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Introduction to the Special Issue on the Environment

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Human population growth and increasing consumption per capita are causing environmental impacts that threaten the survival and well-being of humans and other species on Earth. To sustain natural ecosystems and human populations with a high standard of living, humanity must now reinvent our systems for the production and delivery of goods and services to dramatically reduce the environmental impacts associated with consumption. The operations management community can contribute critical know-how to do so, as demonstrated by the papers in this special issue.

Key words: environmentally sustainable operations management; product design; energy efficiency; climate change; population; adaptation; chemical toxicity
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In 1971, biologist Paul Ehrlich famously defined the "IPAT equation" to emphasize that human impact on the environment (I) is determined by population (P), affluence (A), and technology (T):

$$Impact = Population \times Affluence \times Technology.$$

The human population (P) has grown exponentially, from 1 billion in 1800 to 7.1 billion at present. The United Nations projects that population is likely to surpass 10 billion before 2100 and may stabilize near that level thereafter. However, a recent small upward revision in fertility rates implies that global population could reach 15.8 billion by 2100 (United Nations 2011). See Figure 1.

Affluence (A), world per capita GDP, also has grown exponentially in the past two centuries and is projected to continue to grow (Maddison 2008), compounding the environmental impacts of population growth.

Environmental impacts (I) are already at dangerously high levels, according to a team of prominent scientists from multiple disciplines (Rockström et al. 2009). They have quantified eight "planetary boundaries" beyond which the potential exists for irreversible environmental damage with disastrous consequences for humanity. As shown in Figure 2, the rate of extinction of species, the conversion of atmospheric nitrogen into reactive forms such as fertilizer, and the atmospheric concentration of CO_2 already exceed their "safe" levels. (Chemical pollution and atmospheric aerosol loading are also of concern, and current scientific knowledge is inadequate to quantify their planetary boundaries.)

In the parlance of operations management (OM), climate change is an inventory buildup problem. Because the inventory level (atmospheric concentration of greenhouse gases) is already dangerously high, we need to reduce anthropogenic greenhouse gas emissions to zero in the immediate future (Peters et al. 2013, Meinshausen et al. 2009). Delay in eliminating emissions will result in a higher inventory level of greenhouse gases in the atmosphere and, correspondingly, greater warming and impacts of climate change.

The IPAT equation shows the opportunity for the OM community to help reduce "T." For example, in the case of CO_2 emissions from the use of fossil fuels, T is the product of energy intensity (megajoules/\$) and carbon intensity (kg CO_2/megajoule). To reduce energy intensity, OM scholars can expand the knowledge base to design products, services, and systems for their production and delivery that require little energy. The OM community can also help to develop alternative energy systems that do not rely on fossil fuels and thus reduce carbon intensity. World average energy intensity and carbon intensity decreased by 34% and 3%, respectively, from 1980 to 2010, according to statistics assembled by the Global Carbon Project. However, the increases in population and

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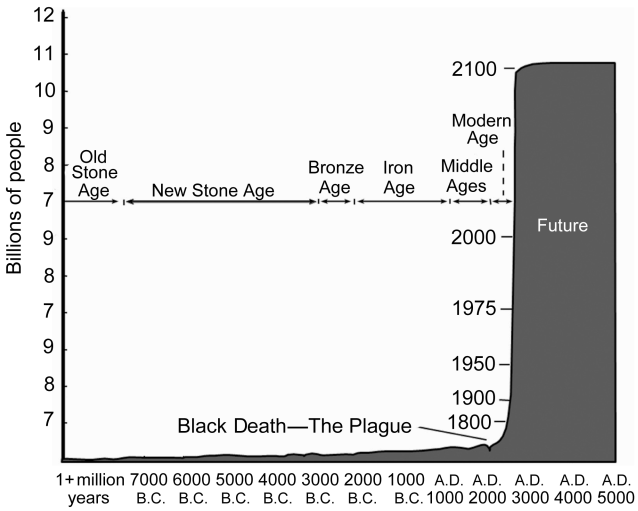
Figure 1 **Human Population Growth Through History, Based on United Nations Data and Forecasts**



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affluence dominated the decreases in energy intensity and carbon intensity, such that the rate of CO_2 emissions increased by a factor of 72% over the same period. (See Raupach et al. 2007, Le Quéré et al. 2012.) Clearly, much greater reductions in energy intensity and carbon intensity are necessary and will require OM innovation. This special issue contains three OM forum papers and nine research papers that shed light on how to reduce T.

The forum paper "Operations Management Challenges for Some 'Cleantech' Firms" by Plambeck describes five innovative business models that, collectively, offer hope for humanity to largely eliminate its CO_2 emissions. It identifies some operations management challenges in doing so and associated research questions. The OM community can also promote innovation for environmental sustainability through teaching. In the forum paper "Business Model Innovation for Sustainability," Girotra and Netessine describe a conceptual framework and experiential approach to help students invent new, environmentally sustainable business models.

