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Economic performance and supply chains: The impact of upstream firms' waste output on downstream firms' performance in Japan[☆]

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ABSTRACT

A novel application of input–output analysis is used to statistically map out average levels of generation of unwanted solid and liquid waste materials and also greenhouse gases along manufacturing supply chains for the final demand products of manufacturing industries in Japan. One key finding is that assembler dominated manufacturing supply chains have different within-chain waste generation patterns than manufacturing supply chains that are not assembler dominated. A second key finding is that assemblers with suppliers that produce less waste tend also to have better economic performance. This suggests that for manufacturing supply chains in Japan at least, the adoption by a downstream assembler of green procurement policies can improve both environmental and economic performance. This in turn suggests that both the private sector and public policies aimed at reducing manufacturing waste should take account of the incentives for achieving waste reduction all along a supply chain of a downstream assembler or other focal firm in a position to coordinate product/service flows, knowledge flows, information flows and flows of funds within a supply chain.

1. Introduction

"Sustainability: The key issue is not what we do, but how we do it. For example, if we make something with less energy and less waste, we save money that can be invested to further increase productivity."

John Wiebe, CEO, The GLOBE Foundation, March 25, 2014 (Wiebe, 2014)

Production of goods people need and want also yields unwanted waste materials and atmospheric emissions. Landfill space is filling up, and growing citizen resistance makes it increasingly hard to create new landfill sites. Waste incineration creates new solid wastes as well atmospheric emissions. Emissions of CO_2 and other greenhouse gases (GHG) are raising global temperatures and causing more severe storm activity. So far, the efforts of governments have failed to arrest the global warming in progress. Boin et al. (2010) warn we must prepare for disasters that will outstrip local capacities to help the affected population groups.

Silva and Zhu (2009, 2011) remind us too that the activities of production and the burning of fossil fuels also generate traditional pollutants including sulfur dioxide, nitrogen oxides, volatile organic compounds and particulate matter. In addition to local area damage,[1] these pollutants can travel with prevailing winds and via waterways (including spreading through underground aquifers). New research keeps uncovering new ways in which pollution can cause health problems (Kawamoto, 2008; Memon, 2010).

Moreover, in addition to the damages caused by unwanted products of production, the costs are large of the pollution abatement being carried out already on an ongoing basis by companies. Hadjiyiannis et al. (2009) note that in many advanced nations, a large share of the costs of pollution abatement activities are covered by public funds. Thus there are multiple reasons why growing numbers of firms are striving to reduce *at source* the

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[1] Many studies about waste management are at the municipal level (e.g. Huang et al., 1994; Wada et al., 2008).

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generation of unwanted waste and atmospheric outputs of production (e.g., European Commission, 2001; Kovács, 2008).[2] Reductions in the waste produced, as opposed to pollution abatement of produced wastes, is, of course, the only sort of pollution control that can also yield longer run cost savings for businesses. We present empirical and other evidence that taking account of supply chain interrelationships might help encourage this sort of pollution control.

Large manufacturing corporations (e.g., 3M, Cisco, 2010; NEC Corporation, 2004; Sony, 2010; Toshiba Corporation, 2006) are publicly promoting green procurement policies and proclaiming their use of environmentally friendly suppliers.[3] What, though, are the outcomes? (Ernst & Young, 2010: cover page and p. 6) and Cetinkaya et al. (2011), among others, stress the importance of having concrete numerical indicators for the sustainability performance of firms within supply chains as well as for whole supply chains.[4] Yet, as of 2010 Mollenkopf et al. (2010) found little published research *quantifying* supply chain environmental performance. We believe that is still a fairly accurate assessment. The fundamental reason for this state of affairs is that inter-firm transactions data are unavailable in general even to the managers of dominant businesses in manufacturing supply chains. Usually a firm has data only for its own transactions. Thus, as Vachon and Klassen (2008) point out, the available empirical studies virtually never use actual inter-firm transactions data.

We present an input–output (I–O) methodology that allows us to back out estimates of the production of waste along manufacturing supply chains using data available for Japan as a whole at a detailed industry classification level. Using this new empirical approach, we study the generation of waste and GHG along manufacturing supply chains in Japan.[5] One key finding is that assemblers with suppliers that produce less waste and GHG also, on average, have better economic performance. Governments have enacted regulations for toxic waste that apply at the level of individual manufacturing establishments or firms.[6] However, in a world where firms are interconnected in supply chains, these regulations might usefully be supplemented by measures that take account of supply chain relationships.[7]

The industry results can be related to theories and other evidence concerning other observable aspects of the supply chains in specific industries. This is feasible because the industry classification of a manufacturing establishment by the Japanese official statistics system depends on the main products produced by the establishment. These classifications are then used in constructing the official I–O tables for the nation.

Our industry results also demonstrate what data would be needed to produce key performance indicators (KPIs) for a specific supply chain using our methodology. If supply-chain-wide transactional data *were* available to the dominant assembler in a supply chain, then our methodology could be used to produce supply chain specific KPIs.[8] Those supply chain level KPIs could then be compared with the industry benchmarks that can be produced using detailed input–output data of the sort we have for Japan.

There are two basic approaches to reducing waste products so a business or supply chain can become greener. One is to capture and manage the waste: the abatement approach. Abatement operations are a pure cost addition for a business, and one that is often very substantial for manufacturers (e.g., General Motors Corporation, 1997). The other approach is to redesign the products or the processes for producing the products so less waste is produced. This more fundamental approach usually requires insight and large upfront expenditures.

Large, vertically integrated firms can undertake high cost redesign exercises because they are in a position to recoup their expenditures via overall profit margin gains on the final product sales. In contrast, an independent supply chain firm making an intermediate component of some final product may lack both needed resources and the security of knowing they will continue to be used by the final assembler. Moreover, the sort of knowledge exchanges needed for successful product and process redesign work can be greater than what independent companies in a supply chain are willing to undertake.[9]

However, close supplier–manufacturer relationships of the sort observed in Japan's auto industry are believed to enable adoption of the second approach (Bozdogan et al., 1998; Clark and Fujimoto, 1991; Dyer and Ouchi, 1993; Pagell et al., 2007; Flynn and Belzowski, 1996). A variety of management and organizational economics theories have addressed the issue of how certain sorts of supply chains and supply chain management approaches allow a supply chain to recapture the benefits that large vertically integrated firms have had in terms of enabling returns to scale for product and process research and development while still retaining the sorts of flexibility that have led to supply chains increasingly being a preferred form of business organization. In Section 2, we briefly review some of these theories.

In Section 3 we present our input–output (I–O) approach. We explain why I–O analysis, which has been widely used in studies of inter-industry economic flows and for economic development and planning, can also be used for statistically mapping out the average flows of wanted and unwanted outputs along the supply chains for industry-specific categories of final demand products. In Section 4 we discuss our data and empirical findings. Section 5 concludes.

Appendix A gives the list of 37 waste materials used in our analysis and descriptive statistics for the variables used in our regression equations. Appendix B provides an extended numerical application of our empirical approach for the Japanese auto industry, with estimates of the amounts of waste and GHG

[2] A number of business sector associations are also actively involved in trying to find supply chain public policies and management practices that will help achieve more greening with minimum damage to firm profits.

[3] Blome et al. (2014) and Zhu and Sarkis (2007) discuss, respectively, internal management issues and external institutional pressures, associated with firms' green procurement policies.

[4] See Piplani et al. (2008), Seuring et al. (2008), Akyuz and Erkan (2010), Hall et al. (2012) and González-Benito (2008). Also, Seuring and Müller (2008) outline key points from over 190 articles on this topic.

[5] Japan's Waste Management and Public Cleansing Act (1970) includes a clause which regulates business activity regarding toxic and other industrial waste. Several other laws on promoting recycling have been established since 1999 (http://www.env.go.jp/recycle/recycling). And now, Japan's green procurement laws also cover atmospheric pollution including CO_2 and other GHG emissions (Japanese Ministry of the Environment, 2013).

[6] Some firms involve only one establishment, whereas others include many. We will use the terms establishment and firm somewhat interchangeably throughout most of this paper. However, a large vertically integrate firm will almost always involve multiple establishments. In contrast, many of the establishments in a supply chain will often be one-establishment firms. A manufacturing plant is one sort of an establishment.

[7] In this paper we assume that upstream suppliers are generally not vertically integrated. Our working hypothesis is that firms in supply chains seek to maximize their respective profits while satisfying government regulations and that any supply chain level requirements are determined by the dominant final assembler firm in a chain.

[8] The production data for the supply chain would be used to estimate a supply chain specific comprehensive I–O table for the wanted as well as the waste outputs of the supply chain, and then that table along with the transactions information would be used to produce supply chain specific KPIs based on regressions that would also make use of the supply chain transactions and economic performance information. However, it would still be a nontrivial problem to produce overall supply chain performance KPIs (Ernst & Young, 2010; Cetinkaya et al., 2011).

[9] These examples suggests the importance of contracts, ownership and other forms of inter-firm business relationships associated with supply chains when it comes to firm or government policies to encourage greening.

emissions generated in the production of a passenger car with a 2000 cm^3 engine. This example is provided as an aid for those interested in the specifics of our methodology, and further specifics are available as well from the authors (Appendix C).

2. Previous studies that provide motivation and theoretical context for our research

In this section we provide an overview of studies in the literature developing two broad groups of theories that underpin our empirical research: theories from the management literature, and organizational economics theories. Both point toward our featured Green Pays hypothesis that we specify and then empirically explore using regression analysis. From the battery of regression analyses carried out, we show results in Section 4 that we hope help readers understand the nature of the evidence supporting our Green Pays hypothesis. We also hope this illustrates the range of ways in which the proposed methodology can be tailored depending on data availability, and the pollution and other supply chain performance indicators of interest.

2.1. Management theories

Researchers have been intently interested in the management methods and conditions that lead to product and process development and other sorts of collaboration within a manufacturing supply chain. Management theories we introduce in this section provide the main theoretical basis for our empirical study, with this foundation being supplemented with additional organizational economics theories. We begin with the relevant management theories.

According to the Resource Based View (RBV), collaboration within supply chains can enable a member firm to directly benefit from access to needed assets and competencies of other firms, and hence can be a source of competitive advantage (Barney, 1991). A key tenet of the related Relational View (RV) proposed by Dyer and Singh (1998) is that even a truly critical resource can span firm boundaries. Organizational capabilities may be developed that enable the combined exploitation of resources existing in different supply chain firms (Dyer and Singh, 1998; Takeishi, 2001). These sorts of capabilities may also result from inter-organizational learning (Dyer and Singh, 1998; Schroeder et al., 2002).

