states that the cross-price response for users of primary material must be greater than or equal to the cross-price response for users of secondary material; in other words, buyers who commonly use primary material must be at least as willing to substitute for secondary material as buyers of secondary material are willing to substitute for primary material. For all highly recycled materials, the primary version of the material is of higher quality or purity than the secondary version, and is therefore more versatile. For example, primary aluminum can be used in both wrought and cast applications, but the higher silicon content in secondary aluminum limits its usefulness to mainly cast applications (McMillan et al., 2012). Because primary material is more versatile, it is a better substitute for secondary material than secondary material is for primary material. Thus, buyers of primary material will be less responsive to price changes of secondary material than buyers of secondary material are to price changes in primary material, violating the condition $\lambda_2 \geq \gamma_2$. Doubtless, there are special cases where this condition is met (one of which is discussed next). This condition also relies on the assumption that the cross-price responses are positive, so it does not hold for goods that are complements (however, as discussed above, goods that are complements result in negative displacement). In sum, the model suggests that unless one has particularly convincing reasons to believe that primary buyers are equally or more sensitive to secondary prices than vice versa, assuming full displacement is likely to overstate the benefits of reuse or recycling.

Nonetheless, one interesting case where all the conditions of eq. (8) will be met is when the cross-price responses of both materials are equal but not zero $(\lambda_2 = \gamma_2 \neq 0)$, both the own-price responses of demand are zero $(\lambda_1 = \gamma_1 = 0)$, and the own-price response of primary supply is not zero ($\beta_1 \neq 0$). In economic terms, this means that buyers of both types of material have exactly the same technical ability or preference to use the alternative material (i.e. they are indifferent between the two materials), that their willingness to switch is non-zero, that their level of consumption is completely unresponsive to changes in the price of their usual material, and that suppliers of primary material are responsive to price changes.

There are special cases where these conditions may hold. For instance, Zink et al. (2014) performed an LCA of repurposing a smartphone as an in-car parking meter. One of the questions addressed in this study was whether the repurposed phone prevents the production of a purpose-built parking meter. The authors argued that demand for in-car parking meters is fully satiable, since a person typically purchases only one in-car parking meter (meaning that the condition $\lambda_1 = \gamma_1 = 0$ will be true after the initial purchase). They further argue that consumers are roughly indifferent between a smartphone–parking meter and a purpose built model since both provide the same function and neither has any special features or ancillary benefits (meaning that

$\lambda_2 = \gamma_2 \neq 0$). For the last condition, producers of purpose-built parking meters presumably respond to changes in parking meter selling prices ($\beta_1 \neq 0$). Thus, this case represents a good candidate for a product system where full displacement occurs.

Nonetheless, these conditions are unrealistic for any standard good in any reasonably competitive commodity market. The second condition implies completely fixed demand with zero response to price changes, and the first condition implies complete indifference between material types (in the case of downstream producers, it means that the marginal costs of substitution of primary buyers and secondary buyers are identical—an unlikely scenario).

Model limitations and suggestions for further research

The model presented in this article was kept as simple as possible in order to illustrate how price responses affect displacement. We wish to address six simplifications that we made because they affect the generalization of the results to real-world situations. Some of these limitations we address in the aforementioned companion piece to this article in which we illustrate the methodology using a case study of aluminum recycling (Zink et al., 2015). Others we must leave to future research.

First, the market model used in this study, and therefore the displacement results, are entirely described by price responses. The focus on prices means the model may ignore non-market factors to the extent that they are not captured in price changes. This is a limitation common to any partial or general equilibrium-based model.

Second, the model presented is linear and static; that is, no time variables or lags are considered, and there is a constant relationship between changes in price responses and changes in displacement. The result of this simplification is that no distinction is made between short-term and long-term market behavior, and displacement is independent of the size of the modeled shock. It is possible that large shocks may affect displacement differently than relatively small ones, and economic theory suggests that long-run price responses are higher than short-run responses. Thus, this simplification may have important implications for calculated displacement. The model can easily be expanded to account for dynamic effects by making each of the supply and demand equations a function of lagged supply or demand. Including lags allows for the estimation and inclusion of long-term price responses. This approach is demonstrated in our aluminum case study. Including nonlinearity in the model may be a worthwhile endeavor for future research.

Third, this model does not account for supply and demand behavior in the scrap market (an input to secondary material production), including the possibility of scrap dealers holding stockpiles in response to price changes. The model could be expanded to include scrap market behavior; however the added complexity would complicate the exposition of the model and detract from the main point of this article, which is to illustrate the role of prices in determining displacement. Future modelers should consider endogenizing the scrap market. Along these same lines, we currently assume that the materials market clears instantly (by utilizing the identity $S_i = D_i$). This requirement could be relaxed to allow for stock-holding, imports, and exports, as we demonstrate in our aluminum case study.

