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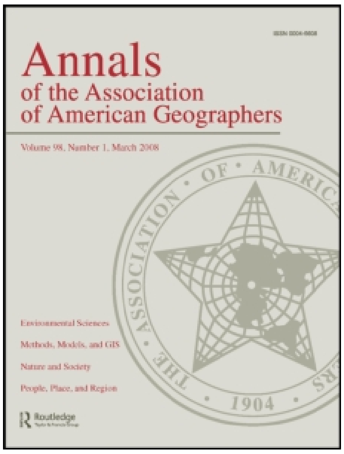

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# “Papering” Over Space and Place: Product Carbon Footprint Modeling in the Global Paper Industry

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We are witnessing an explosion in carbon calculators for estimating the greenhouse gas (GHG) emissions (i.e., carbon footprint) of households, buildings, cities, and processes. Seeking to capitalize on the emergent “green” consumer, corporations are leading the next iteration in carbon footprinting: consumer products. This potentially lucrative low-carbon frontier, however, faces steep challenges due to complexities of *scale,* largely a function of the number of actors and geographies involved in globalized commodity and energy networks, and *scope,* which increasingly demands inclusion of emissions due to land use change (e.g., biofuel production, timber harvest, livestock grazing, mining). Life cycle assessment (LCA)—the principal method behind product-level GHG emissions footprint protocols—frequently avoids these challenges by narrowly delineating system boundaries, thereby excluding the “messiness” of space and place. Through a comparative model of energy sources and emissions in the globalized paper industry, this article reveals how complexities associated with geographic variation and land use change create indeterminacy in footprints based on these protocols. Using industry and trade data, the authors develop geographic information system transportation and energy models to map the globally dispersed pulp supply networks and to rescale Intergovernmental Panel on Climate Change GHG inventory guidelines to include carbon loss associated with land use change in the carbon footprint of coated paper. Given their integrative abilities to conceptualize and model coupled human–ecological systems, sophisticated understanding of time–space dynamics and critical theoretical insights, geographers have much to contribute to the LCA and product carbon footprinting enterprise, which to date has been largely the intellectual domain of engineers. *Key Words: carbon labels, emissions, land use change, life cycle assessment, paper industry.*

我们正在目睹一个估算住户，建筑，城市和过程温室气体（GHG）排放的（如碳足迹）碳计算器的激增。那些试图利用这一新兴的“绿色”消费的公司正带领下一次碳足迹的叠代：消费产品。然而，这种潜在的有利可图的低碳前沿，由于规模，主要是全球化商品和能源网络中的行为者和地理的数量，以及范围，即日益俱增的要求罗列土地利用变化产生的排放量（例如，生物燃料生产，木材采伐，放牧，采矿），而面临着极端的挑战。生命周期评估（LCA），这一产品级别 GHG 背后的排放足迹协议的主要方法，通过狭义地划定系统边界，从而排除了空间和地点的“混乱”，因此频繁地避免了这些挑战。通过在全球化造纸工业中能源和排放的比较模型，本文揭示了与地理和土地利用变化有关的复杂性是如何创建基于这些协议上的足迹的不确定性。利用工业和贸易数据，本文作者开发了地理信息系统运输和能源模型，以测绘分散在全球的纸浆供应网络，并重新调整政府间专门小组在气候变化 GHG 的清单指南以包括有关土地利用在涂碳纸的碳足迹变化的损失。鉴于他们概念化和模型耦合人类生态系统的综合能力，对时空动态和重要理论观点的复杂的理解，地理学家对迄今主要是工程师智力领域的 LCA 和产品的碳足迹事业，都作出了重大贡献。*关键词：碳标签，排放，土地利用的变化，生命周期评价，造纸工业。*

Estamos presenciando una explosión de calculadoras de carbono para calcular las emisiones de gases de invernadero (GHG, sigla en inglés), o polución atmosférica (es decir, la huella del carbono) originadas en viviendas, edificios, ciudades y procesos. Buscando capitalizar a expensas del emergente consumidor “verde”, las corporaciones están apuntándole a la siguiente edición de la huella de carbono: productos de consumo. Esta frontera de bajo carbono potencialmente lucrativa, enfrenta, sin embargo, retos escabrosos debido a complejidades de *escala,* lo que en gran medida es una función del número de actores y geografías involucradas en las cadenas energéticas y de mercaderías globalizadas, y de *ámbito*, que cada vez más clama por la inclusión de las emisiones debido al cambio de usos del suelo (e.g., producción de biocombustibles, explotación maderera, pastoreo ganadero, minería). La

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evaluación del ciclo de vida (ECV)—principal método en el que se basan los protocolos de huella del carbono para emisiones de GHG a nivel de producto—con frecuencia le sacan el bulto a estos retos delineando con estrechez los sistemas de límites, para así descartar los "caos" de espacio y lugar. A través de un modelo comparativo de fuentes de energía y emisiones en la industria papelera globalizada, este artículo revela cómo las complejidades asociadas con variación geográfica y cambio de uso del suelo crean indeterminación en la huella de carbono con base en estos protocolos. Utilizando datos de industria y comercio, los autores desarrollaron modelos de sistemas de información geográfica para transporte y energía para cartografiar las cadenas de suministro de pulpa de papel dispersas globalmente y para cambiar la escala de las guías del inventario de los GHG del Panel Intergubernamental de Cambio Climático, a fin de incluir la pérdida de carbono asociada con los cambios de uso del suelo en la huella del carbono del papel esmaltado. Dadas sus habilidades integradoras para conceptualizar y modelar los sistemas humano-ecológicos en acoplamiento, su comprensión sofisticada de la dinámica tiempo-espacio y su perspicacia teórica crítica, los geógrafos pueden contribuir mucho a la tarea de la ECV y de generar la huella del carbono, que hasta hoy ha sido el dominio intelectual de los ingenieros. *Palabras clave: etiquetas de carbono, emisiones, cambio de uso del suelo, evaluación del ciclo de vida, industria papelera.*