The Natural Resource Based View (NRBV) results from bringing the natural environment into the RBV. An environmental management strategy founded on resources that exhibit the properties proposed by the RBV can theoretically create a sustained competitive advantage. Russo and Fouts (1997) provide related empirical evidence that the environmental performance of firms can improve their asset returns.[10]

Cooperation is usually required to reduce the environmental impacts of material flows in a supply chain (Bowen et al., 2001; Carter et al., 2011). This can necessitate the exchange of technical information requiring a mutual willingness of supply chain partners to learn about each other. Waste prevention technologies (e.g., product/process modifications) can depend on skill development and "green" teams that span multiple supply chain partners (Hart, 1995).[11] An integrated life cycle management (ILCM) approach involves considering both efficiency and environmental sustainability in firm decision making across time and across supply chain echelons (Linnanen et al., 1995; Wolters et al., 1997; Koh et al., 2013). Major companies have been adopting ILCM practices (e.g., Caterpillar, 2008; Toyota Motors, 2013).[12]

Resource advantage theory (R-A theory), as developed by Hunt and Davis (2012), makes explicit the idea that when resources are tacit, causally ambiguous, and socially or technologically complex, these resources are relatively less likely to be quickly and effectively neutralized by competitors and hence are more likely to produce a sustained competitive advantage. R-A theory also posits that a firm's primary objective is superior financial performance as indicated by measures such as profits, earnings per share, return on investment, changes in stock prices and capital appreciation.[13]

Multiple studies provide examples of R-A theory in practice and of the financial performance benefits of green supply chain management (GSCM).[14] For example, Dyer (1996) examines data for Nissan and Toyota and the big three US automakers. For samples of the suppliers of those automakers, he finds evidence that as site, physical, and human asset collaboration increase among an automaker and its suppliers, the combined profitability of the network increases. Vachon and Klassen (2008) test the relationship between environmental collaboration and manufacturing performance using 2002 plant-level survey data for the North American package printing industry. A sample of 366 plants with at least 90 employees each was compiled from the Packaging Sourcebook (United States) and Scott's Industrial Directory (Canada). A potentially important causal insight is that manufacturing organizations involved in collaborative activities with their suppliers and customers can develop organizational capabilities which translate into cost savings (Porter and Van der Linde, 1995).

As Kelle and Akbulut (2005) note, a large literature has evolved as well focusing on quantitative models for buyer–supplier cooperation, including alternative inventory management approaches.[15] They discuss ways of extending buyer–supplier cooperation models to supply chain networks. They use quantitative modeling to show that the system cost can be reduced by coordinated supply chain policies, though they note information barriers to this coordination.

Tacit knowledge may play a role in waste control in many firms and supply chains, and, by basic nature, is difficult to replicate. More advanced environmental management practices that necessitate the integration of different sorts of stakeholder groups in socially complex ways are typically rich in tacit knowledge (Hart, 1995; Nakamura et al., 2001). In this regard, we note that the hierarchical perspective of Flynn and Flynn (2005) recognizes that

[10] See also Kumar et al. (2012) and Mishra et al. (2012).

[11] See e.g. Hult et al. (2006) and Schroeder et al. (2002) regarding the RBV. See Dyer and Singh (1998) and Dyer (1996) regarding the RV, and see Hart (1995), Vachon (2007) and Vachon and Klassen (2006, 2007) regarding the NRBV.

[12] In substantively related research based on data collected from 96 Turkish manufacturers, Ateş et al. (2012) find that environmental investments act as a mediating variable between proactive environmental strategy and environmental performance.

[13] Profit and value added maximization serve similar purposes in models of firm behavior. but some evidence exists for Japanese firms that value added maximization may better explain their behavior (Tsurumi and Tsurumi, 1991).

[14] See, for example, Feng et al. (2014), Rao (2002), Tukker et al. (2001), Cairncross (1992), Hart (1995), Narasimhan and Schoenherr (2012), Schmidheiny (1992), Shrivastava (1995), Porter and Van der Linde (1995), Vermulen (2002), Rao and Holt (2005), and Chen et al. (2006). Although there are many competing definitions (e.g., Zhu and Sarkis, 2004), GSCM methods can be broadly classified into internal and external management approaches (Rao, 2002). Internal environmental management focuses on compliance with needed certifications and the creation of and commitment to environmental management systems within organizations (Zhu and Sarkis, 2004). External environmental management focuses on parties external to producers, especially including suppliers and their purchasing and product innovation efforts (Bowen et al., 2001; Lloyd, 1994; Rao, 2002; Hamner, 2006; Makower, 1994; Green et al., 1998; Rajagopal and Bernard, 1993; Rao and Holt, 2005; Chen et al., 2006).

[15] See, for example, Golhar and Sarker (1992), Kelle and Schneider (1992), Banerjee and Kim (1995), Fazel (1997), Miller and Kelle (1998), Kelle et al. (1999), Ganeshan et al. (2001), Myers et al. (2000), Weber (2000), and Viswanathan and Piplanib (2001).

the best suppliers have much more to offer than simply producing an item according to buyer-provided specifications

Building on these ideas, Vachon and Klassen (2008) develop a framework linking environmental collaboration via a supply chain to manufacturing performance. In this context, encouraging suppliers to grow greener leads to green product, process and managerial innovations, which in turn tend to enhance competitive advantage chain-wide. Based on a large-scale survey study conducted in China in November 2002 on business strategy and innovations, Li et al. (2005) find that when pressure for change comes from external parties, R&D and new product development tend to be emphasized and positive long-term impacts on market position tend to result. As Lavassani et al. (2008) explain, network theory points to the potential value of long-term, trust based relationships within supply chains of the sort that are featured as being beneficial in the Vachon–Klassen framework.

Green practices can be directed either upstream toward suppliers or downstream toward customers. Vachon and Klassen (2008) study the effects of collaboration in each direction for multiple objective indicators (though none involve transactions data) and for perceptual measures of manufacturing performance using data for plants in the package printing industry. The benefits of collaborative green practices involving upstream suppliers are found to primarily take the form of process-based performance improvements, and tend to be greater in value than the benefits of collaboration with customers. Their study reveals that the separation of upstream from downstream supply chain effects is important. Traditionally, many studies combined these activities into one unified construct (Rosenzweig et al., 2003; Zhu and Sarkis, 2004). Overall, Vachon and Klassen (2008) find a significant correlation between environmental performance and competitive advantage, with the upstream effects proving most important.

It is upstream effects that we explore in the empirical portion of this study. Those are what our data permit us to examine. (We have no data for consumer waste production.)[16] Also, the upstream effects are what Vachon and Klassen (2008) find to be most important.

Chiou et al. (2011) provide evidence that greening the suppliers via product and process changes can contribute not only to environmental performance but also to the competitive position of a supply chain. Their study is based on data collected via a questionnaire-based survey of 124 companies in eight industry sectors in Taiwan. Their findings support the implications of the RBV, the NRBV, the Relational View and R-A theory. Their results point toward the potential importance of the development of metrics and data analysis methods that take account of interrelationships between environmental and financial performance for supply chains rather than just for the individual establishments comprising a supply chain.

Some studies have provided evidence that greater integration of suppliers into product and packaging innovation initiatives can improve the outcomes (e.g., Bonaccorsi and Lipparini, 1994; Ragatz et al., 2002; Johnsen, 2009; Lau et al., 2010). Geffen and Rothenberg (2000) find too that suppliers in partnership roles are more willing to provide their latest innovations to their automotive assembler partners and, with more feedback from the assemblers about customer needs, are better able to provide technologies suited to particular supply chain needs.

The innovative technologies needed to improve the environmental performance of automotive assembly supply chains require skills and competencies from both suppliers (e.g., detailed knowledge of paint chemistry and environmental effects) and assemblers (e.g., detailed knowledge of the final product requirements and assembly plant operations). An evaluation by Geffen (1997) of patents provides hard evidence of the importance of suppliers as sources of innovation for new product development. Based on a survey of automotive assembly plants in North America and Japan, Rothenberg (1999) also reports evidence of participation of suppliers in environmental innovation. The environmental performance improvements achieved by the assembly plants studied by Geffen and Rothenberg (2000) were found to have required high levels of trust among the major partners: trust reinforced by contracting and other mechanisms providing assurance that the environmental improvements will be lucrative for the suppliers too.

The theories referred to imply a need for methods that can provide industry benchmark KPIs for supply chain environmental and economic performance, as well as guidance on the needed data collection on transactions and production methods (i.e., the input and output quantities) for supply chain partners so chain level KPIs can be computed. Reflecting on how far the information revolution has come in the last decades, it seems reasonable to hope that supply chain partners will soon enjoy full intra-chain transactions visibility.

In this paper we show how various sorts of benchmark industry level KPIs can be evaluated with the data available to us now. We show that these can be used to test hypotheses about supply chains producing narrow lines of final demand products that are recognized in the I–O tables for the nation. We argue too that the method proposed can be adapted for production of KPIs for a specific supply chain given the needed data.

2.2. Organizational economics theories

Most economic transactions occur not in the fully frictionless markets assumed in some branches of economics but, rather, in market situations managed via contractual arrangements, government regulations, and interpersonal expectations. Organizational economics seeks to understand managed transactions (i.e., those that do not occur in frictionless markets). For example, factors that enhance or undermine mutual trust within an organization and the impacts on economic performance are examined (e.g., Kelle and Akbulut, 2005).[17] Theories developed in this literature of relevance for our research include those regarding how economic incentives can be used to enhance and render more enduring a competitive advantage based on complex interactions within a chain as is suggested by the RVB and related theories.[18] The organizational economics theories of greatest relevance for our study are those that point toward circumstances or management choices with incentive effects that management theories imply to be important.[19]

Three possible types of organizational structures for a supply chain can usefully be distinguished here. Market-driven arrangements are the first type. With this type, there is little or no equity ownership among supply chain partners. Instead, the firms are formally bound only by limited legal arrangements such as supply

[16] Clearly, downstream effects and the economic effects of final consumers in a life cycle assessment (LCA) context can matter. e.g., see MacLean and Lave (2003) for a LCA study of a “greener” car with a well-managed end-of-life.

[17] Kelle and Akbulut (2005) consider supply chains based on adversarial, partnership, and network relationships. A lack of trust can result in assembler or supplier unwillingness to share proprietary information, and hence can rule out sorts of network relationships that would prove beneficial for all participants if implemented.

[18] Our theoretical approach below builds on the work of others (Halldorsson et al., 2007) who suggest a mixed use of RBV theories and organizational economics theories for modeling supply chain decision processes.

[19] See, for example, Brousseau and Glachant (2008), Krishnan and Winter (2011), Milgrom and Roberts (1992) and Williamson (1985) on the economics of organizations and institutions.

contracts and intellectual property rights agreements. In these supply chains, theory and anecdotal evidence suggest that suppliers may have inadequate incentives to cooperate for or invest in product or process improvements that a final assembler wants to introduce. In this circumstance, it is also difficult to coordinate actions to promote common objectives such as sustainability.[20]

Fully owned supply chains are the other extreme. This is the structure for what traditionally have been called fully vertically integrated firms. This arrangement is believed to solve most of the coordination, control and trust issues that occur for supply chains of the first type. However, it is well known that an assembler firm that owns most of their supply chain can build up unsustainable agency costs (e.g., GM before their Chapter 11 restructuring in 2009).

