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Author
O'Rourke, Dara

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REVIEW

The science of sustainable supply chains

Dara O'Rourke*

Recent advances in the science and technology of global supply chain management offer near–real-time demand-response systems for decision-makers across production networks. Technology is helping propel "fast fashion" and "lean manufacturing," so that companies are better able to deliver products consumers want most. Yet companies know much less about the environmental and social impacts of their production networks. The failure to measure and manage these impacts can be explained in part by limitations in the science of sustainability measurement, as well as by weaknesses in systems to translate data into information that can be used by decision-makers inside corporations and government agencies. There also remain continued disincentives for firms to measure and pay the full costs of their supply chain impacts. I discuss the current state of monitoring, measuring, and analyzing information related to supply chain sustainability, as well as progress that has been made in translating this information into systems to advance more sustainable practices by corporations and consumers. Better data, decision-support tools, and incentives will be needed to move from simply managing supply chains for costs, compliance, and risk reduction to predicting and preventing unsustainable practices.

A buyer for a global apparel company can see sales data in each of their retail outlets, track and communicate with consumers, monitor orders being sent to factories, and assess the location of shipments in their global distribution system (*1*). Yet it is still almost impossible to trace the cotton in a popular shirt from the store back to the farms where it was grown (although the technology for radio frequency identification tagging of cotton exists), let alone to measure the full impacts and externalized costs of the apparel supply chain.

The scale of environmental and social impacts from global production and consumption makes this lack of knowledge—and failure to manage these impacts—increasingly concerning. Analysts have estimated that there are $4.7 trillion in environmental costs externalized each year from global production systems (*2*); 6.4 billion tons of carbon dioxide emitted, more than 20% of global emissions, through production of traded goods (*3*); and 567 km^3 per year of water associated with the global food trade alone (*4*). Also, current levels of global production and consumption are using 50% more natural resources and services than ecosystems regenerate (*5*, *6*). With growth in populations and in per capita consumption levels, expanding consumer classes around the world and the production networks that support them are driving major ecological pressures.

Corporations, nongovernmental organizations (NGOs), and governments have initiated a range of programs to measure and analyze the impacts of natural resource extraction, manufacturing, transportation, retail operations, product use, and end-of-life disposal. The science of sustainability measurement has progressed alongside efforts to advance supply chain traceability and transparency, data collection, impact assessment, and aggregation of data into indicators, scorecards, and eco-certifications. Advances in life-cycle assessment (LCA) and product "footprinting" (*7*, *8*) are increasingly being deployed in efforts to turn data into decision-support tools for global brands and retailers (*6*, *9*). Some companies have begun to institute incentives for change; to ban particularly problematic practices (from child labor to hazardous chemicals); and to develop new tools to better integrate sustainability into compliance, sourcing, and design (*10*–*12*).

These actions are being motivated by four major drivers: (i) regulatory pressures (led by a mix of U.S. states and European Union legislation); (ii) competitive pressures (for both cost reductions and supply chain innovations); (iii) stakeholder pressures (particularly targeting brand reputations and demands for greater transparency); and (iv) risks from supply chain disruptions (brought about by regional resource shortages and extreme weather events) (*6*, *13*).

Firms are responding to these pressures by demanding more information than ever before from their supply chains. However, accessing data from full supply chains can be expensive, time-consuming, and, sometimes, impossible. Companies are thus joining forces to motivate suppliers to divulge information to allow them to track performance and incentivize improvements. This has motivated the creation of several new industry collaborations and software platforms to help firms track and analyze data that have been hidden in global supply chains.

However, there are continued challenges in managing these collaborations and in connecting data from global supply chains to decision-makers inside companies and government agencies (*14*). Major impact areas from production remain hidden in supply chains, with unsustainable production practices implicitly or explicitly subsidized. This creates real barriers to addressing pressing sustainability challenges (*15*, *16*). There is a critical need to improve sustainability measurement systems, data collection and sharing processes, and decision-support tools to turn data into meaningful information to help change the behavior of retailers, brands, manufacturers, and, ultimately, consumers (*17*).