Carbon labels now appear on potato chips, milk, breakfast cereal, sugar, bread, Japanese beer, and a wide range of other products. Facing increased pressure to reduce greenhouse gas (GHG) emissions in their operations and enticed by the lucrative prospects of an emergent green consumer, corporations have been active proponents of these labeling systems. Retail giants Tesco (UK) and Wal-Mart (U.S.) are engaged in major efforts to fund research and shape international protocols for product labeling (Brenton, Edwards-Jones, and Jensen 2009). Embracing the neoliberal faith that "buyer-driven" global commodity chains (Gereffi 1995) can use quality conventions and standards (e.g., certification, corporate social responsibility policies) to rescale governance, nongovernmental organizations (NGOs) and governments view carbon labels as a means to harness the power of the "green" markets to forge a more sustainable world. The governments of Japan, South Korea, Germany, and the European Union (EU) are developing carbon label standards (Bolwig and Gibbon 2009), and legislators in California have called for debate about a Carbon Labeling Act (AB 19), designed to facilitate carbon labels for products sold in the state. Meanwhile, recent research reveals the significance of consumer products in overall GHG emissions, sparking trade debates about who should take responsibility, producer countries (e.g., China) or consumer countries (e.g., the United States), and providing further impetus for product footprint accounting systems (Kejun, Cosbey, and Murray 2008).[1]

The race to establish an industry-standard international protocol for product carbon footprinting has narrowed to three hybrid public–private efforts. Publicly Available Standard (PAS) 2050 is the most specific and rigorous protocol to date (British Standards Institution, Carbon Trust, and Department for Environment 2008; Sinden 2009). The NGO in this partnership, Carbon Trust, which secured funding from Tesco and PepsiCo to implement specifications of the protocol on selected products, has created the Carbon Labeling Company, a private firm expanding corporate labeling efforts across the globe. But PAS 2050 faces stiff competition from the Product Life Cycle Accounting and Reporting Standard, which was developed by World Resources Institute and the World Business Council for Sustainable Development, with financial support from Wal-Mart. Finally, the International Organization for Standardization (ISO) has issued draft standard ISO 14067 (Carbon footprint of products).

The methodology underlying these protocols and labels is life cycle assessment (LCA), a central tool within the field of industrial ecology (Graedel and Allenby 2003; Matthews and Lifset 2007). Starting in the late 1970s in Europe, LCA methods developed rapidly, culminating in international standardization under the ISO 14040 protocol (SETAC Europe LCA Steering Committee 2008). LCA quantifies environmental impacts of products and processes for major phases of the life cycle, from material extraction to disposal (see top of Figure 1). The standard LCA method consists of sequential steps: definition of goal and functional unit, delimitation of scope or system boundary, life cycle inventory (LCI) and life cycle impact assessment (LCIA). LCI refers to the accounting of pollution and resource extraction in each life cycle phase, and LCIA is a decision-support model built on LCI to measure impacts (e.g., on human health or ecosystem quality). The field of LCA has expanded rapidly in recent years, with studies on a diverse set of products and processes, including buildings, fuels, renewable energy sources, nanotechnologies, and water.

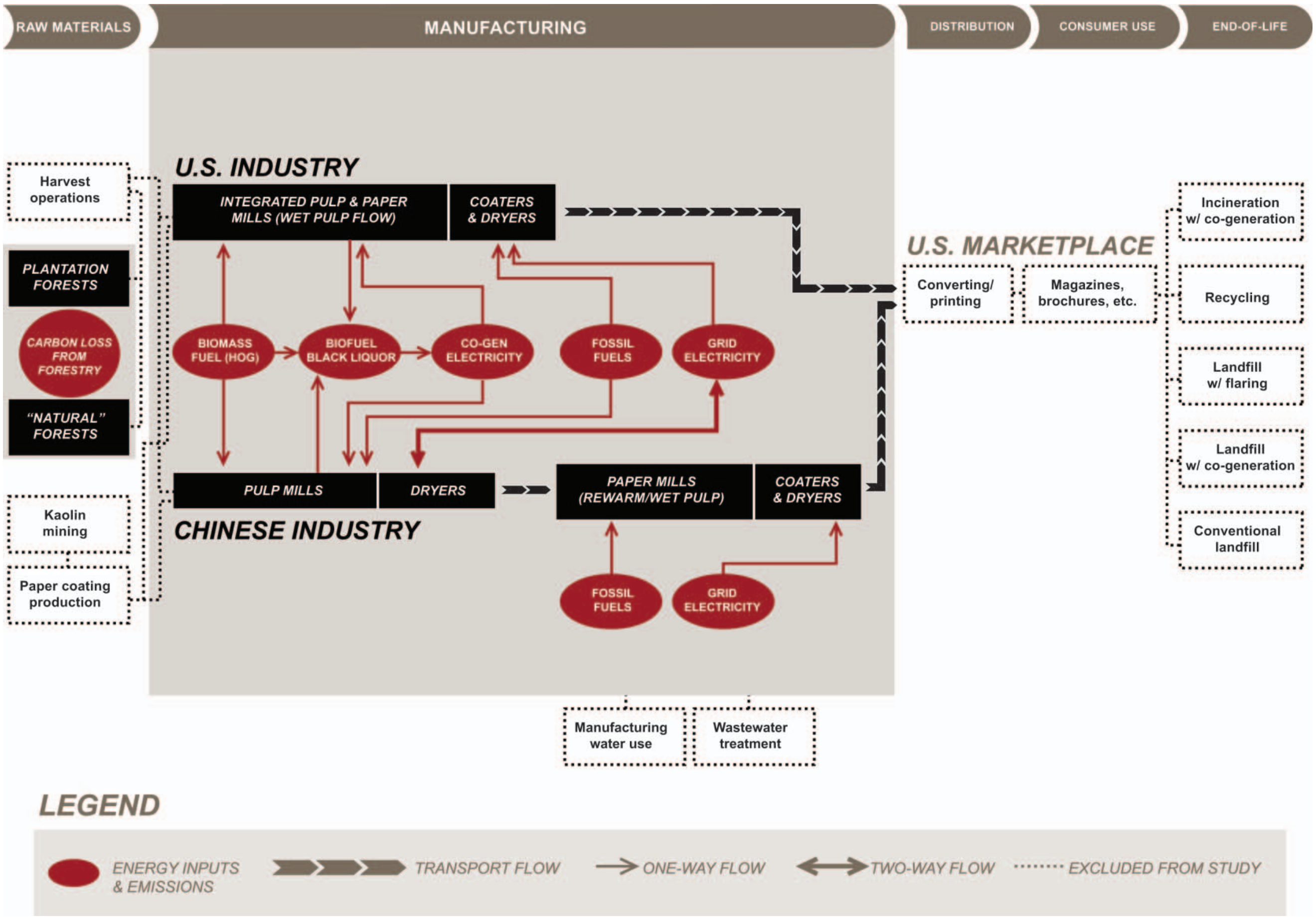

**Figure 1.** Comparative life cycle inventory of U.S. and Chinese coated paper: System flow and boundary scope diagram.

## Flattened Geographies in Life Cycle Assessment

Basic building blocks of LCA include activity data and emission factors. To reduce uncertainty in LCA studies, company-specific rather than industry average data are preferable. Similarly, data for emission factors (i.e., GHGs emitted per unit of energy) should be as site-specific as possible. In globalized post-Fordist supply chains, however, the production and distribution of a single product can involve dozens of actors, including material suppliers, manufacturers, shippers, wholesalers, and retailers scattered across multiple countries. Shifts in price, resource availability, production method, and demand can abruptly shift the input–output structure and territoriality of these complex supply networks. In stark contrast, a carbon label offers the consumer a static and fixed accounting of the GHGs embedded in a particular product.

