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A causal analysis framework for land-use change and the potential role of bioenergy policy☆

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ABSTRACT

We propose a causal analysis framework to increase understanding of land-use change (LUC) and the reliability of LUC models. This health-sciences-inspired framework can be applied to determine probable causes of LUC in the context of bioenergy. Calculations of net greenhouse gas (GHG) emissions for LUC associated with biofuel production are critical in determining whether a fuel qualifies as a biofuel or advanced biofuel category under regional (EU), national (US, UK), and state (California) regulations. Biofuel policymakers and scientists continue to discuss to what extent presumed indirect land-use change (ILUC) estimates should be included in GHG accounting for biofuel pathways. Current estimates of ILUC for bioenergy rely largely on economic simulation models that focus on causal pathways involving global commodity trade and use coarse land-cover data with simple land classification systems. This paper challenges the application of such models to estimate global areas of LUC in the absence of causal analysis. The proposed causal analysis framework begins with a definition of the change that has occurred and proceeds to a strength-of-evidence approach that includes plausibility of relationship, completeness of causal pathway, spatial co-occurrence, time order, analogous agents, simulation model results, and quantitative agent–response relationships. We discuss how LUC may be allocated among probable causes for policy purposes and how the application of the framework has the potential to increase the validity of LUC models and resolve controversies about ILUC, such as deforestation, and biofuels.

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1. Introduction

Causes of land-use change (LUC) need to be better understood, and models of LUC should reflect evidence about causation. One application of these models is for renewable energy policies that require accounting of greenhouse gas (GHG) emissions from biofuel-induced LUC to determine whether a fuel meets the minimum targets for emissions reductions. For example, to contribute to a renewable energy mandate in the European Union (EU), biofuels must result in at least 35% lower emissions than fossil fuels. The requirement escalates to 50% in 2017 (EU, 2010). Uncertainties surrounding projections of LUC have led to a debate about whether policy targets for reducing emissions are met by particular biofuel production systems (Hertel and Tyner, 2013).

Calculating direct life-cycle GHG emissions reductions from crop-based biofuel production and use is complicated, requiring knowledge and assumptions about baseline landscapes, carbon stocks, and land management, and how fossil fuel and biofuel production interact and influence these and other variables. Uncertainty in emissions estimates increases when poorly defined indirect LUC (ILUC) attributed to biofuel policy is projected in places distant from biofuel production (Liska and Perrin, 2009; Plevin et al.,

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2010; Di Lucia et al., 2012; Sanchez et al., 2012; Warner et al., 2014). Yet ILUC estimates are mandated by some biofuel regulatory systems (USEPA, 2010; ARB, 2010) and may be required by the EU or others in the future.

LUC induced by a biofuel policy is generally estimated using simulation models with distinct assumptions about causal pathways. Most estimates of ILUC have relied on economic models developed for other sectors, such as global trade in agricultural commodities (Hertel et al., 2010; Britz and Hertel, 2011). Typically, a computable general equilibrium model is "shocked" with higher demand for the commodities associated with a biofuel policy, and the distribution of agricultural production under new conditions is compared to a baseline simulation (Banse et al., 2009; Britz and Hertel, 2011).

The model structure and parameters are often based on the assumption that the production and use of a feedstock commodity for biofuels increases demands for food crops, thereby increasing crop prices and expanding total agricultural land area at the expense of natural vegetation, particularly forests. An analysis by Searchinger et al. (2008) was the first to suggest that this series of contingencies was not only plausible but would necessarily be triggered as "farmers around the world respond by clearing more forest and grassland to replace crops for feed and food." However, this analysis has been criticized for these specific causal pathway assumptions that do not reflect policies, social factors, potential trade effects and potential changes in yield (Kline and Dale, 2008; Mathews and Tan, 2009). In contrast, LUC is known to involve interactions among many context-specific factors (Wear and Bolstad, 1998; Geist and Lambin, 2002; Van Asselen et al., 2013). Lapola et al. (2010) note that their ILUC projections for biodiesel in Brazil are a hypothesis, because the causal relationships have not been established.