Supply Chains and Sustainability

Global brands and retailers deploy complex and fluid supply-and-demand networks, connecting global systems of marketing, branding, and distribution to regional nodes supplying raw materials, components, and finished products (Fig. 1). These networks often span the globe, extend five or six tiers deep, and can reconfigure overnight in response to changes in consumer demands, commodity prices, currency fluctuations, political risks, and so on (*18*).

The public tends to know only the top brands and retailers in these systems, such as Apple, Nike, and The Gap. Only recently have tier 1 suppliers such as Foxconn (the largest electronics manufacturer in the world), Pou Chen (the largest footwear manufacturer in the world), Li & Fung (the largest apparel manufacturer in the world), and Asia Pulp and Paper (one of the largest manufacturers of paper and packaging) come to public attention. However, these manufacturers are critical nodes connecting commodity markets for fibers, chemicals, metals, ingredients, and components to fast-changing consumer markets around the world.

The speed and dynamism of modern supply chains creates challenges for incorporating sustainability into production decisions (*19*). Product cycle times have become so compressed (*20*), and sourcing from real-time commodity markets so fluid, that even knowing what to measure and manage can be challenging (*21*). In areas where it directly benefits corporations, we have seen progress in measuring and accounting for energy, water, waste, and packaging. However, sustainability initiatives without direct cost savings have not advanced as far or as fast (*13*, *22*).

Fortunately, the scope of what matters and what directly benefits corporations is expanding (*6*, *22*). Companies increasingly need to know not only cost-related matters, but also supply chain–disruption risks related to extreme weather events, resource shortages, commodity price spikes, and labor unrest (*6*, *23*). Companies also need to track impending regulatory risks and manage risks to their brand reputation from pollution incidents, labor rights controversies, and the like. Companies thus need to know more than ever before about their full

Department of Environmental Science, Policy, and Management, 130 Mulford Hall, University of California, Berkeley, Berkeley, CA 94720, USA
*Corresponding author. E-mail: orourke@berkeley.edu

supply chain impacts and risks, ideally before their stakeholders (*6*, *9*, *13*, *24*–*26*).

Mapping Supply Chain Impacts

Global production systems have global ecological impacts, both "upstream" and "downstream" of a specific manufacturer or supplier. It is thus necessary to measure factors such as energy use, carbon emissions, water use, waste emissions, and land-use conversions across the full life cycle of production (*16*, *27*, *28*). A number of industries have been working to connect environmental indicator data to their production (*29*) and, as a first step, to map their supply chains (*17*, *30*). Recent efforts by global brands and retailers to map four or five layers of suppliers, including initiatives to trace commodities such as cotton; tin, tungsten, tantalum, and gold (so-called conflict minerals); and palm oil have faced surprising challenges (*6*, *24*, *31*). As one recent survey noted, "49 percent of global manufacturing executives, and 54 percent of those in the U.S., admit that their companies do not have supply chain visibility beyond their Tier 1 suppliers" (*32*).

A growing number of firms however, are now mapping and publishing supply chain information (*6*, *13*, *33*) (Table 1). These initiatives lay the groundwork for measuring primary impacts at each stage in the life cycle of a product from raw material extraction to transport, manufacturing, retail, use, and end-of-life management.

Firms are also increasingly reporting on their global operations and impacts. The Global Reporting Initiative (GRI) has become the leading standard for supply chain–impact reporting (*15*, *34*). The GRI provides guidance for companies to produce reports covering sustainability impacts. More than 80% of the largest 250 companies in the world and almost 6000 organizations in total now publish GRI-compliant reports. It should be noted, however, that GRI does not require measurement of impacts but, instead, focuses on implementation of environmental management systems. More companies and industry associations are now emphasizing supply chain impacts in these reports, requiring reporting and disclosure of sustainability performance (*35*, *36*).

Aggregating and Analyzing Impacts

LCA has been the primary methodology for turning sustainability data into useful information for decision-makers (*7*). LCA helps companies assess the environmental impacts associated with each stage in a product's life and to identify the "hot spots," or most important environmental impacts across the supply chain (*9*, *37*). Although the International Standards Organization and the United Nations have worked to codify and standardize LCA (*9*, *37*, *38*), heated debates remain on the merits of different approaches.