Japan's production keiretsu (or vertical keiretsu) are a third organizational type. In this network of companies structured along a supply chain, a dominant assembler is connected to its first-tier suppliers, which are in turn connected to their suppliers, and so on. The keiretsu companies in the different stages of the supply chain collectively produce all parts (e.g., over 25,000 auto parts) used for production of the final products of the chain. In this sense, a production keiretsu is like a fully vertically integrated company. Typically, a final assembler produces only final demand products (e.g., passenger car assembly in the automobile industry) using first-tier upstream supplier intermediate products (e.g., engine assembly, electrical system assembly, etc.), which, in turn, are produced using second-tier supplier intermediate products, and so on, with each of the tiers of suppliers producing main products that constitute separate classifications in the detailed input–output tables for Japan.

Unlike U.S. supply chains that are usually bound together by contracts (Liker and Wu, 2000), the main agreements bonding keiretsu members are implicit. Blinder (1991) explains:

> "But the Japanese have hit upon an imaginative third way. When Toyota, Hitachi, and other Japanese giants go looking for parts, they do not shop on a truly open market; they turn first to their regular suppliers. And the deals they make are not arm's-length transactions but rather part of ongoing business relationships that all parties expect to continue. The sturdy, but not indestructible, relationships that constitute the production keiretsu seem to combine artfully the contrasting virtues of hierarchical control and market competition."

A key specific, according to Blinder, is that the implicit agreements

> "… promise suppliers stability, but not too much stability. Once admitted to the inner circle, a supplier of parts to, say, Toyota knows it will not soon lose the giant company's business. So it has every reason to be reliable, to share information with Toyota, to participate in joint development of new products, and so on. General Motors Corp.'s suppliers enjoy less security and hence have less reason to invest in the relationship."

On a pure trust basis, a final assembler in a Japanese production keiretsu shares their designs and other strategic information with their first tier suppliers, which do the same with their suppliers, and so on. Yet, Blinder explains, these relationships have a discipline component:

> "[C]ompanies maintain several suppliers for most parts and vary "market shares" to reward the best performers and punish the worst. Thus, a kind of ersatz market is created within the keiretsu."

[20] Supply chains are sometimes characterized as examples of quasi-vertical integration. Under quasi-vertical integration, an assembler invests in specialized resources and loans, leases, or rents them to their suppliers. Quasi-vertical integration is common in the automobile industry (Milgrom and Roberts, 1992).

2.3. Relevant implications of the management and organizational economics theories

As shown in Section 2.1, RBV, NRBV and other related theories emphasize that well-functioning supply chains enjoy competitive advantages generated by upstream supplier firm-specific advantages. This implies that optimally operating supply chains in assembly based manufacturing industries generally allocate the production of resource (raw material) intensive operations to upstream suppliers which have comparative advantages in running those operations. In such supply chains we expect the final assembler to have more indirect generation of waste and GHG emissions by their suppliers relative to their own direct generation. We do not explain this to be the case, however, for supply chains in industries where neither assembly operations nor the use of raw materials is relevant.

We present this expectation in the form of hypothesis H1. As stated immediately below, H1 predicts that, in supply chains in resource (raw material) intensive assembly based manufacturing industries, the generation of waste and GHG emissions is skewed towards upstream suppliers.

H1. Assembly based manufacturing industries have larger shares of indirect waste generation (relative to direct waste generation) in their supply chains than non-assembly type manufacturing industries.

For example, due to the nature of their non-assembly based production processes, mining industries are expected to generate much more direct than indirect waste and GHG emissions. In contrast, in resource intensive assembly based manufacturing industries such as auto and machinery industries, upstream suppliers in the supply chain are expected to generate most of the waste.

In the following empirical section, Section 4, we provide statistical evidence that H1 holds for assembly versus non-assembly based manufacturing industries in Japan. H1 implies that in an assembly based manufacturing supply chain, we can expect upstream supplier environmental costs (waste and emissions) to be reflected as indirect environmental costs of the downstream assembler firm. We elaborate on this point below in introducing our hypothesis H2.

Application of the theories reviewed leads to the perspective that manufacturing firms in well-functioning supply chains have incentives not to cheat on supply chain partners because of a focus on longer-term benefits. Certainly it is observed that Japanese suppliers and assemblers often cooperate in areas such as new product development, design, R&D, and quality control.

One main way in which the body of literature covered in this section connects to our interests in the at-source reduction of waste is that a final manufacturing assembler is typically in a position to both profit from product innovation that has appeal for the final customers and also to determine the conditions of the relationships between the final assembler and its suppliers. Thus the final assembler is in a position to realize the sorts of gains envisioned in the theories covered. We draw from the above background material the following hypothesis:

H2. Our Green Pays hypothesis: The economic performance of a downstream assembler firm is negatively affected by not only their own waste generation, but also by the waste generation of their upstream suppliers.

In the empirical portion of our study, to which we now turn, we provide objective empirical evidence that some manufacturing supply chains in Japan are, indeed, realizing the hypothesized Green Pays benefits. Our results suggest there are sound economic reasons to expect the continuation and expansion of the Green Pays win-win outcomes.

3. Our empirical methodology

In presenting our empirical methodology we first provide an overview. We then give details, treating separately the estimation of desired versus waste and GHG supply chain outputs.

3.1. Overview of our empirical approach

Even in case studies, inter-establishment transactions data are generally not available (Hall, 2000; Lamming and Hampson, 1996; Vachon and Klassen, 2008). It is only financial attributes such as total revenue and employment data that are commonly available for business establishments. When transactions data for business *are* available to researchers, the data usually include only information about the final product sales for businesses (e.g., the scanner data that researchers work with for grocery stores) as opposed to input purchasing transactions details.[21]

Indeed, much of the data available to researchers for supply chains pertain to perceptions rather than to transaction quantities or values. For example, Vachon and Klassen (2008) collected by survey a body of perceptions data about manufacturing and environmental performance and combined that data with financial performance data (without transactions information) from 80 plants in the US and Canadian package-printing industry. Commenting on their data, Vachon and Klassen (2008, p. 305) note that:

> "For perceptual measures of performance, 13 items captured the four traditional dimensions of manufacturing performance – cost, quality, delivery, and flexibility. In addition, three items were added to measure perception of environmental performance, similar to Judge and Douglas (1998). These items required the respondent to evaluate the performance of their plant versus major competitors."

Regarding this feature of the literature, Vachon and Klassen (2008, p. 305) observe:

> "While many studies of performance in operations management have employed perceptual measures (Chen et al., 2004; Rosenzweig et al., 2003; Zhu and Sarkis, 2004), relatively few have simultaneously used objective measures (Frohlich and Westbrook, 2001; Vachon and Klassen, 2002)."

For this study, we too lack transactions data for establishments. What we have are data on outputs and inputs for establishments grouped according to a detailed industry classification. The data on the inputs and desired outputs are assembled by the Japanese official statistics system and were given to us as I–O tables. We also have data by industry on waste production. These tables provide aggregate value flows among 399 industry sectors of the Japanese economy. As already noted, in the data collection for these national I–O tables, as is standard official statistics practice, the industry classification of each establishment was determined by the main product or products of the establishment. It is this method of classification structure that permits us to use the national I–O tables in order to back out the flows for the various tiers of suppliers for intermediate and final goods. The breakdown into 399 industry sectors, which is the level of detail at which we were given the I–O data, is believed to be fine enough to allow us mostly to capture the flows for the various tiers of suppliers for intermediate and final products for the relevant Japanese manufacturing supply chains.[22]

We show how this I–O data can be combined with detailed industry level waste and GHG data and can then be used to map out the aggregate amounts of wanted outputs and waste and GHG generated along the successive stages of supply chains. Nobel laureate Leontief (1970) foresaw the potential to use nation-level I–O data to map out industry level patterns of the production of waste along with the desired outputs, but did not explain (or perhaps see) the associated possibility of using the same assembled information from business establishments to back out supply chain I–O relationships. To our knowledge, ours is the first application of this approach for mapping out waste production along supply chains.[23]

In I–O analysis, the interdependence of an economy's industries is recognized by explicitly representing the output of each industry as consisting of an industry-specific mix of final demand (sometimes also referred to as final consumption, though both capital investment and inventory stocks are included too) and intermediate products needed for the production of other goods (i.e., products needed by other businesses as intermediate inputs).

For estimating the outputs of wanted products of a supply chain, we utilize a 399 sector I–O table for Japan. Each horizontal row describes how one industry's total product is spread over various production processes (i.e., for final demand and for the various intermediate product outputs) and final demand. And, each vertical column denotes the combination of productive resources used within an industry. For a one unit increase in final demand output (e.g., for a car), the I–O tables can be used to trace the required increases in each of the other sectors of the economy (e.g., from downstream to upstream production steps for an auto supply chain).[24]

Readers interested in our substantive findings, but not in the details of the estimation methodology, can now skip to Section 4.

3.2. Estimation of desired outputs along a supply chain

As explained in greater detail in Hayami et al. (1997) and in Hayami and Nakamura (2007), in the I–O tables from the Japanese official statistics system, each technical coefficient, denoted here by a_{ij} ($i,j = 1, 2, \ldots, n$), is the value of input from sector i per yen of output of sector j. Suppose x_j denotes the output from sector j.

[21] See, for example, Nakamura et al. (2011).

[22] What is readily available are the tables for 13 and for 104, sectors (http://www.stat.go.jp/english/data/io/io00.htm). However, we were able to gain access to data for 399 sectors. Our approach would not work well without that level of detail. Otherwise, the data for establishments producing very different sorts of intermediate or final products would all be grouped together within the cells of the I–O matrix. We use the Japanese I–O table for 2000, since that is the table that was in effect when the waste survey was implemented for which we also use data. As explained in the following section, we must use an I–O table for which a bridge matrix is provided by the Government of Japan. Otherwise, we would not be able to combine the data from the two sources.

[23] Leontief (1970, 1986) does not relate the industry flows to chain transaction patterns. One likely reason he did not focus on that further application of his industry-level I–O approach is that supply chains were a far less recognized and developed phenomenon over the years when he wrote. Also, the detail of the I–O data available then would not have been adequate for that sort of extension of his methodology we make here. He did, however, explicitly show results for the use of I–O table data to map out the inter-industry flows of waste as well as wanted products, albeit at a far higher level of aggregation then our data for Japan permit.

[24] We have used *R* to do our statistical calculations, and the programming language Python for compiling and manipulating our datasets. Further information is available on request from the authors.

The a_{ij} values are given by

$$a_{ij} = (X_{ij}/x_j), \tag{1}$$

where X_{ij} denotes the input from sector i required for the production of x_j.[25] Using supply chain terms, we say that a_{ij} connects the downstream sector j output value to its immediate predecessor upstream sector i input value.