In theory, LCIs and impact assessments require data collection within these spatially and temporally contingent supply networks—following complex chains of interaction in production systems wherever and however production occurs. But hindered by an inability to situate production in space and to obtain regionally specific data, LCIs as practiced often draw on activity data and emission factors that are essentially global averages and therefore decidedly aspatial. Or they privilege regions where LCIs are well-developed (Curran 2006), such as Western Europe, by applying emission factors from these LCIs for products manufactured in other regions.

In essence, by minimizing areal differentiation for the purpose of expediency, these practices "flatten" geography. LCA software, which draws heavily on inventory databases generated from European case studies, has facilitated these tendencies, although practitioners do sometimes build out regionalized grid averages for electricity use. Some LCA scholars recognize the implications of this lack of geographic variability and nuance, and are developing procedures to make LCIs more spatially explicit (Weidema 2004) and to better incorporate spatial differentiation in impact modeling (Pfister, Koehler, and Hellweg 2009; Steinberger, Friot, and Jolliet 2009). For example, in the nascent field of product water footprinting, geographical information system (GIS)-based models reflecting the variability of freshwater supplies help specify the impacts of consumption in arid regions (Berger and Finkbeiner 2010; Ridoutt and Pfister 2010).

## System Boundaries Change the Story

How the system boundary or scope is delineated—essentially which life cycle phases, inputs, and outputs to include or exclude—in LCA can fundamentally change the result. Varying system boundaries can render studies of the same product (or process) contradictory or incompatible for comparison. System boundary delineation hinges on the level of data, time and funding constraints, as well as other factors such as study objectives, geographic complexity, and levels of uncertainty.

To reduce complexity, temporal boundaries for use and disposal phases in particular are often narrowly structured or excluded entirely. As an example, consider these phases with respect to paper products. Carbon could be sequestered for decades in the form of books or it might be disposed of after one use in the case of copy paper. In the disposal phase, paper can release carbon as $CO_2$ following waste incineration, flaring or cogeneration from landfill gas, or as untreated methane gas from a landfill (Figure 1). The emission profile of disposal phases varies temporally and spatially, contingent on the type of local solid waste system in place.

Furthermore, most product LCAs exclude emissions associated with land use. Biomass fuel generally has been treated as "carbon neutral," based on the rationale that biomass stock (e.g., forest) will grow back and, over time, cancel out the global warming potential of the GHG emissions from the initial combustion. Recent research on biofuels and indirect land use change calls this into question. Searchinger et al. (2008) demonstrated that biofuel crops might displace food crops, leading to widespread conversion of forests or grasslands for agricultural production. Other research on indirect land use changes suggests more moderate emission scenarios (Hertel et al. 2010). Debate over the emissions associated with indirect land use change remains contentious, as evidenced by uncertainty about how to account for it in California's Low Carbon Fuel Standard, a state regulatory mandate.

There are also significant, albeit uncertain, emissions associated with some forms of direct land use change (e.g., forestland to cropland) and land cover modification (e.g., "primary" or "frontier" forests to managed or plantation forests). Accurate accounting of these emissions requires modeling land use as a complex, tightly coupled human–ecological dynamic over time and space. Forests as carbon pools (e.g., live biomass, decomposing organic matter, and soil) simultaneously accumulate and release carbon. The carbon flux of these pools varies depending on forest type, location, age, disturbance history, climate change, and forest management. Human factors such as forestry practices affect the degree of immediate carbon loss and the ability of forest ecosystems to recover sequestration capacity (Thornley and Cannel 2000). Forest ecologists have concluded that primary or frontier forests, across a range of geographic regions and ecosystem types, generally hold more carbon biomass than do managed forests or plantations (Harmon, Ferrel, and Franklin 1990; Dean, Roxburgh, and Mackey 2003; Luyssaert et al. 2008). Some NGOs advocate accounting for the opportunity cost of such logging because it could take decades to regain carbon sink capacity (Ford 2009). With such dynamic interactions, emissions associated with land use and land cover change are perhaps the most uncertain component of the global carbon cycle (Ramankutty et al. 2007).

Product footprint protocols make limited attempts to incorporate simplified elements of land use. PAS 2050 stipulates inclusion of GHG emissions resulting from direct land use change but excludes indirect land use change and land cover modification. Direct land use emissions are assessed in accordance with 2006 Intergovernmental Panel on Climate Control (IPCC) *Guidelines for National Greenhouse Gas Inventories*, using a twenty-year time scale. However, the *Guidelines* are for country-level reporting and provide no specific guidance on how to rescale these methodologies for products.

To explore how spatiality, land use issues, supply chain complexity, and system boundary decisions are negotiated in LCA modeling, this article models and compares LCI phases for coated freesheet paper (i.e., the sort of paper that is glossy in feel and commonly used in magazines, etc.) produced in China and in the United States. Specifically, we critique LCA practice by deploying the most rigorous product carbon footprint protocol available: PAS 2050. We focus on $CO_2$ inventories for three life cycle phases: carbon loss from timber harvest, transportation, and pulp and paper production.

Following the protocol's general guidance but supplied with no specific method to actually incorporate direct land use change, we develop an initial methodology to rescale IPCC guidelines for specific products. More broadly, our spatially explicit approach illustrates how geographic variation in the fiber supply structure for the U.S. and Chinese industries shapes the $CO_2$ emissions profiles for these phases and creates indeterminacy in terms of calculating an accurate product-level carbon footprint.

## Modeling a Spatially Explicit Product Footprint for Coated Paper

Approximately 40 percent of the world's industrial wood harvest is used to produce paper with a rise to 50 percent predicted by 2050 (Abramovitz and Mattoon 1999). The paper industry is the third-largest consumer of industrial energy in the United States and about one third of the municipal solid waste stream consists of paper (U.S. Department of Energy 2005). China and the United States are the world's two largest producers of paper and paper products (Haley 2010). Biomass fuel including burning of timber harvest residue ("hog" in industry parlance) is a significant source of energy, especially for coated freesheet paper because it relies almost entirely on "virgin" rather than recycled wood fiber. A tightly networked North American industry, long the global leader in coated paper production, is gradually being supplanted by Chinese producers, who manage an increasingly complex, global web of fiber sourcing, pulping, paper production, and converting operations.