Two papers address measurement of greenhouse gas emissions in supply chains as the first step toward emission reduction. In "Double Counting in Supply Chain Carbon Footprinting," Caro, Corbett, Tan, and Zuidwijk illuminate a teamwork problem. A supply chain's greenhouse gas emissions are determined jointly by the collaborative efforts of multiple firms in that supply chain. Therefore, the supply chain emissions must be overallocated (meaning that the sum of emissions assigned to each firm in the supply chain must exceed their total supply chain emissions) to motivate the firms to make the socially optimal efforts to reduce emissions. This is true even if the firms bear a carbon tax equal to the social cost of carbon. In "Engaging Supply Chains in Climate Change," Jira and Toffel examine the propensity of suppliers to share information about their greenhouse gas emissions, their goals for reducing emissions, and their risks associated with climate change, both physical and regulatory. Suppliers tend to share such information more readily when more of their buyers request the information and are committed to using it, when the suppliers belong to more profitable industries, and when they are located in countries with greenhouse gas regulations.

Recall that to reduce CO_2 emissions, we can either reduce the carbon intensity of energy (i.e., substitute renewable energy sources for fossil fuels) or reduce energy intensity. The primary renewable energy sources (sun and wind) are intermittent, which creates operational challenges for electricity grids. Currently, electricity system operators give priority to renewable energy sources in meeting the demand for electricity, so fossil fuel generators must adjust their output in response to variation in the sun and wind. In "Curtailing Intermittent Generation in Electrical Systems," Wu and Kapuscinski show that this practice can substantially increase the costs—both economic and environmental—of operating the electricity system. They provide insight on how to optimally curtail the output from renewable energy sources.

Three papers address energy intensity (of which the reciprocal is energy efficiency). In "Energy Efficiency in Small and Medium-Sized Manufacturing Firms: Order Effects and the Adoption of Process Improvement Recommendations," Muthulingam, Corbett, Benartzi, and Oppenheim use a novel field data set of energy efficiency improvement assessments. Taking a list perspective reveals recommendations appearing earlier in the list have higher adoption rates, and the effect is significant: Moving a recommendation one position down is equivalent to increasing its cost by 17%. Taking a portfolio perspective reveals that the overall adoption rates are higher for assessments where recommendations are listed by increasing payback. Identifying these new behavioral factors has important implications for how recommendations should be sequenced in an energy efficiency assessment. In "Dynamic Capacity Investment with Two Competing Technologies," Wang, Ferguson, Hu, and Souza characterize the optimal policy for a multiperiod problem of investing in two sorts of capacity (with high and low energy efficiency, respectively) under uncertain demand and fuel prices. In a numerical example based on Coca-Cola's truck fleet management, they find that a policy that invests only in the trucks with high energy efficiency (HEVs) performs well and is optimal in the absence of demand seasonality. In

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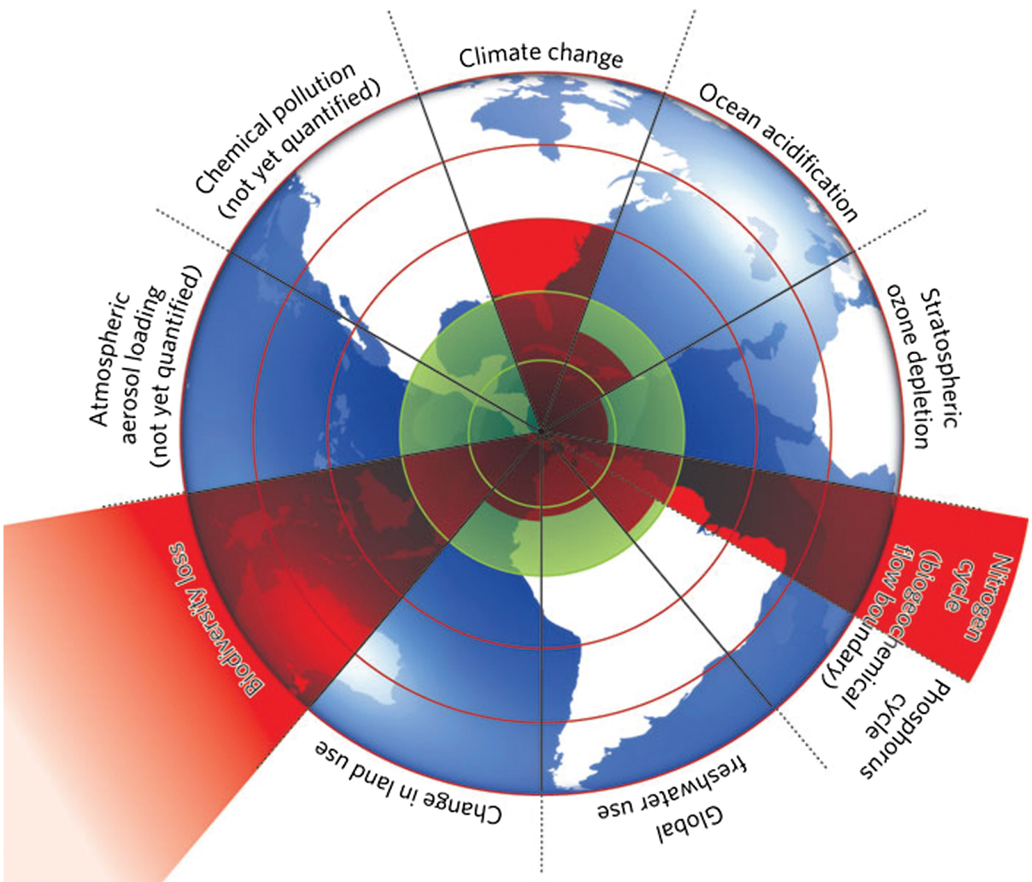
Figure 2 **The Safe Operating Space for Humanity (Green) and Actual Operations (Red)**