LCAs require the collection of substantial amounts of data to analyze even a simple product. SAP, IBM, SAS, and other software vendors have built tools to extract energy and water data from supply-chain procurement systems. However, companies must combine this with a life-cycle

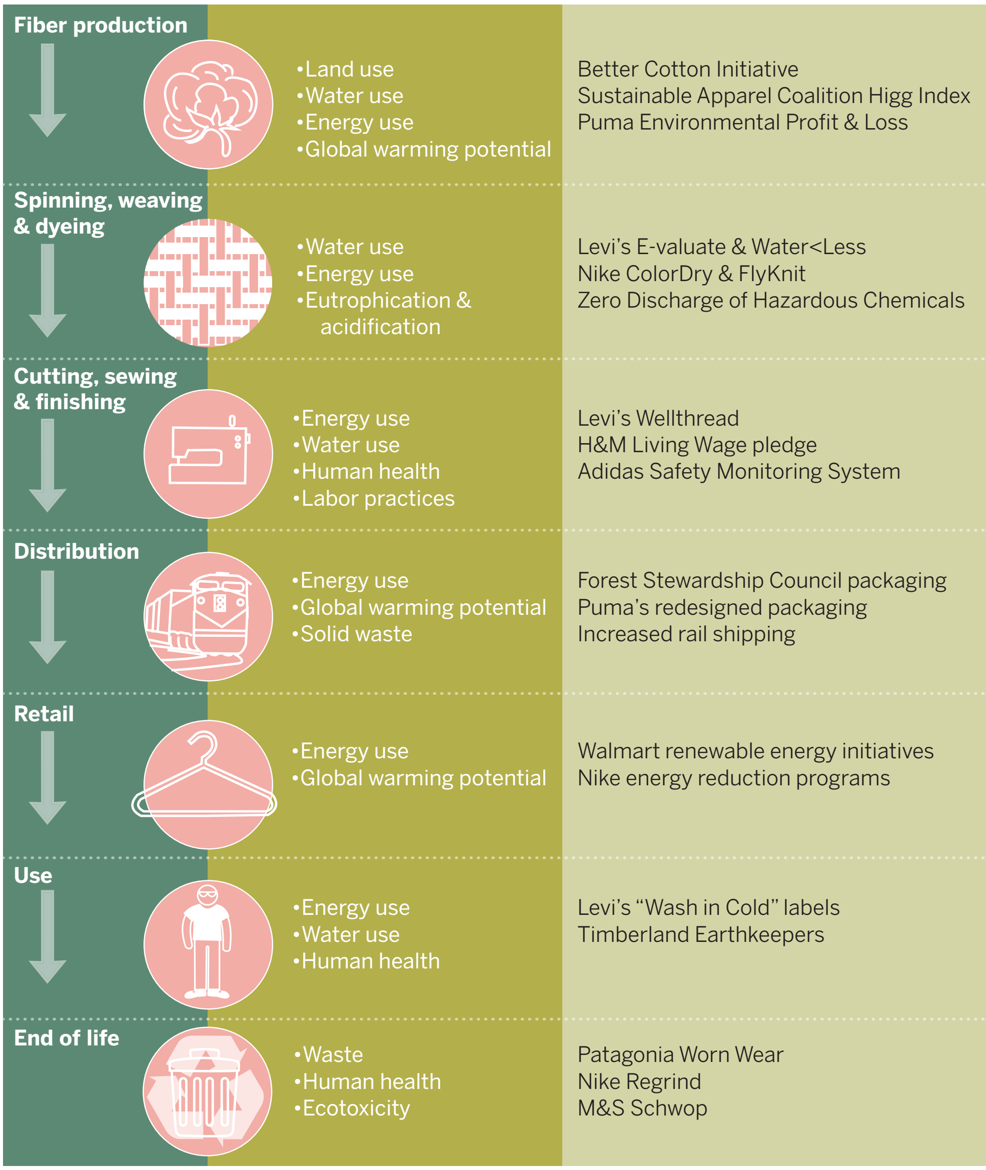

Fig. 1. Apparel supply chain initiatives. The apparel industry is an interesting sector for examining supply chain sustainability initiatives. LCA has been central to the work of the apparel industry. Leading brands and retailers have also experimented with a number of other strategies, driven by intense NGO and consumer pressures, including initiatives around traceability, impact assessment, and score-carding. Recently, a number of programs have come together within the Sustainable Apparel Coalition to develop the "Higg" sustainability index. These efforts are being translated into tools for product design, material selection, sourcing, manufacturing, use-phase interventions, and end-of-life management.