To elucidate how these contrasting production network structures shape and problematize product carbon footprint modeling, we compare $CO_2$ emissions from coated paper produced by the Chinese and U.S. industries. Six mills making coated paper for the largest North American manufacturer represent the U.S. supply chain. Given that the largest Chinese manufacturer has just one mill producing coated paper, we broaden the comparative analysis to include the eight largest mills in China for various manufacturers. Smaller producers are virtually impossible to track using industry data, so by including a number of mills as well as the largest producer in each country, the underlying models provide comparable representations for the two supply chains.

Our functional unit is the delivery of one metric ton of finished paper to Los Angeles (2007). We look solely at the paper's wood fiber, excluding other primary materials such as clay and treatment chemicals, additives, and processes such as wastewater treatment, harvesting equipment emissions, and emissions specific to cultivating plantations (Figure 1). We only quantify $CO_2$ emissions, excluding other GHGs, and our study scopes out the use and disposal phases, including landfill emissions, elements researched in previous paper LCAs (Leach and Givnish 1996). In short, this article probes underlying geographic variation in carbon footprints for coated paper using a partial comparative life cycle inventory approach for the timber harvest, transportation, and pulp and production phases of the production process.

To develop a spatially explicit product footprint, we first map the fiber supply structure and production processes for both supply chains. We then develop weighted averages for timber harvest yield at the national scale and for pulp and paper production at the facility scale. This model of spatial variation underlies calculations for emissions from transportation and energy used in manufacturing, as well as carbon loss from timber harvest.

Although we use the same industry data set (Resource Information Systems [RISI] 2007) to capture activity data for production processes at the mills, due to data availability, our methodology for the two supply chains differs slightly for fiber supplies. Through personal interviews, we acquired firm-specific fiber supply data for the six U.S. mills. Like virtually all major North American manufacturers, this U.S. manufacturer has integrated, facility-level pulp and paper production and sources logs within a 100-mile radius. About 10 percent of the wood fiber is imported, essentially softwood pulp from Canada, which we were able to track to individual Canadian mills. In contrast, China imports more than 90 percent of its pulp from mills across the globe (Wood Resources International and Seneca Creek Associates 2007). Unable to obtain firm-specific data for China's industry, we model the fiber supply structure for the eight mills using industry (RISI 2007) and trade data (Global Trade Information Services 2008).

The virgin fibers required for coated paper production are pulped in two basic commodity types: bleached hard kraft pulp (BHKP) and bleached soft kraft pulp (BSKP). In 2007, over 75 percent of the BHKP China imported came from Indonesia, Brazil, and Chile, and about 71 percent of the BSKP came from Canada, Chile, Russia, and the United States. A large number of countries (including New Zealand, Finland, and Thailand) supply the remainder. To identify pulp mills, the model estimates locations based on the countries (including China) where pulp is produced, followed by the size of each mill's production as a share of total BHKP and BSKP produced within each country.[2]

## Transport

Following standard LCI procedures and PAS 2050 specifications, the model applies transport mode (U.S. Department of Energy 2008) and fuel type (U.S. Energy Information Administration 2008) emission factors based on the mass, distance, and modes of pulp and paper (i.e., ton mile by ship, rail, and truck). We model distances by data mining for exact locations of 116 global pulp mills, the Chinese paper mills, and U.S. integrated mills and use ArcGIS (Environmental Systems Research Institute 2009) to estimate the total distance that pulp is traveling from mills to papermaking facilities, and onto the consumer market (i.e., Port of Los Angeles). Calculations for route variations and distances rely on a suite of tools, including NetPas Distance (http://www.netpas.net), which allows the user to identify origin and destination ports to calculate shipping routes and distances. For mills less than 250 miles from a marine port or final destination mill, we model truck (rather than rail) as the transport mode of choice.

## Pulp and Paper Production

To quantify the facility-level $CO_2$ emissions from electricity and fossil fuel use, the model assigns fuel use profiles for each facility on the basis of a weighted average for the overall supply chain, based on the mass of total production given in RISI (2007). From these mill use profiles, we then apply the weighted average to generate a GHG emissions factor for embedded $CO_2$ for BHKP, BSKP, and finished paper for both supply chains. The general formula is

$$P * E_f * E_{mf} = CO_2 \text{ per finished metric ton} \qquad (1)$$

where P = percentage of pulp supply (BHKP or BSKP), or percentage of finished paper supply (i.e., weighted average); $E_f$ = energy factor for each fuel type, terajoules (TJ)/air dried metric ton (ADMT); and $E_{mf}$ = emissions factor for each fuel type, metric tons of $CO_2$/TJ. We then sum values for each facility to obtain overall estimates of BHKP, BSKP, and finished coated paper.

## Different Fuel Types

For specific distillate fuel oil and natural gas types listed by facility (RISI 2007), the model uses energy content factors from the International Energy Agency (IEA 2008) and emission factors from the IPCC (2006). *Coal* is nomenclature for a continuous range of solid organic fuels with varying energy content values and GHG emission factors, so using IEA (2008) consumption data we develop a soft coal (subbituminous and lignite)–to–hard coal (anthracite and bituminous) ratio for each country and then assign it to each facility. For electricity grid emissions, the model uses IEA (2008) data on the energy source mix (e.g., coal, natural gas, nuclear, oil, hydropower, renewables) for each country. Pulp mills and integrated mills both run on biomass sources, including residuals from production. Residual waste from the delignification process, known as *black liquor*, is almost always burned in recovery boilers (see Figure 1). Previous studies treat these biomass fuels as carbon neutral, but emissions from these sources are inherent to our model because we include carbon loss from timber harvest as detailed next.

## Carbon Loss from Timber Harvest

The model includes two scenarios for carbon loss from timber harvest. Scenario 1 assumes that, in the supply chains, the country of pulp production is known but the specific land use changes from timber harvest in that country are unknown. As instructed by PAS 2050 for products with this unknown origin, Scenario 1 assumes forestland-to-annual-cropland change following logging in each producer country. Scenario 2 adds geographic nuance by using estimates from Wood Resources International and Seneca Creek Associates (2007) to develop "natural" versus plantation forest ratios for BHKP and BSKP from each country. Scenario 2 assumes all direct land use change associated with conversion to plantations to be pre-January 1990, which—based on PAS 2050 and IPCC guidance—renders plantations carbon neutral. We recognize they are not neutral due to uncertain levels of emissions specific to plantation cultivation (e.g., seeding, thinning, and fertilizing) and indirect land use change, but to be consistent in both scenarios we excluded emissions associated with forest management and the actual harvesting. Furthermore, the model only considers the above-ground biomass carbon pool, with changes to other pools (e.g., dead organic matter, below-ground biomass, and soil carbon) excluded. Essentially, our model accounts for the release of biogenic carbon from fuel combustion during pulp and paper production, from wood residue left at logging sites, and from solid residuals due to production.