Many drivers of LUC and deforestation, as well as feedbacks from land management and land manager motivations are omitted from ILUC models. For example, land appreciation (Richards et al., 2014) and causal factors for LUC that vary spatially, such as national land policies (Warner et al., 2014), enforcement of laws, migration, and accessibility via roads, are not represented at the highly aggregated level of most models used for biofuel policy (Kline et al., 2011). Land management and crop production practices (Langeveld et al., 2013) and feedbacks that reinforce or mitigate LUC (Verburg, 2006) are usually ignored. Some land managers may respond only partially to market prices by maximizing rent per acre, as they have other values (Piorr et al., 2009), they may be capital- or labor-constrained (Angelsen and Kaimowitz, 2001) or they may be interested primarily in asserting tenure claims (Lapola et al., 2010; Fearnside, 2008). Insecure tenure is an important driver of deforestation in some regions of the world (Rudel et al., 2009), and tenure regimes can affect deforestation in manners independent of and counter to simple land-rent maximization predictions (Godoy et al., 1998).

If mechanistic LUC models omit important causal factors or steps in a causal pathway, the outputs become dubious. Uncertainties are difficult to quantify, especially when formal validation is lacking (Baldos and Hertel, 2013; Brown et al., 2013).

The few studies that have attempted to examine the potential causal relationships between LUC and U.S. biofuel policy during the period of increasing corn ethanol production since 2001 have found little empirical evidence to support prevailing ILUC conceptual models (Kim and Dale, 2011; Oladosu et al., 2011; Wallington et al., 2012; Langeveld et al., 2013; Babcock and Iqbal, 2014). Empirical studies have been difficult to undertake because of the complexities of potential drivers, lack of consistent definitions of LUC, and limited land-cover and spatially explicit land-management data, especially for quantifying historic trends and background LUC.

Place-based studies of key influences on land changes must accompany global economic models to improve our understanding of causal relationships underlying LUC (Meyfroidt et al., 2013; Richards et al., 2014). More empirical evidence is needed to test linkages between bioenergy and distant land change.

We propose a causal analysis framework to identify when and where biofuel policy is a probable driver of LUC, using deforestation as an example. The framework employs an analysis of multiple lines of evidence and builds on a standard epidemiological approach (Hill, 1965). Without the use of causal analysis, models of policy-induced LUC only produce plausible rather than probable outcomes.

2. Causal analysis

Causal analysis is a formal process that uses evidence to infer causal relations or to link effects and causes. Analyses begin with an association and ask if the most likely interpretation is causation (Hill, 1965). Potential causal pathways and complex webs of influence are evaluated. The concept of a web of causation is prevalent in epidemiology (Krieger, 1994), referring to the characteristics of the host, agent, and environment that cause, prevent, or otherwise affect the rate of spread of a disease.

Unlike definitions of ILUC for biofuels that presume a causal pathway, a more general definition of an indirect effect is used in causal analysis, i.e., a greater relative distance of an event from a cause compared to other variables in a causal pathway diagram (Shipley, 2002). Indirect effects are more uncertain than direct effects, and the number of the former is potentially very large. They often have weak causal linkages, have a delayed effect, act at a distance from the cause, and are mediated by factors not in the direct causal pathway (Njakou Djomo and Ceulemans, 2012). Even where a causal pathway has just two steps [e.g., greenhouse gas emissions leading to regional climate change, and warming temperatures leading to changes in natural systems such as species ranges (Rosenzweig et al., 2008)], this "joint attribution" has reduced statistical confidence compared to attribution of each of the two steps.

Strength-of-evidence approaches can be applied to causal analysis for which causes are not easily diagnosed (Hill, 1965; Morton et al., 2006a,b; Suter et al., 2010). Such analyses consider multiple types of evidence from the case and from related cases, as well as their consistency and coherence.

Some causal relationships are general, whereas others are highly specific. For example, the use of causal analysis frameworks developed by the Surgeon General's advisory committee in the United States (USDHEW, 1964) and Hill (1965) in Great Britain established the general causal relationship between smoking and lung cancer. In a more location-specific example of causal analysis, petroleum production was investigated as a potential factor contributing to regional subsidence and wetland loss along the Gulf Coast of the U.S. (Morton et al., 2006a,b). Ecological applications of causal analysis are typically specific to a location and clearly defined effects (USEPA, 2013).

3. Framework for attributing LUC to bioenergy

We develop a causal analysis framework for determining the probable causes of LUC (and ILUC), with an emphasis on bioenergy (Fig. 1). The framework begins with a clear statement of the problem and definition of the LUC, followed by the generation of hypotheses to explain changes and causal pathway diagrams. Along the way, historic trends and baselines are characterized, and sufficiency of data is considered (Fig. 1). The core of the framework is a strength-of-evidence approach derived from epidemiology that incorporates multiple categories of evidence. Deforestation is used as an example of an important effect. Finally, alternative

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