Table 1. Supply chain transparency initiatives.

Transparency type	Company initiatives
Supply chain traceability	Levi's Supplier List
	Nike Manufacturing Map
	Patagonia Footprint Chronicles
	All American Clothing
	Dole Organic banana tracker
Production processes information	ASDA—Factory web cams
	Levi's—Energy, water, chemicals commitments
	Tesco—Carbon emissions goals and performance
	Ben & Jerry's—From Cow to Cone
Production impacts	Puma's Environmental Profit and Loss Account
	Timberland—Green Index
	Nike—Our Impacts
	Apple—Environmental Footprint
	Unilever—Sustainable Living

inventory database such as the "ecoinvent" database (a collaborative effort of five Swiss research institutes) to bring together data sets covering relevant environmental flows, such as resource extractions, land use, emissions, and other material inputs (*39*).

Unfortunately, not every impact can be quantified, and some LCA data can be so variable that they lead to highly uncertain results. Data from generic upstream processes are often based on industry averages, which may not reflect a specific supply chain's impacts. Differing assumptions, system boundaries, data sets, and product uses, can influence the results of an LCA. Inconsistent rules and processes applied by LCA practitioners thus sometimes lead to contradictory conclusions (*6*, *9*, *37*).

A number of initiatives attempt to promote streamlined processes to measure product and supply chain impacts (*16*, *40–42*). A growing number of NGOs, academics, and government agencies are conducting "footprinting" exercises (*43–45*). Development of the "ecological footprint" in the early 1990s sought to create a measure of human demand on the Earth's ecosystems (*46*). The footprinting concept is now being applied to specific environmental resources, such as carbon and water (*8*). A number of analysts have built on emerging standards to develop tools for rapidly assessing thousands of products in a company's portfolio (*47*).

Use of divergent methodologies, data sets, assumptions, scopes of analysis, and system boundaries have led to confusion across footprinting initiatives (*48*). Recent efforts have thus sought to focus and constrain footprinting methods, to provide guidelines for how to conduct assessments of a specific product category (*49*), and to make the growing number of product assessments comparable (*38*).

Several large retailers are now developing their own LCA-like methods for quantifying product impacts and then turning these data into scorecards, indexes, and ratings systems (*13*, *18*, *50*, *51*). Target Corporation asked its suppliers of personal care and household chemical products to disclose product and supply chain information on ~7500 products. Target is evaluating these products and vendors for environmental and health performance, packaging, animal testing, and ingredient disclosure (via a tailored sustainability standard). Walmart has asked its suppliers to submit category-level sustainability data and is supporting the creation of a "Sustainability Index" via the Sustainability Consortium (*6*, *12*), an industry-academic collaborative working to create common sustainability measurement and reporting systems (*52*).

Decision Support

It is important to assess how these emerging footprints, indexes, and LCA results are actually used, as well as how newly gathered sustainability information is influencing decision-makers inside and outside companies (*21*). Perhaps the most ambitious strategy has been to translate environmental and social impact information into monetary terms, including, in some cases, into "profit-and-loss" statements [e.g., Puma, the footwear and apparel company (*15*, *53*)]. Companies calculate the value of the ecosystem services their supply chains draw on and estimate costs of degrading these ecosystems via their production processes (*54*). A related strategy has been to "price" resources and emissions, such as recent efforts to create internal pricing for carbon emissions at companies (such as Disney), and then to use this pricing in costing and sourcing decisions (*15*).

A related strategy has been to translate sustainability information into forms that investors can use, such as quantifying risks to a company's business (and stock value) from sustainability issues such as climate risks, stranded assets, water risks, and reputational risks. Many groups are now pressuring for companies to produce "integrated reports" in which they systematically report on financial and nonfinancial performance and risks (*36*).

A range of tools has been developed for decision-makers inside companies (*55*). These include tools for designers to incorporate sustainability concerns and trade-offs into their product decisions (*56*), for sourcing departments to incorporate analysis of resource risks into their selection of countries to source from (*17*, *18*, *56–58*), and for buyers inside retailers to assess the sustainability of products and brands they put on their shelves (*59*).