We denote by A an $n \times n$ matrix with elements a_{ij}, and by x an $n \times 1$ vector in which each component x_j represents the production (output) of a sector j (j=1, 2,.., n). We also denote by f_i the final downstream demand for sector i, and f denotes the corresponding $n \times 1$ final downstream demand vector.[26] Thus, $f_i = 1$ denotes a one unit final demand for sector i output.

In order to produce the final downstream demand f, the total amount of input required from sector i in the first intermediate predecessor stage (denoted by $k=1$) is given by the ith element of the vector

$$x^{(k=1)} = Af. \tag{2}$$

Here the ith element of $x^{(1)}$ can also be interpreted as the indirect demand for sector i for the first intermediate predecessor production stage ($k=1$) which is induced by final demand f. In order to produce $x^{(1)}$, the total amount of input required from sector i in the next intermediate predecessor stage (denoted by $k=2$) is given by the ith element of the following vector:

$$x^{(2)} = Ax^{(1)} = A^2 f. \tag{3}$$

Tracing production activities backward along the supply chain, we get

$$x^{(k)} = Ax^{(k-1)} = A^k f, \quad k = 1, 2, \ldots\ldots \tag{4}$$

Here $x^{(k)}$ denotes the kth stage indirect output of final demand f (k=1, 2, ...) for the average supply chain for each final demand category. In supply chain terms, the final assembler produces the final product represented in the respective element of vector f, using inputs $x^{(1)}$ (from their first-tier suppliers), $x^{(2)}$ (from their second-tier suppliers), $x^{(3)}$ (from their third-tier suppliers), and so on, with each of the designated sorts of inputs being in a different product group and hence in a different group for the industry classification used for the I–O tables for Japan. This breakdown is illustrated in the row labeled "production output along the stages of a supply chain" in Table 1. So to produce final demand f, the following total indirect output must be produced[27]:

$$x^{(indirect)} = Af + A^2 f + \ldots\ldots\ldots + A^k f + \ldots\ldots = A(I-A)^{-1} f \tag{5}$$

As already noted and is generally the case for studies in this subject area, we lack establishment level data on the flow of goods and services that expands out from the downstream final assemblers to the upstream first tier suppliers, and to their suppliers, and so on. However element a_{ij} of the I–O matrix $A = \{a_{ij}, i,j = 1, 2, .., n\}$ is the reported average fraction of output of sector i that goes to sector j. Matrix A (called the commodity flow method in the I–O literature) thus allocates input X_{ij} from the reported total output for jth sector x_j (United Nations, 1999). That is, a_{ij} statistically connects downstream sector j to its immediate upstream sector i. We have used this property of matrix A to estimate the average production of wanted and unwanted outputs along the stages of the average supply chain, given $x^{(k)}$ and $w^{(k)}$ where k=1, 2, ..., denote the categories of final demand as represented in the observed downstream demand vector f. (This is a first-order approximation rather than an exact result because of the linearity embedded in the computation of the a_{ij} values which define the I–O matrix A.)

Our estimation methodology uses an $n \times n$ matrix A consisting of I–O technical coefficients a_{ij} (i, j=1, 2, ..., n), where n is the number of industries or sectors represented. Estimated values for a_{ij} (i, j=1, 2, ..., n) are published by the Japanese government every five years in the form of I–O tables for various levels of aggregation. In this paper, we use the Japanese I–O table for Year 2000 with 399 sectors (n=399). In addition to the I–O matrix $A = \{a_{ij}$ (i, j=1, 2, ..., n)$\}$, the Japanese I–O table includes additional information on economic performance for establishments in each of the 399 sectors.

3.3. Estimation of the production of waste by-products along a supply chain

Our next task is to relate the production of waste along a supply chain to the production of desired products. For data reasons, we treat the undesired waste materials and the GHG emissions separately from each other and from the production of desired outputs. The Japanese Ministry of Economy, Trade and Industry (METI) has been conducting annual waste and by-products surveys of Japanese establishments sampled at the 4 digit industry level of the Japan standard industrial classification (JSIC). At this level, there are 562 SIC industry sectors (q=562). We use the data from the 2006 Waste and By-Products Survey (WBPS) based on responses from 5048 establishments and 1700 companies regarding the amounts of waste materials they generated.[28] The WBPS survey asked each establishment to report the amount it created in the reporting period for each of 37 types of waste. These by-products are listed in Table A1 in Appendix A along with two characteristics: toxic versus non-toxic, and solid versus liquid. This information aggregated to the level of the 562 JSIC sectors at which the data were provided to us is represented here by y, which is a qx1vector.[29]

Letting $E1_j$ denote the amount of waste generated per unit of output produced in sector j (j=1, 2, ..., n), and denoting by E the corresponding $n \times n$ diagonal matrix with $E1_j$ in the jth diagonal position, the amount of waste material produced by sector j at each successive stage of a supply chain is given as follows. In the final stage 0 (k=0) of a supply chain, the demand is f and the waste generated is

$$w^{(0)} = EA^0 f = Ef, \tag{6}$$

which is the waste generated from assembly operations for the final output f. Here we denote by w_j the amount of waste generated in sector j, and w denotes an $n \times 1$ vector consisting of w_j (j=1, 2, .., n).

[25] To ensure positive output values, it is assumed that the Hawkins–Simon condition (Solow, 1952) is satisfied. In our notation, this condition is satisfied if the a_{ij} all lie between 0 and 1 and their column sums are less than one.

[26] We must ignore the explicit impacts of international trade; the data available to us do not allow us to differentiate between inputs produced domestically versus in other nations.

[27] In (5) $(I-A)^{-1}$, the Leontief inverse matrix, exists if the a_{ij} satisfy the Hawkins–Simon condition given above.

[28] See the National Institute for Environment (NIES) (2010). http://www.nies.go.jp/gaiyo/pamphlet/nies2013-e.pdf.

[29] Based on a comparison of the I–O matrix A and the waste data used in our calculations for this study with new data recently released in Japan, we find the differences to be small, which is fortunate for our analysis. The data we use are the most suitable that were available for our purposes. National level I–O tables are not updated frequently using comprehensive fresh data (revisions referred to as "benchmark") in any nation we know of, though efforts are made in some nations to use annual Gross Domestic Product and other national balance sheet statistics produced annually to make annual adjustments to the benchmark national level I–O table produced based on data collection exercises repeated only every several years.

Table 1
Production and waste output along the stages of a supply chain.[a]

Upstream	Stages of a supply chain →→→closer to the final demand→→→					Downstream: final stage of a supply chain (final demand)
Total indirect output and waste in upstream stages (k=1, 2, .., ..)	←←←	Indirect output for the mth stage in upstream ($k=m$)	←←←	Indirect output for the second stage in upstream (k=2)	Indirect output for the first stage in upstream (k=1)	Direct output for final assembler (stage, k=0)
Production output along the stages of a supply chain						
$x^{(\text{indirect})}=Af+A^2f+\ldots\ldots+A^kf+\ldots.=A(I-A)^{-1}f$	←←←	$x^{(m)}=Ax^{(m-1)}=A^mf.$	←←←	$x^{(2)}=x^{(1)}=A^2f.$	$x^{(1)}=f.$	f (direct output, final demand)
Waste output generated along the stages of a supply chain						
$w^{(\text{indirect})}=EAf+EA^2f+\ldots\ldots..+EA^kf+\ldots.=EA(I-A)^{-1}f$	←←←	$w^{(m)}=EA^mf.$	←←←	$w^{(2)}=EA^2f.$	$w^{(1)}=EAf.$	Ef (direct waste generated)

[a] A supply chain here consists of final assembler (k=0) and kth tier suppliers (k=1, 2, 3, …). For example, vectors f and Ef denote, respectively, final assemblers' production output and output of wastes and GHG emissions. Production output by first and second tier suppliers to final assembler are, respectively, denoted by $x^{(1)}=Af$ and $x^{(2)}=Ax^{(1)}=A^2f$. Total output by suppliers to final assembler is given by $x^{(\text{indirect})}=Af+A^2f+\ldots\ldots+A^kf+\ldots.=A(I-A)^{-1}f$ in the first column. The same relationship holds for Ef and $w^{(k)}$ (see the last row).

In the immediate predecessor upstream stage 1 (i.e., $k=1$) of a supply chain, the amount of waste generated (called the indirect output for stage 1) can be represented as

$$w^{(1)}=EAx^{(0)}=EAf. \tag{7}$$

Similarly we can derive the amount of waste generated along the upstream stages (k=2, 3,..,) of the supply chain as

$$w^{(k)}=EAx^{(k-1)}=EA^kf, \quad k=2,\ 3,\ \ldots\ldots. \tag{8}$$

These waste product amounts are represented in the row labeled "waste output generated along the stages of a supply chain" at the bottom of Table 1.

The industry classifications for which we have waste data differ from the industry classifications for our I–O table data. Fortunately, however, a so-called bridge matrix, denoted here by B, is provided as a supplement to the Japanese input–output tables and can be used to merge the WBRS waste data provided according to the 562-sector SIC system into the 399 sectors for the Japanese I–O data. B consists of elements b_{is} for i=1, 2, .., n and s=1, 2, .., q where n=399, and q=562. Here b_{is} represents the amount of input of I–O sector i that is required to produce the unit amount of output in SIC sector s.

Using B, the output vector y for the SIC sectors can be rewritten as $x=By$, where output vector x in the I–O table denotes the total production of the Japanese economy and vector y denotes the output for the sample being surveyed in the WBPS dataset. Matrix B bridges the two classification systems and also includes a government supplied scaling factor that blows up the sample WBPS figures into estimates for the national economy.

Suppose that the amount of a particular waste material generated by SIC sector s reported in the WBPS is given by z_s, s=1,2, .., q. Then, the estimated amounts of the waste materials generated in the 399 I–O sectors are given by an $n\times 1$ vector w consisting of elements w_i, i=1, 2, .., n, with w defined by

$$w=B\,z. \tag{9}$$

The vector w represents the final output vector for waste for the I–O sectors and satisfies the same I–O relationships as for x and f. As mentioned above, this vector is represented in the last row of Table 1.

Using the above procedure, we estimated amounts of waste by-products for each of the I–O sectors, measured per unit output (one million yen worth of output), with one million yen worth about $9345.79 using the year 2000 exchange rate.

In this paper we consider multiple waste materials associated with industrial production activities. (Appendix B gives further details and a numerical example.) We use the estimated waste amounts for each of the 37 types of solid and liquid waste in multiple ways. For some sorts of analysis, the different types are treated separately. For other sorts, we work with the categories of toxic and non-toxic waste. And, for our measure of GHG emissions, we use the sum total of GHG emissions for all the different greenhouse gases for which we have data, with the data aggregated in the form of carbon dioxide equivalents.[30]

4. Empirical findings

As explained in Section 3, our methodology and data allow us to break out successive upstream production supply chain stages for each industry-specific product group in the final demand vector. The analysis typically starts from the final stage of downstream demand, as shown in Fig. B1 in Appendix B, and moves backward through the predecessor upstream stages of production. We now turn to empirical discussions of our two hypotheses.