Source. Reprinted with permission from Rockström et al. (2009).

"On the Value of Input Efficiency, Capacity Efficiency, and the Flexibility to Rebalance Them," Plambeck and Taylor explain how a carbon tax or cap-and-trade system might backfire by reducing the incentive for a basic material manufacturer to improve its energy efficiency. (Basic material manufacturing accounts for 85% of all industrial energy use.)

Innovation in product design or supply chain design can improve energy efficiency, reduce chemical pollution, and/or mitigate various other sorts of environmental impacts. In "The Role of Modular Upgradability as a Green Design Strategy," Agrawal and Ülkü show that, contrary to conventional wisdom, modular upgradability can increase environmental impact. For example, in the case of personal computers, CO_2 emissions from the production of the fastest-improving component (processor) dominate the overall emissions, and modular upgradability increases the optimal rate of introduction of new processors and hence CO_2 emissions. Modularity tends to be green for products for which production of a slower-improving component has the dominant environmental impact, or for products for which the dominant environmental impacts occur during use and are reduced by innovation in the faster-improving component. Chemical toxicity is the focus of "The NGO's Dilemma: How to Influence Firms to Replace a Potentially Hazardous Substance" by Kraft, Zheng, and Erhun. In the absence of an explicit ban, firms may be reluctant to incur the cost of redesigning products to remove potentially hazardous substances. NGOs have a role in driving change by either targeting the regulatory body or raising consumer awareness to create a demand-side effect. Exploiting the demand-side effect can be particularly effective and works by either leveraging competition between similar-sized firms or leveraging the risk of a significant market share loss to compel a dominant firm to replace. "Plant Networks for Processing Recyclable Materials" by Demeester, Qi, and Van Wassenhove develops an operations strategy framework based on the miniscaling, material versatility, and localization constructs to explain the emergence of minimill networks in process industries. Numerical examples for rolled aluminum and nylon resins plant networks in Europe demonstrate that the complementarity effects between these constructs are large if recycling is nascent and challenging economically and if the plant network is too centralized at

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first to benefit from an increased recyclate ratio or increased localization.

The special issue closes with a tribute to Paul Kleindorfer, who was named MSOM Distinguished Fellow in 2012, but sadly passed away soon thereafter. A scholar of insatiable intellectual curiosity and relentless focus on relevance and impact and a generous mentor, Paul Kleindorfer's legacy lives on in his work and in the people he influenced. In the forum paper "Sustainable Operations Management: An Enduring Stream or Passing Fancy?," Drake and Spinler draw on inspiring conversations with Paul Kleindorfer to posit that the need for research in sustainable business practices will only grow. The operations management community has a unique perspective to bring to this body of research, and can be most effective by forging connections to the broader interdisciplinary body of work and remaining focused on having an impact in practice.

A majority of the papers in this special issue address the measurement and mitigation of CO_2 emissions from climate change. Clearly, operations management researchers can make diverse and important contributions to CO_2 emission reduction, and many are gearing up to do so. We encourage the operations management community to also contemplate adaptation to climate change (including, e.g., water scarcity, agricultural yield reduction and uncertainty, and sea port disruption) and the other environmental challenges illustrated in Figure 2.

We thank the many people who submitted papers for the special issue and the many people who reviewed and provided feedback on those papers. This issue would not have been possible without the dedication of a wonderful set of associate editors: Barış Ata, Saif Benjaafar, Laurens Debo, Charles Corbett, Magali Delmas, Karen Donohue, Wedad Elmaghraby, Özlem Ergun, Mark Ferguson, Roman Kapusinski, Rob Klassen, Laura Kornish, Serguei Netessine, Alan Scheller-Wolf, Matthew Sobel, Gilvan Souza, John Sterman, Valerie Thomas, and Mike Toffel. We also thank the many referees who provided constructive, insightful, and timely reviews that were essential to the quality of the special issue. Frances Moskwa's responsiveness and professional administrative support were very helpful in ensuring the timely processing of submissions. Finally, we thank Editor-in-Chief Stephen Graves for the inspiration to offer a special issue on the environment and for engaging very actively in the editorial process.

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