The model uses Food and Agriculture Organization (FAO 2001) data for average timber harvest yields per hectare and to identify major forest ecosystem types (e.g., tropical, temperate, boreal) for each country. It then averages IPCC Tier I estimated biomass values for each forest type to develop a per-hectare average biomass profile. The customized formula is

$$(B_{\text{before}} - B_{\text{after}}) * (C_{\text{fd}}) = C_{\text{removal}} \qquad (2)$$

$$C_{\text{removal}} \,/\, Y_{\text{yield}} = C_{\text{loss}} \qquad (3)$$

where $B_{\text{before}}$ = biomass stocks before conversion in tons dry matter/hectare (average for each country), $B_{\text{after}}$ = biomass stock for annual cropland (IPCC factor of 5 tons dry matter/hectare), $C_{\text{fd}}$ = carbon fraction of dry matter (IPCC factor of 0.5), $C_{\text{removal}}$ = carbon removal in kg of carbon/hectare, $Y_{\text{yield}}$ = yield given in $m^3$/hectare (FAO factor for each country), and $C_{\text{loss}}$ = kg of carbon per $m^3$ of wood (for each country).

Then based on the model of weighted averages, we obtain carbon loss estimates per $m^3$ for BHKP and BSKP in the China and U.S. supply chains. For finished paper, the formula is

$$P * C_{\text{loss}} * W_{\text{ef}} * 44 / 12 = \text{kg of } CO_2 \text{ per finished metric ton} \qquad (4)$$

where P = percent of pulp or wood supply for each country (supply chain weighted average), $W_{ef}$ = wood efficiency factor of 3.65 $m^3$/finished metric ton, and 44/12 = conversion of elemental carbon to $CO_2$.

Biogenic carbon is embedded in the coated paper until it is released during disposal or remains embedded in the form recycled paper products. As our study excludes the end-of-life phase, we estimate and subtract embedded carbon in the product from the direct land use change $CO_2$ emissions using the following formula:

$$D_{\text{average}} * C_{\text{fd}} = C_{\text{density}} \qquad (5)$$

$$C_{\text{density}} * W_{\text{ef}} * 44 / 12 = \text{kg of } CO_2 \text{ embedded per finished metric ton} \qquad (6)$$

where $D_{\text{average}}$ = average carbon density of wood species (IPCC 2006), in oven dry tons/$m^3$; and $C_{\text{density}}$ = carbon density in kg/$m^3$ of wood.

## Space and Place Change the Story: Indeterminacy in the Product Footprint

Our comparative analysis of U.S. and Chinese coated paper illustrates how geographic variation and system boundary exclusions fundamentally shape the carbon footprint of products. Including direct land use change in the raw material phases of the system boundary changes the story dramatically, as our model reveals the potential magnitude of $CO_2$ emissions due to changes in above-ground forest biomass (Figure 2). In contrast, studies of the paper life cycle that exclude land

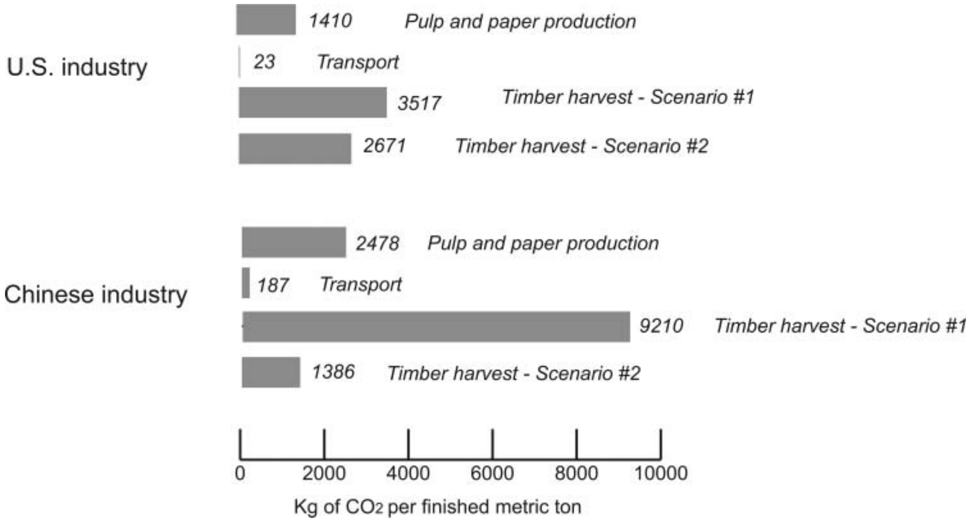

**Figure 2.** Comparative coated-paper carbon footprints for three life cycle phases, U.S. and Chinese industry.

use emissions conclude the pulp and paper production phase is the most carbon intensive (Gower 2006; Miner and Perez-Garcia 2007).

Consistent with earlier studies of paper (Subak and Craighill 1999; Gower 2006) and those for other land-based products, such as meat (Basset-Mens and van der Werf 2005), transportation emissions are a comparatively small portion of overall emissions in both supply chains. For China's industry, transport-related emissions are higher due to greater wood fiber to paper mill (BHKP average of 8,800 km) and consumer market delivery distances (Figure 2). The U.S. industry sources most fiber locally for integrated mills, with the imported Canadian BSKP averaging 2,400 km. A sensitivity analysis—in a typical uncertainty range (±20%–±40%) for transport emissions factors (Kioutsioukis et al. 2004)—changes neither the significance of the transport phase nor the overall result, because the transport footprint is small and the comparative difference between the U.S. and Chinese industries is large. From a product carbon footprint perspective, these findings counteract the "buy local" cliché in popular energy sustainability discourse—which, by overemphasizing transport as an emission source, conflates "greenness" with local sourcing.

The difference in the pulp and paper production phase (China: 2,478 kg/metric ton; U.S. 1,410/kg metric ton) stems from the Chinese industry's lack of integrated pulp mills and its greater dependence on carbon-intensive coal both for process heat and in the electricity grid. Integrated production in the U.S. supply chain is made possible by colocation of the industry near the forests. The integrated mills use cogenerated electricity to run both pulp and papermaking machinery (including coaters) and avoid using fossil fuels to rewarm and rewet pulp at the paper mill (Figure 1). Ashby's (2009) meta-analysis of carbon footprint studies of the pulp and paper production phase gives an uncertainty range of ±11.5%, considerably less than the difference seen here.