4.1. Discussion of results for hypothesis H1

Fig. 1 shows the relative shares of indirect waste generation (totals for all 37 wastes combined, and GHG emissions) along supply chains in different Japanese manufacturing industries for which we have data. These figures of direct and indirect waste generation were computed using our input–output method discussed in the previous section. We see from Fig. 1 that, in assembly dominated manufacturing industries (industries 9 through 13 here), the generation of toxic waste and GHG emissions is systematically skewed towards upstream firms of supply chains.[31] Simple t-tests reject the null hypotheses of no difference in the means between the resource intensive assembly based manufacturing industries and other industries for both toxic wastes and GHG emissions. Hence hypothesis H1 is accepted.

The resource intensive assembly based manufacturing industries (industries 9 through 13) have the largest relative shares of indirect waste generation.

[30] We use our estimates for GHG emissions obtained in an earlier study that are based on the estimated emissions data and Japanese Input–Output database as stated above (Hayami and Nakamura, 2007).

[31] See Hayami and Nakamura (2013).

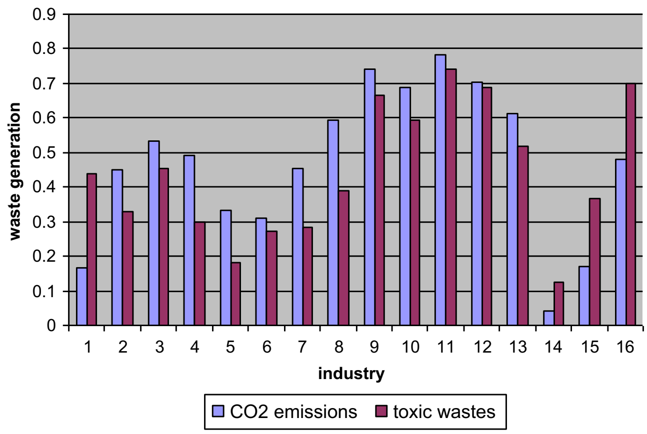

Fig. 1. Shares of waste generation by upstream firms (indirect generation): GHG emissions (denoted by CO_2 here) and toxic wastes (Series 1=GHG emissions. Series 2=toxic wastes). *Notes*: The amounts of the wastes generated were obtained by the authors using the input–output analysis. The ratios of the indirect generation to the sum of direct and indirect generation are reported here. Industries 9, 10, 11, 12 and 13 are assembly based industries. Simple *t*-tests reject the null hypothesis of no difference in the means between assembly based manufacturing industries and other industries for both CO_2 and toxic wastes decisively. *P* values for CO_2 are: 0.00003 (1-sided) and 0.00006 (2-sided). *P*-values for toxic wastes are: 0.02352 (1-sided) and 0.04703 (2-sided). The industries included in the figure are below. (*Note*: * means assembly based manufacturing industries.). List of industries: (1) Mining; (2) Food Production; (3) Textiles; (4) Pulp/paper; (5) Chemicals; (6) Petro/coal production; (7) Basic materials; (8) Non-ferrous metals production; (9*) general Machinery; (10*) Electric machinery; (11*) Auto; (12*) Transportation machinery; (13*) Precision machinery; (14) Electric power; (15) Public utility; (16) Service.

4.2. Discussion of results for hypothesis H2, our Green Pays hypothesis

Using regression analysis, the estimated toxic and nontoxic waste and GHG emissions for each upstream stage in the production of the final demand output for an industry can now be related to the data regarding the economic performance of the producers. This combined data set can be used to test our Green Pays hypothesis, given in Section 2. We restate that hypothesis here taking account of the specifics that we have data on the generation at each stage along a manufacturing supply gain of GHG as well as for solid and liquid waste. Moreover, for the solid and liquid waste products, we know which are toxic versus nontoxic. These additional pieces of information can be used to further modify our Green Pays hypothesis, as it is now restated here:

Modified H2. The economic performance of a downstream assembler firm is negatively affected by not only their own toxic waste and GHG generation, but also by the generation of these pollutants by its upstream suppliers.

In this paper, we measure economic performance for a final assembler firm by its value added per yen of annual output.[32] We expect that upstream firm toxic waste and GHG generation have negative impacts on the assembler firm value added, but that generation of nontoxic waste may not have a negative effect or could even have a positive effect since some nontoxic waste has commercial value.

Many regressions were run with value added as the dependent variable and explanatory variables consisting of alternative measures of the amount of pollutants generated directly by downstream assembler firms as well as the amounts generated indirectly by their upstream suppliers.[33] For example, in Table 2, we show the results when we focus on two particular sorts of toxic waste (waste plastics and used acidic liquid).

From row 2 of Table 2, we see that the estimated impacts per yen on firm value added due to a one ton increase of direct output of waste plastics, used acidic liquid or GHG, respectively, are estimated to be −1.33696, −0.07225 and −0.00180, respectively. Next, from row 3, the corresponding estimates of the contributions to firm value added due to the indirect waste output from first stage upstream suppliers are seen to be −6.71895, −0.59712 and −0.01154. Comparing these values with the respective row 2 direct waste output effects, we see that the indirect waste output effects are both considerably larger in magnitude and are more statistically significant.

The results shown in columns D, E and F of Table 2 differ in that we now take account of all upstream waste production instead of only what comes from first stage suppliers. We see that the direct waste output impacts in row 2 are still negative, but are no longer statistically different from zero. However, for the indirect effects shown in row 4 for all upstream stages, the impacts on the downstream assembler firm value added are larger and these coefficients are significant.

In the first two columns of Table 3, regression results are reported for two specifications: with direct and first-stage indirect pollutant output terms for both toxic and nontoxic waste products (column A); and with direct and first-stage indirect pollutant output terms for toxic and nontoxic waste products as well as, in this case, the effects of GHG emissions (column B). Both regressions show that firm value added is negatively affected by both direct and first-stage indirect toxic waste output (rows 2 and 3) with the indirect effects being greater. The GHG emissions coefficients in column B (rows 8 and 9) have negative signs too as expected, but are statistically insignificant. On the other hand, for the nontoxic waste, the direct effects are negative but insignificant (row 5) and the first-stage indirect effects are significantly positive (row 6). This is consistent with the reality that *non*toxic waste often has commercial value. In the regressions reported in columns C and D, the estimated impacts of upstream firm indirect toxic waste output as well as the GHG emissions are for all upstream stages combined (in contrast to just the first-stage upstream stage). The results are consistent with those in columns A and B.

Our results in Tables 2 and 3 show that downstream assembler firm performance, measured by firm value added, is negatively affected by the toxic waste and GHG production of their upstream supply chain partners in addition to the immediate negative impacts of their own toxic waste and GHG production. These empirical findings support our Green Pays hypothesis.

The regressions for which results are shown in Tables 2 and 3 are a small subset of the specifications of potential interest and for which we produced results. Looking at our full results, in general, we find that final assembler firms face significant financial losses, measured by their value added, from direct and especially from indirect output of toxic waste solids and liquids. Moreover, the indirect effects are consistently more negative than the direct effects. The corresponding GHG effects are generally negative, but mostly are not statistically significant. And the corresponding nontoxic waste effects are a mix of negative and positive impacts.

These results, in an overall sense, suggest that downstream assemblers have economic incentives to reduce not only their own

[32] We repeated our estimation using other measures of economic performance, including profit defined in various ways, and obtained essentially the same results. Value added, standardized as we have done, is thought to better reflect the general economic performance of firms.

[33] All standard errors shown in our tables for regression results are heteroskedasticity-corrected (e.g., White, 1980).

Table 2
Determinants of downstream assembler firms' value added, direct and indirect effects by type of waste.

	Type of waste					
	A. Waste plastics	B. Acidic liquid	C. GHG	D. Waste plastics	E. Acidic liquid	F. GHG
1. Constant	0.4871[a] (0.0105)	0.4561[a] (0.0093)	0.4640[a] (0.0099)	0.5264[a] (0.0163)	0.4835[a] (0.0099)	0.5087[a] (0.0204)
2. Direct waste (downstream)	−1.3370[a] (0.5115)	−0.0722 (0.0617)	−0.0018[c] (0.0011)	−0.9390 (0.6127)	−0.0262 (0.0638)	−0.0016 (0.0011)
3. Indirect waste (upstream, first stage)	−6.7190[a] (1.3692)	−0.5971[a] (0.1926)	−0.0115[a] (0.0030)	–	–	–
4. Indirect waste (upstream total, all stages)	–	–	–	−7.4655 (2.1850)	−0.7464[a] (0.1352)	−0.0150[b] (0.0070)
5. Adjusted R^2	0.1102	0.0429	0.0437	0.1567	0.0730	0.1210
No. of obs.	396	396	396	396	396	396

Columns B and E: used acidic liquid. Columns C and F: waste plastics excluding synthetic rubber.

[a] Significance for a two-sided critical region of 0.01 using heteroskedasticity corrected standard errors.
[b] Significance for a two-sided critical region of 0.05 using heteroskedasticity corrected standard errors.
[c] Significance for a two-sided critical region of 0.101 using heteroskedasticity corrected standard errors.

Table 3
Direct and indirect effects by type of waste on downstream firm value added.

		A	B	C	D
1.	Constant	0.4900[a] (0.0106)	0.4935[a] (0.0110)	0.5433[a] (0.0135)	0.5591[a] (0.0144)
2.	Direct toxic waste (downstream)	−0.0707[a] (0.0263)	−0.0586[b] (0.0279)	−0.0489[b] (0.0241)	−0.0145 (0.0211)
3.	Indirect toxic waste (upstream, first stage)	−0.3701[a] (0.0798)	−0.3656[a] (0.0825)	–	–
4.	Indirect toxic waste (upstream total, all stages)	–	–	−0.4200[a] (0.0623)	−0.3684[a] (0.0667)
5.	Direct nontoxic waste (downstream)	−0.0025 (0.0045)	−0.0005 (0.0048)	−0.0050 (0.0071)	0.0003 (0.0027)
6.	Indirect nontoxic waste (upstream, first stage)	0.0358[b] (0.0184)	0.0467[b] (0.0235)	–	–
7.	Indirect nontoxic waste (upstream total, all stages)	–	–	0.0481[a] (0.0133)	0.0862[a] (0.0180)
8.	Direct GHG emissions (downstream)	–	−0.0011 (0.0012)	–	−0.0014 (0.0012)
9.	Indirect GHG emissions (upstream, first stage)	–	−0.0037 (0.0051)	–	–
10.	Indirect GHG emissions (upstream total, all stages)	–	–	–	−0.0138[a] (0.0042)
11.	Adjusted R^2	0.1224	0.1216	0.2279	0.2279
	No. of obs.	394	394	394	394

[c]Significance for a two-sided critical region of 0.10 using heteroskedasticity corrected standard errors.