Finally, a number of initiatives have emerged to provide sustainability information directly to consumers. This has historically occurred through product eco-certifications (such as the Forest Stewardship Council, the Marine Stewardship Council, and Green Seal). More recently, initiatives have aggregated data from multiple public sources, including ratings and certification data, and then delivered it to consumers through Web and mobile apps at the point of purchase, such as GoodGuide.com (*12*, *15*, *17*).

Limitations of Current Science and Tools for Sustainability

There are still major debates on how best to conduct product and supply-chain sustainability assessments, as well as continued variations in methodologies, software tools, databases, and regional contexts (*6*, *22*). There are also continued limits to LCA and footprinting analyses (*9*) with researchers only recently bringing in critical issues such as biodiversity impacts (*39*) and social impacts such as working conditions and human health (*60*). Challenges also remain in connecting tier 1 data (collected by a supplier) to data for tiers two through five (which is often modeled) (*24*). Different levels of data often do not connect (*9*, *44*), and there are myriad weaknesses in publicly available data (*18*).

Tools such as LCA remain both too complicated and not specific enough (because of continued dependence on industry-average upstream data sets). Corporations complain about the cost and time required to conduct LCAs. It remains infeasible to conduct LCAs on every product in a large brand's portfolio, let alone in a major retail store. LCAs are often thus currently being used for more narrow purposes, such as identifying hot spots or supporting design improvements.

Progress in integrating sustainability analyses into core business processes and supply chain decisions (*6*, *15*) is limited. Sustainability efforts remain focused largely on finding incremental eco-efficiencies or risk reductions (*6*, *13*). A number of companies have been criticized for "greenwashing" because of poor data or of drawing system boundaries so selectively that they are representing only one node or one issue in a supply chain (*33*, *49*).

Future Prospects and Implications

Most firms still do not have good means to measure or manage upstream or downstream impacts, and very few firms are measuring their full externalities (*15*, *58*). There is thus still substantial work needed to advance the science and technology to support full supply-chain sustainability (*31*). Although some progress has been made to track conflict minerals because of recent regulation, there is a need for better tracing of supply chains, and in particular of raw materials such as cotton, minerals, and palm oil, from farms and mines all the way through to manufacturing and retail. There is also a need for continued investment in global monitoring and assessment systems that connect upstream resource extraction to downstream consumption and disposal. The recent launch of the Global Forest Watch program hints at the potential for this kind of connected, almost–real-time monitoring and reporting.

In order for these systems to generate accurate assessments, there is a need for consistent LCA inventory data and common data sets for upstream activities (such as electricity generation, transportation, and water use) (*6*, *37*); consistent life-cycle impact factors; better uncertainty analysis; localization of LCA data sets; modeling of nonlinear responses and ecosystem dynamics; and improved systems for valuing ecosystem services (*6*, *9*, *39*).

There is also a need to bring in issues that companies do not naturally value, or do not want to pay for, such as labor and human rights, toxics, and biodiversity loss (*31*). Companies need to account for the full impacts and costs of their production chains and to integrate this information into their business models, sourcing, and innovation strategies (*31*, *56*, *61*). The market is moving toward "demand-driven supply chains," so it is critical to connect consumers not only to product design and retailing but also to the full impacts of their choices (*15*, *17*). Improved reporting systems should provide actionable information to stakeholders from CEOs to NGOs to consumers (*34*).

There is a real opportunity to connect global measurement systems, with targeted monitoring, comparative ratings, and reporting. Even as LCA scientists work through technical challenges rooted in the complex ecologies of supply chains, they must simultaneously integrate recent lessons from the behavioral sciences related to effective sustainability communication and behavior change in order to design tools that have any chance of being useful for decision-making. Better data, decision-support tools, and incentives are needed to move from policing supply chains to predicting and preventing unsustainable practices.

The future of global production and consumption can and must learn from new supply-chain management systems to improve environmental and social sustainability (*31*). Initiatives should go beyond cost-saving, compliance, and risk reduction, to literally rethinking supply chains, closing loops, moving from products to services, and changing business models (*15*, *22*, *26*, *31*, *51*). Major opportunities remain to apply innovative design, sourcing, and stakeholder engagement programs to help invent a more sustainable supply chain of the future.

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