Geographical differences underlying the transport and pulp and paper production phases are significant but, as noted, the potential emissions associated with direct land use change, at least in Scenario 1, overwhelm these two phases (Figure 2). The results from modeling Scenario 1—which follows PAS 2050 carbon accounting guidance when the specific "land use change impact of an input cannot be determined" (10)—indicate much higher carbon loss from timber harvest for the Chinese supply chain (9,210 kg) than for the U.S. supply chain (3,517 kg). This model essentially assumes that all forests are "natural." As such, the Chinese industry imports more pulp from tropical forests, which (based on IPCC methodology) carry a larger $CO_2$ emissions conversion burden than do temperate and boreal forests. But if we go beyond PAS 2050 default guidance in Scenario 2, by incorporating natural forest-to-plantation ratios for each pulp-producing country, the results shift so much as to invert the comparison. The Chinese industry generates less $CO_2$ during the timber harvest phase (1,368 kg) than does the U.S. industry (2,671 kg) due to greater sourcing from countries that rely on plantations to produce pulp (e.g., Brazil and Chile).

Although these results provide insight into the relative importance of key life cycle phases, the more significant outcome of the study is the revelation that the overall footprint of coated paper is essentially indeterminate. Land use assumptions dictate the result. Scenario 1 illustrates a much larger overall footprint for Chinese paper than for U.S. paper. In Scenario 2, however, the two footprints are nearly even. These scenarios demonstrate the inadequacy of PAS 2050 to model essential system boundary inclusions when confronted with the spatial variation of globalized pulp supply chains.

As a way forward, the model we have presented offers an innovative attempt to incorporate land use change in product carbon footprinting by rescaling and customizing IPCC (2006) guidelines. As the results show, however, indeterminacy in the footprint persists. To refine this method, we would need to address geographic and temporal scales in forest growth cycles, include carbon pools currently excluded in PAS 2050 (belowground biomass, soil carbon, and dead organic matter), and gradually incorporate emerging science on frontier forests and the effects of forest management practices on carbon sequestration and regrowth rates. To better model these complexities at the outset, we suggest narrowing the geographic scale by comparing two major pulp-producing regions that harvest timber from different forest ecosystem types (e.g., frontier forests, managed forests, and plantations) such as Canada and Indonesia.

The results of this study have important ramifications for pulp and paper energy use models, which indicate that energy conservation and environmental benefits of recycled paper are limited because recycled fiber increases reliance on fossils fuels due to the lower level of biomass residuals (i.e., hog) available as fuel at the mills (Ruth and Harrington 1998; Villanueva and Wenzel 2007; Gaudreault, Samson, and Stuart 2010).

If $CO_2$ emissions from biomass are included in these models, rather than being treated as carbon neutral, using more recycled paper will have obvious benefits in terms of reducing demand for fiber from forests. How can the models developed here be extended to other paper types that, unlike coated freesheet paper, incorporate recycled content? Future modeling would need to investigate the carbon intensity trade-offs between higher levels of fossil fuels and reduced use of biomass fuels, hinging primarily on spatial variation in fuel and land cover types.

Although this study is limited to the pulp and paper sector, LCA modelers have recently called for similarly spatially explicit LCIs that include land use to fully capture the emissions associated with emerging technologies in renewable energy sectors like biofuels, wind, and solar energy (Kim, Kim, and Dale 2009; Seager, Miller, and Kohn 2009). Studies indicate the impacts from these sectors vary based on scale, location, and production practice (Potting and Hauschild 2006; Canals et al. 2007). Case studies of product systems that do not depend on materials requiring significant land use change (or modification) are also needed to indicate the degree to which spatially mismatched inventory models and fundamental land use exclusions are pervasive problems in carbon footprinting.

## Inserting Spatiality into LCA and Product Carbon Footprints

To more accurately model the energy and carbon footprints of coated paper, in this article, we have argued that LCA must be spatially explicit and account for emissions associated with land use change. So how might geographers insert more spatiality into the LCA and product carbon footprint enterprise? A spatially robust LCA requires the ability to conceptualize and model complex natural–human systems, a particular strength of geographers working within the broad traditions of land cover science and political ecology (Turner and Robbins 2008). Advances in remote sensing might make sophisticated accounting of land use tractable. Since the 1990s, industrial ecologists have recognized how GIS might build areal differentiation into LCA (Bengtsson et al. 1998). But in part because LCA has remained ensconced in engineering, efforts to couple GIS and LCA have been limited, although Geyer et al.'s (2010) efforts to do so with geographers—by modeling the impacts of land use change on biodiversity—introduce exciting possibilities.

But neglect of areal differentiation extends beyond modeling complexity and disciplinary turf. Those who deploy LCA for specific projects, such as developing footprint protocols and carbon labels, have economic and political motivations that inevitably shape how geographic complexity and system boundary inclusions are negotiated. PAS 2050 and the attendant carbon labels can be seen as an emergent form of market-based carbon governance (Bailey, Gouldson, and Newell 2010), since they have emerged due to the collective effort of the private sector, NGOs, and government agencies operating within a horizontal network structure (Bulkeley 2005). These actors might be woven together by a faith in the power of markets to rescale governance, but their individual underlying (often contradictory) motivations provide specific insight into *why* spatial complexity is avoided. In principle, the transnational corporation might support a carbon label because of its potential to forestall government standards and regulation or to differentiate products in the marketplace. In practice, however, implementing a spatially robust protocol might be incompatible if it necessitates a hardening and spatial concentration of the complex, fluid supply networks on which the corporation depends to efficiently accumulate capital. NGOs, meanwhile, might feel pressured to develop a "practical" protocol, enticed by the potential financial rewards of pioneering an industry-wide international standard.

One ramification of the papering over space and place is that rather than clarifying, the carbon label obscures. It becomes a warped, arguably more dangerous form of the commodity fetish than the one it intended to replace. The label appears to provide transparency for the consumers, yet the actual spaces of production (and the processes within them) remain obscure. In the consumer's imagination, purchasing products with such labels becomes a form of ethical consumption (Barnett et al. 2005; Clarke et al. 2007). This provides the illusory power of the green consumer to make a difference, further obfuscating the need to reduce overall levels of consumption (Lovell, Bulkeley, and Liverman 2009). As such, carbon labels and product footprint protocols might be theorized as a corporate strategy of "accumulation by [apparent] decarbonization," similar to carbon offsets (Bumpus and Liverman 2008, 127), and they could be readily situated within broader critical literatures on ethical consumption, commodity fetishism (Castree 2001), global commodity networks, and "climate capitalism" (Newell and Paterson 2010).