[a] Significance for a two-sided critical region of 0.01 using heteroskedasticity corrected standard errors.
[b] Significance for a two-sided critical region of 0.05 using heteroskedasticity corrected standard errors.

production of toxic waste and perhaps also of GHG, but also the toxic waste and perhaps also the GHG outputs of their suppliers. The theories and findings of others motivated our study and provided the insight for our empirical methodology, and our empirical findings are complementary to the findings of others, based on survey and other sorts of data and analysis methodologies (e.g., Bhateja et al., 2011; Chiou et al., 2011; Genovese et al., 2013; Wong et al., 2012). Our results constitute a new use of the industry level data for Japan: a use that can be replicated for other nations if they make available to researchers input–output data at a sufficiently detailed level of aggregation. We hope our paper will provide a motivation for other nations to allow researchers easier access to detailed national level input–output data. These results also demonstrate to managers in supply chains the level of sharing of data needed for a similar analysis to be conducted for an individual supply chain.

Finally we point out that our empirical results are also consistent with and explained by management theoretical perspectives discussed in Section 2. For example, RBT, relative theory, and related management theories focus on the resource capacities of each of the suppliers and their main customer (e.g. the downstream assembler). These theories also imply the emergence of collaboration among these supply chain members (Vachon and Klassen, 2008). Particularly Vachon and Klassen (2008, pp. 302–303) emphasize environmental collaboration as a potential consequence of well-functioning supply chain behavior and state that such collaboration can generate a supply chain competitive advantage, leading to cost and quality advantages for the supply chain. They state: “The competitive advantages generated by environmental collaboration are twofold. First, collaboration includes knowledge integration and cooperation between organizations, which are recognized as resources that might generate competitive advantage… As such, manufacturing organizations adopting collaborative activities with their suppliers and customers can develop organizational capabilities, which can be expected to translate not only into improved environmental performance, but also into other dimensions, such as cost and quality.”

Our empirical results, which connect upstream supplier environmental performance to final assembler financial (cost) performance, are consistent with the management theoretical implications and empirical findings put forward by Vachon and Klassen (2008) and others.[34]

5. Concluding remarks

Stimulated by recent management interest in green procurement, sustainability and other environmental management practices for

[34] For example, see references cited in Vachon and Klassen (2008). Our results are also consistent with Vachon and Klassen's (2008) own empirical findings.

supply chains, our empirical methods build on supply chain theories and empirical results of others that take account of environmental as well as economic performance. We use available industry level data to examine two hypotheses. One is that assembler dominated manufacturing supply chains have different within-chain waste generation patterns than manufacturing supply chains that are not assembler dominated. A second is that assemblers with suppliers that produce less waste tend also to have better economic performance: our Green Pays hypothesis. The empirical results support both hypotheses.

The results of this study suggest that encouraging suppliers to reduce waste can lead to internal green product, process and managerial innovations *and* can enhance competitive advantage. If this is so, then the main driving forces for implementation of environmental management include not only compliance with regulations and legislation but also cost savings. If such a downstream assembler implements green procurement policies successfully for their upstream suppliers, our empirical results suggest that the assembler firm's cost performance will improve. Upstream suppliers will likely do better too in economic terms if they produce less waste output.[35] This finding is of practical importance to managers given increasing amounts of firm investment in improving supply chain environmental performance for sustainability, as noted by Ernst & Young (2010, p. 7).[36]

Dominant downstream assembler firms, of course, have multiple means of influencing the business decisions of their upstream suppliers including various specifics of how these plants carry out the purchasing they do from suppliers. One implication of our results is that it may be important to modify public regulations to take into account interrelationships and incentives within supply chains rather than focusing on individual firms and/or establishments as is current practice. Few other studies have considered extended supply chain integration beyond first-tier suppliers and customers (Jayaram et al., 2010). Hence our treatment in this study of the interactions of a dominant assembler with its upstream suppliers is another novel aspect of our study: one, we believe, with potentially important public policy and applied practice implications.

Appendix A

See Tables A1 and A2.

Appendix B. A numerical illustration of waste generation along an average supply chain

We consider the supply chain illustrated in Fig. B1. The JSIC code for an automobile assembly plant in the WBPS is "JSIC 3011", which includes Toyota's Corollas and Honda's CIVICs. JSIC code 3011 corresponds to I–O table classification code 351101 (passenger motor car). The WBPS JSIC code 3013 is for output for both engines and engine parts combined. JSIC code 3013 corresponds to I–O table code 354102 ("internal combustion engines for motor vehicles and parts"). In year 2000, the I–O table indicates that sector 351101 (passenger motor car) received supplies from sector 354102 ("internal combustion engines for motor vehicles and parts") in the amount of 1,938,904 million yen. The output amount for sector 351101 ("passenger motor car") is reported to be 12,180,299 million yen in the I–O table. Hence, the input coefficient for this relationship is given by $a_{ij}=1{,}938{,}904/12{,}180{,}299=0.1592$ where i=sector 354102 and j=sector 351101.

The amount of waste generated is calculated for each type. For example, from the WBPS survey we know that the amount of waste plastics (excl. synthetic rubber) generated at two sample auto assembly plants was 0.0018 tons per million yen, and 0.0015 tons per million yen. Waste plastic generation rates at these two assembly plants are found to be below the industry average (the average of all auto assembly plants in the sample), 0.0023. We see that output for I–O sector 351101 ("passenger motor car") was 12,180,299 million yen, while the total amount of waste plastics generated was 28,025 tons ($=12{,}180{,}299\times0.0023$). This is the direct effect of waste plastic generation.

The amount of output for I–O sector 3541021 ("internal combustion engines for motor vehicles and parts"), which is the passenger car assembly sector's immediate upstream predecessor, can be calculated as the product of the input coefficient 0.1592 obtained earlier and the output (in million yen) for the I–O car assembly sector 351101. According to the WBPS survey, the "internal combustion engines for motor vehicles and parts" sector has a relatively high sector generation of non-ferrous metal scraps. Its generation rate (calculated as the average amount generated at the sample establishments) is 0.0137 tons per every million yen of output. Using these figures we can calculate the amount of non-ferrous metal scraps generated in the "internal combustion engines for motor vehicles and parts" sector indirectly in the course of meeting their downstream demand; i.e., 0.0022 ($=0.1592\times0.0137$) tons of non-ferrous scrap per million yen of output as the first stage indirect effect.

This illustrates the supply chain effects for the propagation of waste generation along the supply chain. We see that passenger car assembly plants do not generate any significant amount of non-ferrous metal scraps, but their immediate upstream predecessors, which are the suppliers of internal combustion engines for motor vehicles and parts, do. Moreover, they are induced to do so by the downstream assembly activities.

Fig. B1 illustrates the first two upstream stages of the supply chain for production of automobiles (the final demand).

For the year 2000, our calculations show that passenger car production directly and indirectly generated 53,962 tons of toxic "inorganic sludge polishing sand." Most of this toxic material was, in fact, produced in upstream industries. In particular, 49,728 tons were produced in the "sheet glass and safety glass" industry, and 3004 tons were produced in the process of generating the "electricity" required for car assembly.

The total amount of nontoxic "waste plastics other than synthetic rubber" from passenger car production was 61,800 tons. Of this, the upstream "motor vehicle parts and accessories" industries produced 31,729 tons, and the downstream "passenger motor cars" assembly industry accounted for 28,188 tons.

Table B1 and Fig. B1 illustrate how the production of output and waste takes place along a supply chain, starting from the final downstream demand. Tracing backward, we see that the final assembly plant receives inputs from suppliers in upstream stage 1. The assembly plant level, in turn, gets inputs from suppliers in upstream stage 2. As previously shown, I–O analysis allowed us to estimate inputs for successive pairs of production along a supply chain.

[35] Toyota's procurement policies roughly follow this scheme in which suppliers are asked to work hard to improve their management quality (Toyota Motors, 2013). Suppliers who successfully improve their management quality are then rewarded.

[36] This phenomenon is not limited to assembly based manufacturing industries or to supply chains in Japan. The Walmart supply chain is an example of this point (see, for example, Nakamura et al. (2009) and Freeman et al. (2011)). We have focused in this study on Japanese assembler dominated supply chains because that is what the data we have access to are suitable to study.

Table A1
METI (2006) list of 37 waste materials.[a,b]

1	Toxic	Solid	Cinders other than coal
2	Toxic	Solid	Coal cinders
3	Toxic	Liquid	Inorganic sludge other than polishing sand
4	Toxic	Liquid	Inorganic sludge polishing sand
5	Toxic	Liquid	Organic sludge
6	Toxic	Liquid	Organic and inorganic mixed sludge other than polishing sand
7	Toxic	Liquid	Organic and inorganic mixed sludge polishing sand
8	Toxic	Liquid	Waste oil other than chlorinated solvent waste
9	Toxic	Liquid	Waste oil chlorinated solvent waste
10	Toxic	Liquid	Used acidic liquid
11	Toxic	Liquid	Waste alkali
12	Non-toxic	Solid	Waste plastics other than synthetic rubber
13	Toxic	Solid	Waste plastics synthetic rubber
14	Non-toxic	Solid	Wastepaper
15	Non-toxic	Solid	Chips and sawdust
16	Non-toxic	Solid	Waste textile
17	Toxic	Solid	Animal and vegetable remnants
18	Toxic	Solid	Waste animal-solidified
19	Non-toxic	Solid	Rubber waste
20	Non-toxic	Solid	Scrap iron
21	Non-toxic	Solid	Non-ferrous metal scrap
22	Non-toxic	Solid	Scrap glass
23	Non-toxic	Solid	Clay, porcelain, ceramic scrap
24	Non-toxic	Solid	Scrap slab concrete
25	Non-toxic	Solid	Waste molding sands
26	Non-toxic	Solid	Slag other than steel, ferroalloy, and copper
27	Non-toxic	Solid	Iron–steel slag
28	Non-toxic	Solid	Ferroalloy slag
29	Non-toxic	Solid	Copper slag
30	Non-toxic	Solid	Slag other than aluminum dross
31	Non-toxic	Solid	Aluminum dross
32	Non-toxic	Solid	Demolition debris
33	Toxic	Solid	Animal manure
34	Toxic	Solid	Animal carcasses
35	Toxic	Solid	Soot and dust other than coal ash
36	Toxic	Solid	Soot and dust fly ash
37	Toxic	Solid	Processed material for disposal of industrial waste[a]

[a] Our 37 waste materials are based on the list of “processed material for disposal of industrial waste” in the Enforcement Ordinance of Japan's 1970 Waste Disposal and Public Cleansing Act.
[b] The distinction between toxic and non-toxic waste and between solid and liquid waste are given by the authors.