Fourth, we illustrate the relationship between price responses and displacement only using a shock to secondary supply, which is meant to model the typical avoided burden approach in life cycle assessment. It has been shown that supply-side and demand-side price shocks can have different effects in some markets (Kilian, 2009), so these results may differ if other shocks are introduced. Our initial experimentation with other types of shocks indicate that the equation for displacement and the variables’ direction of influence do change for a demand-side shock;

the general advice for when full- or zero-displacement are appropriate may also change. Nonetheless, a particular strength of the presented model is that the shock variable could be moved to any of the other equations in the model to simulate other situations or policy options. For instance, the typical recycled content approach could be modeled by including a shock to secondary material demand and following the procedure described. Future work is needed to determine exactly how displacement differs following various shocks.

Fifth, we assume a relatively competitive market. The supply and demand equations we use can be derived from marginal cost and utility curves, respectively, and assume that buyers and sellers are price takers who choose levels of production and consumption based on prices. As discussed, this approach is common in econometric models. Nonetheless, for some industries there may be oligopolistic behavior on the part of buyers or sellers. The nature and extent of the oligopolistic behavior may limit the usefulness or validity of the presented model. Modifying this approach to account for monopoly, monopsony, or oligopoly behavior is worthwhile, but beyond the scope of this paper.

Lastly, this study has focused on displacement of primary material by secondary material *of like kind*. That is, in eq. (3) we constrain Q_p and Q_s to be the essentially the same type of material—virgin aluminum vs. recycled aluminum, PET vs. RPET, etc. However, like-kind displacement is not the only type of displacement that can occur as a result of reuse or recycling, and may not always be the most appropriate or interesting in an environmental assessment context. For instance, even if secondary aluminum displaces little primary aluminum in some applications, it may displace primary copper, steel, or plastics; even though RPET is unlikely to displace primary bottle-grade PET, RPET may still displace primary production of polypropylene, steel, wood, or asphalt. This type of displacement relationship is less common in life cycle assessments, but some examples do exist (e.g., Schmidt & Weidema, 2007), which typically assume full displacement of a different type of material.

Even though this study has focused on like-kind displacement, the demonstrated approach is equally applicable to cross-material displacement. Eq. (2) can be generalized to handle any combination of potentially-displaced materials as follows:

$$E_{net} = E_{prim} + E_{use} + E_{rec} - \sum_{\mathrm{i}} d_i E_{disp_i} \tag{9}$$

where E_{disp_i} is the per-unit impact of production for material i and d_i is the displacement rate for material i, where displacement rate is defined as the change in production quantity of material i caused by a change in secondary production of the studied material Q_s:

$$d_i = \frac{-\Delta Q_{p_i}}{\Delta Q_s} \tag{10}$$

Eqs. (9) and (10) are completely general in that not only can material i refer to primary production of any other potentially–displaced material, it can also refer to *secondary* production of another material. For instance, to account for the possibility that recycled aluminum might displace primary *and* recycled steel, each of these materials could be included in eq. 9 and individual displacement rates could be estimated for each material in eq. (10).[6] The main methodological difference in evaluating these other-material displacement relationships would be that the relevant cross-price responses would not be between primary and secondary material, but between the secondary material of interest and the competing material.

However, other-material displacement significantly complicates the environmental assessment: As discussed, recycling has the potential to create environmental benefit because most recycled materials have lower impacts than their primary production counterparts. In the

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[6] Additionally, eq. 9 need not be limited to production of a physical good; it could, for instance, refer to displacement of one technology by a newer one—displacement of fossil-based energy by renewables, for instance.

case of other-material displacement, there is no guarantee that the displaced primary material has higher production impacts than the recycled material since they are of different kind. For instance, if recycled aluminum were to displace primary *steel* at 100% displacement, the greenhouse gas (GHG) benefits would be about 1/5th as large as if it displaced primary aluminum at 100%; if it were to displace *recycled* steel, it would roughly *double* GHG impacts as compared to not recycling the aluminum at all (recycling steel creates about half the GHG impacts of recycling aluminum) (PE International, 2012).