The few human geographers to write about LCA have generally framed it as aspatial and technocratic, nesting it within the broader ecological modernization movement (Keil and Desfor 2004; Robbins 2004).

Although we clearly see these tendencies in terms of how LCA traditionally has been developed and applied, we do not view the methodology as inherently so. LCA is fundamentally a process useful for thinking through and mapping out the complex assemblages associated with the production, consumption, and disposal of products. A relatively young methodology, LCA can still be as readily shaped and deployed by geographers as it can by engineers. We see the possibility, for example, of using LCA as a form of progressive praxis because of its potential to ground globalization by reconnecting spaces of production and consumption (Hartwick 2000). But left alone and poorly applied, as we have demonstrated with the PAS 2050 protocol, the practice of LCA threatens to paper over geographic variation and complexity and exclude fundamental inputs and processes. We will be left with protocols shaped by self-interested corporate actors and a confusing array of carbon labels that are impoverished and misleading representations of the carbon footprints of the products that line our supermarket shelves.

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## Notes

1. For example, after subtracting for imports, China's surplus embodied $CO_2$ emissions in exports represent approximately 18 percent of that country's total production-based emissions. In contrast, the United States had an export deficit of −7.3 percent (Peters and Hertwich 2007).
2. This study draws on data from *Cornerstone* (RISI 2007), which tracks production inputs and outputs for major paper facilities throughout the world in a materials balance framework.

## References

Abramovitz, J., and A. T. Mattoon. 1999. *Paper cuts: Recovering the paper landscape*. Washington, DC: Worldwatch Institute.

Ashby, M. F. 2009. *Materials and the environment: Eco-informed material choice*. New York: Elsevier.

Bailey, I., A. Gouldson, and P. Newell. 2010. Ecological modernization and the governance of carbon: A critical analysis. Working Paper No. 26, Center for Climate Change Economics and Policy, Norwich, UK.

Barnett, C., P. Cloke, N. Clarke, and A. Malpace. 2005. Consuming ethics: Articulating the subjects and spaces of ethical consumption. *Antipode* 37 (3): 23–45.

Basset-Mens, C., and H. M. G. van der Werf. 2005. Scenario-based environmental assessment of farming systems: The case of pig production in France. *Agriculture, Ecosystems & Environment* 105:127–44.

Bengtsson, M., R. Carlson, S. Molander, and B. Steen. 1998. An approach for handling geographical information in life cycle assessment using a relational database. *Journal of Hazardous Materials* 61:67–75.

Berger, M., and M. Finkbeiner. 2010. Water footprinting: How to address water use in life cycle assessment? *Sustainability* 2:914–44.

Bolwig, S., and P. Gibbon. 2009. *Overview of product carbon footprinting schemes and standards*. Paris: OECD.

Brenton, P., G. Edwards-Jones, and M. F. Jensen. 2009. Carbon labeling and low-income country exports: A review of the development issues. *Development Policy Review* 27 (3): 243–67.

British Standards Institution, Carbon Trust, and Department for Environment, Food, and Rural Affairs. 2008. *PAS 2050: 2008 specification for the assessment of the life cycle greenhouse gas emissions of goods and services*. London: British Standards Institution.

Bulkeley, H. 2005. Reconfiguring environmental governance: Towards a politics of scales and networks. *Political Geography* 24 (8): 875–902.

Bumpus, A., and D. Liverman. 2008. Accumulation by decarbonization and the governance of carbon offsets. *Economic Geography* 84:127–56.

Canals, L. M., C. Bauer, J. Depestele, A. Dubreuil, R. F. Knuchel, G. Gaillard, O. Michelsen, R. Muller-Wenk, and B. Rydgren. 2007. Key elements in a framework for land use impact assessment within LCA. *International Journal of Life-Cycle Assessment* 12 (1): 5–15.

Castree, N. 2001. Commodity fetishism, geographical imaginations and imaginative geographies. *Environment and Planning* A 33:1519–29.

Clarke, N., C. Barnett, P. Cloke, and A. Malpas. 2007. Globalizing the consumption: Doing politics in an ethical register. *Political Geography* 26 (3): 231–49.

Curran, M. A. 2006. Report on activity of task force 1: Data registry—Global life cycle inventory data resources. *The International Journal of Life Cycle Assessment* 11 (4): 284–89.

Dean, C., S. Roxburgh, and B. Mackey. 2003. Growth modeling of *Eucalyptus regnans* for carbon accounting at the landscape scale. In *Modeling forest systems*, ed. A. Amaro, D. Reed, and P. Soares, 27–39. Cambridge, MA: CABI Publishing.

Environmental Systems Research Institute. 2007. ArcMap 9.2. Redlands, CA: ESRI.

Food and Agriculture Organization of the United Nations. 2001. *Global forest resources assessment 2000*. Rome: FAO.

Ford, J. 2009. *Carbon neutral paper: Fact or fiction?* Asheville, NC: Environmental Paper Network.

Gaudreault, C., R. Samson, and P. R. Stuart. 2010. Energy decision making in a pulp and paper mill: Selection of LCA system boundary. *International Journal of Life Cycle Assessment* 15 (2): 198–211.

Gereffi, G. 1995. The organization of buyer-driven global commodity chains: How US retailers shape overseas production networks. In *Commodity chains and global capitalism,* ed. G. Gereffi and M. Korzeniewicz, 95–122. Westport, CT: Praeger.

Geyer, R., D. M. Stoms, J. P. Lindner, F. W. Davis, and B. Wittstock. 2010. Coupling GIS and LCA for biodiversity assessments of land use. Part 1: Inventory modeling. *International Journal of Life Cycle Assessment* 15 (5): 454–67.

Global Trade Information Services. 2008. *World trade atlas*. Columbia, SC: Global Trade Information Services. http://www.gtis.com/english/GTIS_WTA.html (last accessed 10 September 2010).

Gower, S. T. 2006. *Following the paper trail: The impact of magazine and dimensional lumber on greenhouse gas emissions*. Washington, DC: Heinz Center.

Graedel, T. E., and B. Allenby. 2003. *Industrial ecology*. Saddle River, NJ: Prentice Hall.

Haley, U. 2010. No paper tiger. Briefing Paper No. 264, Economic Policy Institute, Washington, DC. http://www.epi.org/publications/entry/no_paper_tiger/ (last accessed 10 December 2010).

Harmon, M. E., W. K. Ferrel, and J. F. Franklin. 1990. Effects on carbon storage of conversion of old-growth forests to young forests. *Science* 247:699–702.