Table A2
Descriptive statistics for the variables used in our regression analysis[a,b]

	Mean	Std. dev.	Median	Min.	Max.	No. obs.
Value added (dependent variable)	0.444286	0.180905	0.408066	0	0.929868	396
GHG						
direct	1.814885	8.023135	0.248137	0	104.2946	396
indirect (all stages)	2.990289	3.992681	1.985274	0	52.45152	396
indirect waste (first stage)	1.423722	2.995839	0.715933	0	44.98735	396
Used acidic liquid						
Direct	0.028767	0.167127	0.000138	0	2.229173	396
Indirect (all stages)	0.029191	0.063672	0.013229	0.000444	0.553377	396
Indirect waste (first stage)	0.016306	0.053554	0.003816	0	0.477698	396
Waste plastics						
Direct	0.008069	0.018504	0.001896	0	0.163885	396
Indirect (all stages)	0.007748	0.008339	0.005149	0.000343	0.091676	396
Indirect waste (first stage)	0.004772	0.006913	0.002517	2.63E−05	0.085598	396
Toxic wastes						
Direct	0.153035	0.384913	0.008867	0	3.385166	396
Indirect (all stages)	0.207204	0.229386	0.150398	0.007886	2.074821	396
Indirect waste (first stage)	0.102049	0.156837	0.058331	0.000101	1.909365	396
Nontoxic wastes						
Direct	0.264867	1.979931	0.015105	0	32.65348	396
Indirect (all stages)	0.281684	0.871492	0.084083	0.00301	11.4848	396
Indirect waste (first stage)	0.098091	0.618622	0.023146	0.000132	11.23971	396

[a] The dataset used was compiled by the authors using *The Waste and By-Products Surveys of Japanese Establishments* (METI, 2006), and *Input–Output Tables for Japan* (MIAC, 2000, 2005), available from http://www.stat.go.jp/english/data/io/index.htm.
[b] Value added and direct waste outputs are measured per sector output. Indirect waste output for each stage is measured per total indirect output (all stages combined).

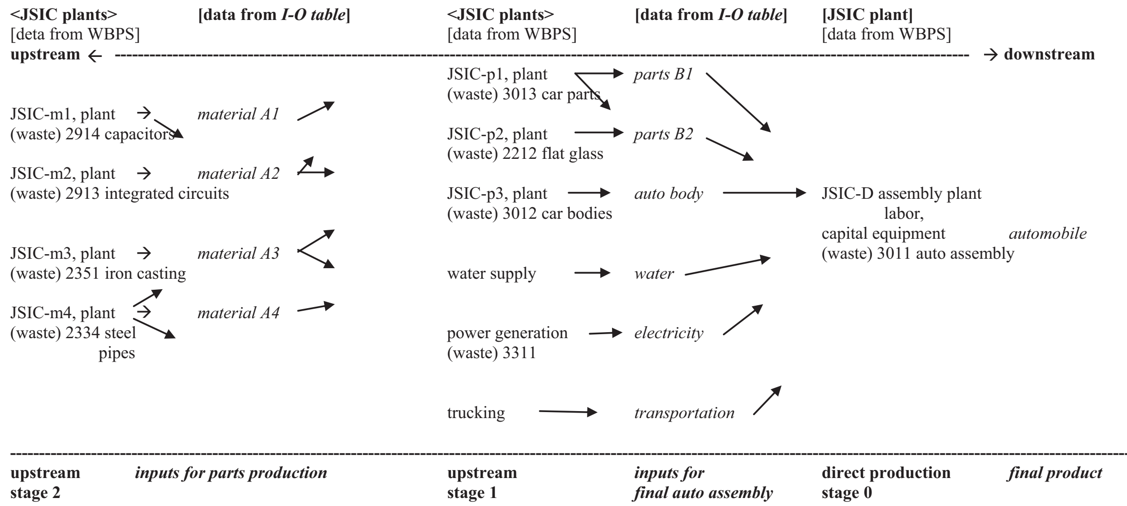

Fig. B1. Auto assembly, supply chain stages with example suppliers and JSIC codes, and the sources of data used: I–O table, waste and by-product survey and Japan SIC classification. *Notes*: In this illustration final production takes place in stage 0. Assembly plant D receives inputs from its supplier plants p1, p2, etc. in the immediate upstream stage, upstream stage 1. Similarly, plants p1, p2, etc. receive inputs from plants m1, m2, etc. in upstream stage 2, the immediate upstream stage. WBPS gives the 4-digit JSIC code to each plant in the sample. WBPS also gives the bridge matrix (B in the text) that re-classify outputs from JSIC plants into I–O sector outputs. WBPS does not distinguish production activities among supply chain stages. We estimate such stage-specific production activity for JSIC industries using I–O analysis. WBPS surveys provide data on wastes at establishments in manufacturing, gas supply and power generation industries. The complete names of the above JSIC classification industries are as follows: 2914 (resistors, capacitors, transformers and composite parts); 2913 (integrated circuits); 2351 (iron castings, except cast iron pipes and malleable iron castings); 2334 (steel pipes and tubes), 3013 (motor vehicles parts and accessories); 2212 (processed flat glass); 3012 (motor vehicles bodies and trailers); 3311 (electric power generation); 3011 (motor vehicles bodies and trailers).

Table B1
Auto industry supply chain effects: waste generated by production of one passenger car with a 2000 cm^3 engine.[a]

Waste generation stage: direct, indirect (1–4)[b]	Amounts generated (tons)	Cumulative amounts (tons)[c]	Ratio to total
Panel A: toxic wastes			
Direct	0.016649	0.016649	0.037535
Indirect (1st stage)	0.061244	0.077892	0.175611
Indirect (2nd stage)	0.119776	0.197668	0.44565
Indirect (3rd stage)	0.111914	0.309583	0.697965
Indirect (4th stage)	0.070204	0.379787	0.856242
Total (all stages)	0.44355	0.443550	1
Panel B: GHG			
Direct	0.107625	0.107625	0.020439
Indirect (1st stage)	0.706568	0.814193	0.15462
Indirect (2nd stage)	1.205888	2.020081	0.383625
Indirect (3rd stage)	1.151894	3.171974	0.602376
Indirect (4th stage)	0.896974	4.068948	0.772717
Total (all stages)	5.26577	5.265770	1
Panel C: nontoxic wastes			
Direct	0.227419	0.227419	0.216778
Indirect (1st stage)	0.201553	0.428972	0.408899
Indirect (2nd stage)	0.106076	0.535048	0.510012
Indirect (3rd stage)	0.142937	0.677985	0.64626
Indirect (4th stage)	0.161449	0.839433	0.800154
Total (all stages)	1.04909	1.04909	1

[a] Source: Authors' calculation.
[b] As noted in Table 1, direct waste output was generated by final assembler. Indirect (1st stage) waste output was generated by first-tier suppliers; indirect (2nd stage) waste was generated by second-tier suppliers, and so on. Total waste output is the sum of direct waste output by final assembler and waste output by all suppliers from all indirect (i.e. (1st+2nd+3rd+…..) stages).
[c] Cumulative quantity excludes waste that has been processed/recycled out of the production process.

Table C1
Generation of toxic wastes by supply chains per production of a passenger car with a 2000 cm^3 engine: auto industry.

Auto: toxic wastes		Ton per 1 passenger car (2000 cm^3 equivalent)									
Direct		1st Stage indirect		2nd Stage indirect		3rd Indirect		4th Indirect		Total Generation	
Passenger motor cars	0.0166	Motor vehicle parts and accessories	0.0129	Electricity	0.02941	Electricity	0.0179	Pig iron	0.013704	Electricity	0.0692
		Electricity	0.0092	Coated steel	0.01389	Hot rolled steel	0.0138	Crude steel (converters)	0.0085	Pig iron	0.0443
		Sheet glass and safety glass	0.0088	Hot rolled steel	0.01205	Cold-finished steel	0.0109	Electricity	0.007014	Hot rolled steel	0.0391
		Cold-finished steel	0.0050	Cold-finished steel	0.00853	Pig iron	0.0078	Hot rolled steel	0.006821	Cold-finished steel	0.0274
		Internal combustion engines for motor vehicles and parts	0.0047	Thermoplastics resins	0.00407	Crude steel (converters)	0.0076	Cyclic intermediates	0.004793	Crude steel (converters)	0.0242
		Hot rolled steel	0.0043	Synthetic rubber	0.00399	Cyclic intermediates	0.0063	Paper	0.003634	Coated steel	0.0189
		Plastic products	0.0025	Steel pipes and tubes	0.00391	Paper	0.0049	Crude steel (electric furnaces)	0.003136	Passenger motor cars	0.0166
		Motor vehicle bodies	0.0023	Other final chemical products	0.00350	Aliphatic intermediates	0.0040	Aliphatic intermediates	0.002644	Motor vehicle parts and accessories	0.0137
		Coated steel	0.0016	Plastic products	0.00340	Thermoplastics resins	0.0034	Petrochemical basic products	0.002277	Paper	0.0136
		Abrasive	0.0016	Crude steel (converters)	0.00264	Crude steel (electric furnaces)	0.0032	Cold-finished steel	0.002087	Cyclic intermediates	0.0131
		Tires and inner tubes	0.0014	Printing, plate making and book binding	0.00210	Synthetic rubber	0.0029	Paperboard	0.001555	Crude steel (electric furnaces)	0.0093
		Printing, plate making and book binding	0.0013	Other metal products	0.00207	Coated steel	0.0025	Printing, plate making and book binding	0.001044	Aliphatic intermediates	0.0091
		Paint and varnishes	0.0012	Paper	0.00184	Printing, plate making and book binding	0.0022	Reuse and recycling	0.001041	Sheet glass and safety glass	0.0089
		Electrical equipment for internal combustion engines	0.001	Other rubber products	0.00169	Petrochemical basic products	0.0021	Petrochemical aromatic products (except synthetic resin)	0.001004	Thermoplastics resins	0.0084
		Other fabricated textile products	0.001	Non-ferrous metal castings and forgings	0.00137	Reuse and recycling	0.0014	Coal products	0.000991	Synthetic rubber	0.0075
		Electric lighting fixtures and apparatus	0.001	Other electronic components	0.00123	Coal products	0.0011	Pulp	0.000951	Printing, plate making and book binding	0.0074
		Miscellaneous manufacturing products	0.000	Aliphatic intermediates	0.00119	Other industrial organic chemicals	0.0010	Private power generation	0.000722	Plastic products	0.0068
		Private power generation	0.000	Paint and varnishes	0.00115	Corrugated cardboard boxes	0.0010	Thermoplastics resins	0.000591	Petrochemical basic products	0.0056
		Other rubber products	0.000	Paperboard	0.00110	Other metal products	0.0009	Coated steel	0.000577	Paperboard	0.0054
		Radio and television sets	0.000	Electrical equipment for internal combustion engines	0.00109	Paperboard	0.0009	Other pulp, paper and processed paper products	0.000404	Internal combustion engines for motor vehicles and parts	0.0048
		Electric bulbs	0.000	Silk and artificial silk fabrics (inc. fabrics of synthetic filament fibers)	0.00102	Thermo-setting resins	0.0009	Industrial soda chemicals	0.000395	Steel pipes and tubes	0.0047
		Other metal products	0.000	Rolled and drawn aluminum	0.00102	High function resins	0.0008	Synthetic rubber	0.000389	Other final chemical products	0.0046
		Electric audio equipment	0.000	Cast and forged materials (iron)	0.00100	Other final chemical products	0.0007	Corrugated cardboard boxes	0.000376	Reuse and recycling	0.0045
		Soap, synthetic detergents and surface active agents	0.000	Crude steel (electric furnaces)	0.00095	Other industrial inorganic chemicals	0.0007	Other industrial organic chemicals	0.000365	Coal products	0.0041
		Gelatin and adhesives	0.000	Corrugated cardboard boxes	0.00092	Other resins	0.0006	Petroleum refinery products (inc. greases)	0.000321	Other metal products	0.0036

