Science AAAS

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Science **344**, 1109 (2014);
DOI: 10.1126/science.1248361

REVIEW

Emerging approaches, challenges and opportunities in life cycle assessment

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In the modern economy, international value chains—production, use, and disposal of goods—have global environmental impacts. Life Cycle Assessment (LCA) aims to track these impacts and assess them from a systems perspective, identifying strategies for improvement without burden shifting. We review recent developments in LCA, including existing and emerging applications aimed at supporting environmentally informed decisions in policy-making, product development and procurement, and consumer choices. LCA constitutes a viable screening tool that can pinpoint environmental hotspots in complex value chains, but we also caution that completeness in scope comes at the price of simplifications and uncertainties. Future advances of LCA in enhancing regional detail and accuracy as well as broadening the assessment to economic and social aspects will make it more relevant for producers and consumers alike.

The complex global supply chains, production technologies, and consumption patterns of the modern economy cause numerous environmental impacts. To identify the most effective improvement strategies and avoid burden shifting from one environmental impact to another, all impacts occurring throughout the entire value chain (supply chain plus use and disposal phases) should be accounted for. This is the goal of Life Cycle Assessment (LCA), a method to quantitatively assess the environmental impacts of goods and processes from "cradle to grave." LCA models cause-effect relationships in the environment and thus helps to understand the environmental consequences of human actions. LCA is an important decision-support tool that among other functions, allows companies to benchmark and optimize the environmental performance of products or for authorities to design policies for sustainable consumption and production.

How Does LCA work?

The currently accepted definition of LCA is the "compilation and evaluation of the inputs, outputs, and potential environmental impacts of a product system throughout its life cycle," which typically occurs in four steps (*1*). The first phase is the description of the goal and scope, which includes defining the objectives of the study and setting the system boundaries. In the LCA of freight transport, for instance, the comparison of rail and road transport to select the most sustainable option could form one objective, and the system boundaries could include the following: resource extraction and processing, the manufacture of the vehicle and infrastructure (rail tracks or roads), the operation of the vehicle, and last, disposal (Fig. 1). The second phase, inventory analysis, compiles inputs and outputs for each process in the life cycle and sums them across the whole system. Typically, several hundreds of emissions and resources are quantified.

In the third phase, life-cycle impact assessment (LCIA), emissions and resources are grouped according to their impact categories and converted to common impact units to make them comparable. For instance, CO_2 and CH_4 emissions can both be expressed as CO_2-equivalent emissions by using their Intergovernmental Panel on Climate Change (IPCC) Global Warming Potentials (this impact category, climate change, is almost identical to the so-called carbon footprint). International consensus has been reached on both the data and the modeling principles used for some impact categories, such as for the assessment of human- and eco-toxicity (*2*). For other impact categories—such as impact of land and water use, acidification, and eutrophication—diverse methods exist, and international initiatives, such as the United Nations Environment Programme (UNEP)/Society of Environmental Toxicology and Chemistry (SETAC) Life Cycle Initiative are working toward global consensus-building on impact indicators (*3*, *4*). Weighting between impact categories facilitates decision-making but, according to the International Organization for Standardization (ISO) (*1*), is not allowed for comparative assertions communicated to the public because it involves subjective judgments. The final phase is the interpretation of the inventory and impact assessment results in order to answer the objectives of the study. In the example of freight transport, outcomes obtained from an LCA include the finding that as compared with rail transport, road transport is associated with higher impacts on human health and ecosystems (Fig. 1).

How Is LCA Applied and What Are Its Potential Future Uses?

The typical use of LCA has been to assess and improve specific product systems (Fig. 2A). Many product LCAs are conducted to support corporate internal decision-making, such as for eco-design of products, process optimizations, supply-chain management, and marketing and strategic decisions. LCA has particularly high leverage at the early stage of product and process design, when there is still the freedom to make substantial changes. However, today its application is much broader. Companies are using LCA to map the key drivers of impact of their entire product portfolios (Fig. 2B) (*5*) and thus to direct their improvement strategies. Increasingly, companies are using LCA results to report on key environmental aspects on a corporate level, presenting the areas across the value chain where product portfolios generate impacts and outlining how the companies are tackling these. This can be beyond the company gates, through improvement in products and technologies, through synergies with industrial neighbors by exchanging materials and energy (*6*), and through better collaboration with other actors in the value chain. As an example, LCAs of clothes-washing have demonstrated that the largest improvement potential lies in lowering the washing temperature (*7*). Cooperation of multiple actors is needed to realize this benefit; for example, washing-powder manufacturers need to produce detergents that clean effectively at cold temperature; washing-machine producers need to manufacture machines that allow selecting cold washing temperatures; and consumers need to change their washing behavior. LCA can reveal whether collaboration between different actors would lead to a greater benefit than that of single-actor action, but making the collaboration happen also requires social and economic conditions to be fulfilled.