Hartwick, E. 2000. Towards a geographical politics of consumption. *Environment & Planning* A 32:1177–92.

Hertel, T. E., A. A. Golub, A. D. Jones, M. O'Hare, R. J. Plevin, and D. M. Kammen. 2010. Effects of U.S. maize ethanol on global land use and greenhouse gas emissions: Estimating market-mediated responses. *BioScience* 60 (3): 223–31.

Intergovernmental Panel on Climate Change. 2006. *2006 IPCC guidelines for national greenhouse gas inventories*. Kanagawa, Japan: Institute for Global Environmental Strategies.

International Energy Agency (IEA). 2008. *Coal information (with 2007 data)*. Paris: IEA Statistics Head of Communication and Information Office.

Keil, R., and G. Desfor. 2004. *Nature and the city: Making environmental policy in Toronto and Los Angeles*. Tucson: University of Arizona Press.

Kejun, J., A. Cosbey, and D. Murray. 2008. *Embedded carbon in traded goods*. Winnipeg, MB, Canada: International Institute for Sustainable Development.

Kim, H., S. Kim, and B. E. Dale. 2009. Biofuels, land use change, and greenhouse gas emissions: Some unexplored variables. *Environmental Science & Technology* 43:961–67.

Kioutsioukis, I., S. Tarantola, A. Saltelli, and D. Gatteli. 2004. Uncertainty and global sensitivity analysis of road transportation emission estimates. *Atmospheric Environment* 38 (38): 6609–20.

Leach, M. K., and T. J. Givnish. 1996. Ecological determinants of species loss in remnant prairies. *Science* 273:1555–58.

Lovell, H., H. Bulkeley, and D. Liverman. 2009. Carbon offsetting: Sustaining consumption? *Environment and Planning A* 41:2357–79.

Luyssaert, S., E. D. Schulze, A. Borner, A. Knohl, D. Hessenmoller, B. E. Law, P. Ciais, and J. Grace. 2008. Old-growth forest as global carbon sinks. *Nature* 455:213–15.

Matthews, S. H., and R. Lifset. 2007. The life-cycle assessment and industrial ecology communities. *Journal of Industrial Ecology* 11 (4): 1–4.

Miner, R., and J. Perez-Garcia. 2007. *The greenhouse gas and carbon profile of the global forest products industry*. Research Triangle Park, NC: National Council for Air and Stream Improvement.

Newell, P., and M. Paterson. 2010. The politics of the carbon economy. In *The politics of climate change,* ed. M. T. Boykoff, 80–99. London and New York: Routledge.

Peters, G. P., and E. G. Hertwich. 2007. $CO_2$ embodied in international trade with implications for global climate policy. *Environmental Science & Technology* 43:6416–20.

Pfister, S., A. Koehler, and S. Hellweg. 2009. Assessing the environmental impact of freshwater consumption in life cycle assessment. *Environmental Science & Technology* 43 (11): 4098–104.

Potting, J., and M. Z. Hauschild. 2006. Spatial differentiation in life cycle impact assessment. *International Journal of Life-Cycle Assessment* 11 (1): 11–13.

Ramankutty, N., H. K. Gibbes, F. Achard, R. Defries, J. A. Foley, and R. A. Houghton. 2007. Challenges to estimating carbon emissions from tropical deforestation. *Global Change Biology* 13:51–66.

Resource Information Systems (RISI). 2007. *Analytical cornerstone: Q3 update*. Bedford, MA: RISI.

Ridoutt, B. G., and S. Pfister. 2010. A revised approach to water footprinting to make transparent the impacts of consumption and production on global freshwater scarcity. *Global Environmental Change* 20:113–20.

Robbins, P. 2004. *Political ecology: A critical introduction*. Oxford, UK: Blackwell.

Ruth, M., and T. Harrington. 1998. Dynamics of material and energy use in U.S. pulp and paper manufacturing. *Journal of Industrial Ecology* 1 (3): 147–68.

Seager, T. P., S. A. Miller, and J. Kohn. 2009. Land use and geospatial aspects in life cycle assessment of renewable energy. Paper presented at the Proceedings of the 2009 IEEE International Symposium on Sustainable Systems and Technology, Phoenix, AZ.

Searchinger, T., R. Heimlich, R. A. Houghton, F. Dong, A. Elobeid, J. Fabiosa, S. Tokgoz, D. Hayes, and T. H. Yu. 2008. Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science* 319:1238–40.

SETAC Europe LCA Steering Committee. 2008. Standardization efforts to measure greenhouse gases and "carbon footprinting" for products. *International Journal of Life Cycle Assessment* 13 (2): 87–88.

Sinden, G. 2009. The contribution of PAS 2050 to the evolution of international greenhouse gas emission standards. *International Journal of Life Cycle Assessment* 14:195–203.

Steinberger, J. K., D. Friot, and O. Jolliet. 2009. A spatially explicit life cycle inventory of the global textile chain. *International Journal of Life Cycle Assessment* 14:443–55.

Subak, S., and A. Craighill. 1999. The contribution of the paper cycle to global warming. *Mitigation and Adaptation Strategies for Global Change* 4:113–35.

Thornley, J. H., and M. G. Cannel. 2000. Managing forests for wood yield and carbon storage: A theoretical study. *Tree Physiology* 20:477–88.

Turner, B. L., and P. Robbins. 2008. Land-change science and political ecology: Similarities, differences, and implications for sustainability science. *Annual Review of Environmental Resources* 33:295–318.

U.S. Department of Energy. 2005. *Forest products: Industry of the future*. Washington, DC: U.S. Department of Energy.

———. 2008. Domestic consumption of transportation energy by mode and fuel type, 2006. In *Transportation energy data book (edition 27)*, ed. S.C. Davis, S. W. Diegel, and R. G. Boundy, 2-8–2-10.

U.S. Energy Information Administration. 2008. Fuel and energy source codes and emissions coefficients. In *Voluntary reporting of greenhouse gases program*. Washington, DC: U.S. Energy Information Administration. http://www.eia.doe.gov.oiaf.1605/emission_factors.html (last accessed 10 September 2010).

Villanueva, A., and H. Wenzel. 2007. Paper waste—Recycling, incineration or landfilling? A review of existing life cycle assessments. *Waste Management* 27:29–46.

Weidema, B. P. 2004. Geographical, technological, and temporal delimitation in LCA. *Environmental News, Danish Ministry of the Environment* 74:1–69.

Wood Resources International and Seneca Creek Associates. 2007. *Wood for paper: Fiber sourcing in the global pulp and paper industry*. Washington, DC: American Forest & Paper Association.

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