		Batteries	0.000	High function resins	0.00091	Petrochemical aromatic products (except synthetic resin)	0.0006	Other industrial inorganic chemicals	0.000297	Pulp	0.0030
		Other pulp, paper and processed paper products	0.000	Thermo-setting resins	0.00083	Plastic products	0.0006	Corrugated cardboard	0.00029	Petrochemical aromatic products (except synthetic resin)	0.0028
		Petroleum refinery products (inc. greases)	0.000	Other industrial organic chemicals	0.00082	Private power generation	0.0006	Compressed gas and liquefied gas	0.000268	Private power generation	0.0027
		Electric wires and cables	0.000	Motor vehicle parts and accessories	0.00078	Other pulp, paper and processed paper products	0.0006	Other final chemical products	0.000242	Abrasive	0.0026
		Publishing	0.000	Abrasive	0.00077	Steel pipes and tubes	0.0005	Other metal products	0.000193	Paint and varnishes	0.0026
30 Sectors sub-total	0.0614		0.109		0.10925		0.1026		0.066626		0.3889
Sub-total	0.0166		0.061		0.11978		0.1119		0.070204		0.4436
Cumulative	0.0166		0.079		0.19767		0.3096		0.379787		0.0638
Cumulative/grand total	0.0375		0.176		0.44565		0.6980		0.856242		1

Panels A, B and C, respectively, of Table B1 show the patterns of generation along the supply chain for toxic wastes, GHG emissions and nontoxic wastes in the production by the final auto assembler of one passenger car with a 2000 cm^3 Japan standard engine.[37] We see from panel A that 0.44355 tons (443.55 kg) of all toxic waste combined is generated by the supply chain in producing one passenger car. The final assembler firm generates about 3.7% of the total toxic waste, with the remaining 96% being generated by the suppliers and other firms involved in the upstream operations.

We see from panel B of Table B1 that firms along the supply chain generate 5.26577 tons of GHG emissions but only 2% of this amount is generated by the final assembler firms. The remaining 98% is generated by suppliers and other upstream firms in the supply chain. This emission pattern is very similar to the pattern of toxic waste generation reported in panel A.

On the other hand, panel C of Table B1 shows that the final assembler firm is responsible for 22% of the 1.04909 tons of combined nontoxic waste generated by the entire supply chain, while its upstream suppliers generate 78%. This contrasts with the supply chain behavior involving toxic waste and GHG emissions. The results from panels A, B and C are consistent with a number of alternative interpretations, one being that dominant downstream firms tend to delegate the activities involving generation of toxic waste and GHG emissions to their upstream firms, but keep a relatively large fraction of their supply chain's nontoxic waste generation activities.

Based on the results presented in Table B1, we conclude that, in order to be effective, government environmental regulations of toxic waste and GHG emissions must somehow encompass not only the final auto producers but also the many upstream suppliers. Similarly, we see that life cycle analysis of an assembled passenger car requires estimates for the environmental performance of both the downstream assembler and the upstream suppliers.

Detailed processes of generation of toxic wastes and GHG emissions by upstream and downstream firms are presented in Tables C1 and C2 in Appendix C. These tables show the amounts of waste generated by the final auto producers as well as their suppliers and other upstream firms.

The figures in Table B1 correspond to production of one passenger car with a 2000 cm^3 Japan standard engine. Tables C1 and C2 in Appendix C provide details for the amount of waste materials generated by each of the industrial sectors, with these details providing the basis of the derivations of the figures reported in panels A, B and C of Table B1.

Appendix C. Generation of toxic wastes and CO_2 by supply chains in auto industry

See Tables C1 and C2.

[37] A detailed numerical illustration of this waste propagation is given in Appendix C.

Table C2
Generation of CO_2 by supply chains per production of a passenger car with a 2000 cm^3 engine: auto industry.

Auto: CO_2		Tons per 1 passenger car (2000 cm^3 equivalent)									
Direct		1st Indirect		2nd Indirect		3rd Indirect		4th Indirect		Total generation	
Passenger motor cars	0.1076	Electricity	0.1722	Electricity	0.5514	Electricity	0.3349	Pig iron	0.3230	Electricity	1.2982
		Motor vehicle parts and accessories	0.1013	Cast and forged materials (iron)	0.1115	Pig iron	0.1840	Electricity	0.1315	Pig iron	1.0449
		Internal combustion engines for motor vehicles and parts	0.0663	Road freight transport	0.0474	Private power generation	0.1040	Private power generation	0.1290	Private power generation	0.4804
		Private power generation	0.0601	Miscellaneous ceramic, stone and clay products	0.0372	Coal products	0.0927	Coal products	0.0831	Coal products	0.3476
		Road freight transport	0.0599	Private power generation	0.0349	Self-transport by private cars (passengers) P	0.0393	Crude steel (converters)	0.0319	Road freight transport	0.1471
		Sheet glass and safety glass	0.0598	Non-ferrous metal castings and forgings	0.0345	Crude steel (converters)	0.0287	Self-transport by private cars (passengers) P	0.0185	Cast and forged materials (iron)	0.1211
		Research and development (intra-enterprise)	0.0282	Self-transport by private cars (passengers) P	0.0268	Miscellaneous ceramic, stone and clay products	0.0268	Petroleum refinery products (inc. greases)	0.0162	Self-transport by private cars (passengers) P	0.1082
		Motor vehicle bodies	0.0209	Research and development (intra-enterprise)	0.0260	Hot rolled steel	0.0244	Paper	0.0144	Motor vehicle parts and accessories	0.1080
		Coastal and inland water transport	0.0165	Synthetic rubber	0.0225	Self-transport by private cars (freight) P	0.0225	Petrochemical basic products	0.0132	Passenger motor cars	0.1076
		Tires and inner tubes	0.0158	Hot rolled steel	0.0212	Road freight transport	0.0209	Hot rolled steel	0.0120	Crude steel (converters)	0.0910
		Plastic products	0.0114	Coated steel	0.0207	Cold-finished steel	0.0202	Self-transport by private cars (freight) P	0.0107	Miscellaneous ceramic, stone and clay products	0.0895
		Waste management services (private)	0.0106	Thermoplastics resins	0.0190	Paper	0.0193	Road freight transport	0.0095	Petroleum refinery products (inc. greases)	0.0695
		Self-transport by private cars (passengers) P	0.0093	Cold-finished steel	0.0158	Synthetic rubber	0.0166	Aliphatic intermediates	0.0089	Hot rolled steel	0.0689
		Cold-finished steel	0.0093	Petroleum refinery products (inc. greases)	0.0154	Thermoplastics resins	0.0161	Miscellaneous ceramic, stone and clay products	0.0087	Internal combustion engines for motor vehicles and parts	0.0687
		Hot rolled steel	0.0076	Plastic products	0.0153	Petroleum refinery products (inc. greases)	0.0148	Coastal and inland water transport	0.0055	Research and development (intra-enterprise)	0.0638
		Miscellaneous ceramic, stone and clay products	0.0071	Other rubber products	0.0131	Aliphatic intermediates	0.0135	Pulp	0.0051	Sheet glass and safety glass	0.0605
		Self-transport by private cars (freight) P	0.0049	Coastal and inland water transport	0.0129	Petrochemical basic products	0.0124	Cyclic intermediates	0.0048	Self-transport by private cars (freight) P	0.0597
		Electrical equipment for internal combustion engines	0.0046	Self-transport by private cars (freight) P	0.0128	Coastal and inland water transport	0.0091	Paperboard	0.0042	Paper	0.0537
		Electric bulbs	0.0044	Coal products	0.0124	Cast and forged materials (iron)	0.0080	Waste management services (private)	0.0041	Cold-finished steel	0.0509
		Petroleum refinery products (inc. greases)	0.0037	Cast and forged steel	0.0115	Air transport	0.0071	Cold-finished steel	0.0039	Coastal and inland water transport	0.0499
		Air transport	0.0032	Other final chemical products	0.0104	Waste management services (private)	0.0069	Industrial soda chemicals	0.0036	Synthetic rubber	0.0424
		Abrasive	0.0030	Wholesale trade	0.0100	Research and development (intra-enterprise)	0.0065	Crude steel (electric furnaces)	0.0035	Thermoplastics resins	0.0392
		Advertising services	0.0029	Crude steel (converters)	0.0099	Cyclic intermediates	0.0063	Air transport	0.0031	Non-ferrous metal castings and forgings	0.0385
		Other rubber products	0.0024	Paper	0.0073	Aluminum (inc. regenerated aluminum)	0.0062	Ferro alloys	0.0031	Petrochemical basic products	0.0327

		Coated steel	0.0024	Air transport	0.0066	Other industrial organic chemicals	0.0050	Cement	0.0029	Aliphatic intermediates	0.0307
		Wholesale trade	0.0023	Motor vehicle parts and accessories	0.0061	Other resins	0.0044	Thermoplastics resins	0.0028	Plastic products	0.0305
		Harbor transport service	0.0023	Steel pipes and tubes	0.0056	Hired car and taxi transport	0.0038	Petrochemical aromatic products (except synthetic resin)	0.0024	Waste management services (private)	0.0300
		Sewage disposal	0.0020	Inorganic pigment	0.0053	Coated steel	0.0037	Synthetic rubber	0.0022	Coated steel	0.0282
		Hired car and taxi transport	0.0019	Waste management services (private)	0.0050	Industrial soda chemicals	0.0037	Research and development (intra-enterprise)	0.0019	Air transport	0.0226
		Coal products	0.0018	Electrical equipment for internal combustion engines	0.0050	Crude steel (electric furnaces)	0.0036	Other industrial organic chemicals	0.0018	Motor vehicle bodies	0.0219
30 Sectors sub-total	0.6983		1.1338		1.1338		1.0656		0.8655		4.8061
Sub-total	0.1076		0.7066		1.2059		1.1519		0.8970		5.2658
Cumulative	0.1076		0.8142		2.0201		3.1720		4.0689		1.1968
Cumulative/ grand total	0.0204		0.1546		0.3836		0.6024		0.7727		1.0000

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