In future research, a comprehensive investigation into multi-material displacement is required. To fully understand the environmental consequences of a reuse or recycling activity, we need to know not only *how much*, but also *what kind* of competing material is displaced. This paper has advanced the methodology on answering the first question; similarly robust, market-based methodologies are needed to answer the second. Furthermore, the six simplifications discussed were made to facilitate understanding of the role of prices in determining displacement. Each of them can and possibly should be relaxed in future work. We hope that this piece is but the first step in a developing line of research that explores the market effects of recycling systems and their implications for environmental impacts.

Additional work is also required to determine how exactly to account for partial displacement in environmental assessments in general and in consequential (CLCA) and attributional (ALCA) life cycle assessments. In CLCA, one issue is to determine which consequences of increased total supply are inside and which outside of the system boundaries. The equivalent question in ALCA is whether the functional unit should reflect the increased total supply or not, since one could argue that, with incomplete displacement, the total amount of service from the product system has increased.

CONCLUSIONS

The market model uncovered underlying mechanisms of displacement, highlighted the relevant price response parameters, and revealed the market conditions necessary for zero or full displacement. These results indicate that displacement of primary material by recycled material is unlikely to be 100% for many commonly recycled commodity materials, although zero displacement is possible and likely in certain situations. Together, the model and results highlight lessons for increasing displacement rate and for environmental assessment in general.

Lessons: Increasing displacement

Overall, these results should be troubling to environmentalists in general and to industrial ecologists in particular. Over the past four decades significant effort has been focused on increasing collection and recycling of a variety of materials, such as metals, glass, paper, and plastic. The results of this study suggest that recycling and reuse do not result in the environmental benefits previously assumed, and if displacement is low enough, these activities may actually *increase* overall environmental impacts.

Nevertheless, the solution is not to start landfilling recyclable materials. After all, in many cases even partial displacement can result in environmental benefit. For instance, based on the relative CO_2 intensity of primary and secondary aluminum production (PE International, 2012), the break-even displacement rate for aluminum is 5%.[7] This means that even if aluminum displacement is quite low, recycling aluminum still creates net benefit; as displacement increases, that benefit becomes substantial.

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[7] The ‘break-even displacement rate’ is the rate at which the net benefit of recycling is zero (Zink et al., 2014). The break-even rate can be calculated as the ratio of recycling impacts to displaced production impacts (E_{rec}/E_{disp}) in any impact category of interest. Displacement above this rate will ensure environmental benefit; displacement below this rate means recycling causes increased impacts.

Instead, therefore, the objective should be to maximize displacement by influencing the way secondary and primary materials interact in the market. For instance, all else equal, an increase in the cross-price response of primary demand for secondary material (λ_2) increases displacement rate. As discussed, cross-price demand response is a measure of buyers' ability to substitute between alternatives, so one way to increase this price response is to improve the technical substitutability of secondary material. Improving sorting, cleaning, and pre-processing of collected materials could significantly improve their quality. An increase in secondary material quality would increase primary producers' willingness to substitute for secondary material, thereby increasing displacement rate.

As discussed, Table 1 shows the direction of influence of other parameters on displacement rate, and other societal or governmental programs may be envisioned to affect one or more of these. One contribution of the market model presented here is to show which economic parameters determine displacement and their direction of influence in order to facilitate efforts to increase displacement.

Lessons: Environmental assessment

The demonstrated methodology and findings suggest a number of lessons for environmental assessment practitioners. First is that environmental analyses involving recycled or reused products *must* consider and take steps to quantify displacement. Assumptions about displacement can reverse the environmental preference order of alternatives; this study has shown that the full displacement assumption will likely lead to overstated benefits of reuse and recycling, and therefore possibly to suboptimal environmental choices. Reducing uncertainty of displacement by conducting market studies using the presented methodology (and improving on this methodology) should be of prime concern. Considering the importance of price responses to a wide range of scholarly and practical pursuits, the dearth of rigorous price response estimates, including cross-price estimates between primary and secondary versions of a commodity, represents an important research gap.

The results also provide qualitative guidance for when it is appropriate to choose $d = 1$ or $d = 0$. For instance, when secondary materials are poor substitutes for primary materials, lower displacement values should be used. As another example, full displacement will only occur when primary buyers are at least as willing to substitute for secondary material as secondary buyers are willing to substitute for primary material. As discussed, this is unlikely in many situations. Thus, practitioners should carefully consider their studied materials and assess whether this assumption is realistic; if it is not, full displacement should not be assumed.

Using the general results derived from our market model, environmental assessment practitioners can assess the market in which they are working on a basic level and select likely displacement rate values, thereby more accurately assessing the benefits of reuse or recycling. As mentioned earlier, additional work is required to determine whether and how partial displacement impacts system boundary selection for environmental assessments such as LCA.

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