In the area of sustainable consumption and production, "top-down" studies of national economies help to pinpoint crucial areas of consumption and drivers of environmental impacts (Fig. 2D). For example, housing, mobility, and food (specifically, heating and cooling of buildings, car and air travel, and meat and dairy consumption) are responsible for the largest share of most environmental impacts in Europe (*8*). More detailed "bottom-up" studies of single products or product groups have also helped to determine that key drivers for impacts may not be linked to the life-cycle stages most commonly associated with high impacts, such as in the case of packaging, which was shown to be of minor importance with regard to the total greenhouse-gas emissions of food products in the UK (*9*). Such information enables the determination of the biggest impact-reduction potentials and the prioritization of political efforts. For instance, the European Commission's Energy-using Products Directive (*10*), which was built on the knowledge gathered through LCA studies, identified the use phase of

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household appliances as the key driver for their environmental impact and now requires electronic products to carry an energy label.

New policy initiatives go a step further by aiming to generalize the life-cycle approach in all consumption sectors, through harmonization of life-cycle–based information on a variety of impact categories to be displayed in product labeling (*11*, *12*). One challenge is how this information can be communicated to consumers in a simple and understandable manner, without hiding uncertainties. Data gaps present another challenge. Information on complete assortments of products might enable the issuing of environmental scorecards that store information on consumer-specific purchases and provide a hotspot analysis of purchases in the future (Fig. 2C). Such information would allow consumers to track the impacts of their purchases and to possibly reduce or offset them. Offsets have already been incorporated in some labels for greenhouse gas emissions but may be difficult to implement for other impacts, such as biodiversity loss (*13*). A key role is held by retailers, who are in direct contact with both consumers and producers and can serve as an information hub. In addition to product labeling (*14*), some retailers use environmental information to guide their internal decisions in supply-chain management so as to only offer products that meet minimum environmental standards (*15*).

Many LCAs have been carried out in the building sector, by urban designers, property developers, architects, engineers, and consultants. Environmental Product Declarations (*16*) have become effective mechanisms to share data about the environmental profiles of materials and semifinished products. Existing studies also assess whole building systems, considering all life-cycle stages (*17*) and even entire urban settlements (*18*, *19*). The results show that energy use within the building dominates impacts in most impact categories. Extra insulation material decreases overall life-cycle impacts in colder climates, although comparisons of low-energy to self-sufficient houses have shown that there is a tipping point at which further material use does not pay off any longer (*20*). Increasing the share of renewable energy supply systems and decreasing the per capita living space are measures with large environmental leverage (*18*). Both the impacts and the environmentally optimal design also depend on building technologies, local conditions, and the behavior of occupants (*17*, *21*).

LCA is particularly suited to support decisions in waste management. For instance, the European Waste Framework Directive (*22*) requires the use of LCA to identify cases in which it is reasonable to deviate from the classical waste hierarchy (avoid, reuse, recycle, recover, and landfill). Models and software tools for assessing the environmental impacts of recycling and disposal options are available (*23*) and have been applied in a range of cases to environmentally optimize waste management (*24*). A challenge for future research will be to widen the system boundaries beyond waste treatment and recycling to cover integrated resource management, so as not to miss improvement potentials through waste prevention and recycling-friendly product design.

LCA has been instrumental in policy-making in the energy sector. LCA can provide information on environmental benefits and costs before money is invested in new energy, grid, and storage infrastructure. For example, biofuels were once widely considered as an environmentally benign source of energy until an LCA study (*25*) showed that depending on the production conditions, biofuels from agricultural products may be responsible for larger environmental impacts than conventional fuels, mainly because of land-transformation issues. This study led the Swiss government to release a law requiring an LCA study of all nonwaste-derived biofuels, which would need to demonstrate environmental superiority over conventional fuels before any tax exemptions are granted (*26*). On a local level, mathematical optimization has been applied to propose environmentally optimal solutions for regional energy supply (*27*) and may be extended to larger regions in the future. LCA is also used to assess scenarios of energy supply mixes, to help design sustainable energy systems (*28*). A future application could be to use LCA to identify desirable scenarios and, on this basis, use backcasting to define appropriate policies.

LCAs are also applied to assess new technologies and promote proactive action, such as with nanotechnology (*29*). However, a review of LCA studies on nanostructured products (*30*) showed that almost all studies neglect nanoparticle emissions and their specific effects, thus missing a potential key concern with regard to human and ecosystem health. LCA relies on the knowledge generated in related fields (such as environmental risk assessment), and data gaps are a problem at an early stage of technology development. Another important issue is that a comparison between new and mature technologies needs to be corrected for upscaling and learning effects, which typically reduce the environmental impacts as a function of cumulated production (*31*, *32*). Last, prospective technology assessments also need models of the future industrial economy (*32*), which so far are only available for electricity generation (*28*).

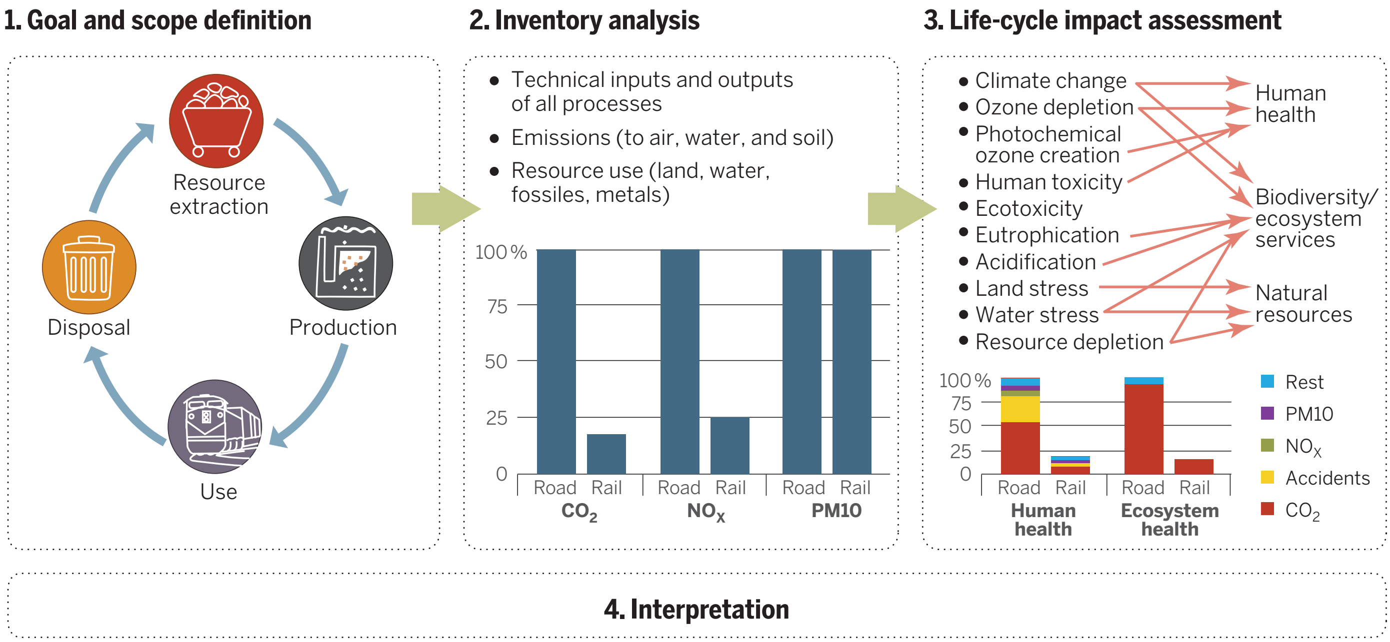

Fig. 1. The four phases of LCA for the example of freight transportation. Comparing road and rail transport for a specific freight transport chain [data are from (*68*)]. Exemplary inventory and impact assessment results (*68*) for three emissions and two damage categories, normalized to road transportation. Further details are available in the supplementary materials.

In view of the growing interest in applying LCA, enhanced coverage of inventory data and impacts is required to be able to provide answers to situations arising from increasingly complex production and consumption systems. A plethora of data must be processed on all phases of the life cycle, including consumer behavior information for the use phase. "Big Data" efforts, such as those devoted to analyzing consumer habit information, constitute a promising knowledge-generation hub (*33*). There is also a practical challenge relating to the access and interoperability of life-cycle inventory databases. Consistent data-quality guidelines are, if at all, only applied within individual databases (*34*), but not among them. Transparency and independent reviews are also crucial (*1*) to allow reproducibility and avoid hidden manipulation. Moreover, access to LCA databases should preferably be open, but this is impeded by the fact that setting up and, particularly, maintaining the quality of data are a costly task. Developments in impact assessment aiming at a better representation of cause-effect chains in the environment are also under way. At the same time, however, the mainstream application of LCA requires simplifications and standardization to enable consistent and easy use in practice (*35*). The European Commission made an attempt in this regard, defining "best practice" in impact assessment (*4*). Although on the one hand this is very helpful to harmonize LCA studies with regard to impact assessment, only LCIA methods before early 2009 were considered, and these guidelines may hamper the use of up-to-date LCIA methods. Enabling a widespread application with "stable" methods, without paralyzing the relevant methodological developments, remains a challenging task.

Emerging Approaches and Challenges in LCA

LCA results can have high uncertainties because of the large amounts of measured and simulated data and the simplified modeling of complex environmental cause-effect chains. Recent studies have highlighted the contribution that system assumptions and value choices can also make to overall uncertainty (*36*, *37*). A number of quantitative uncertainty assessments are available (*38*) but

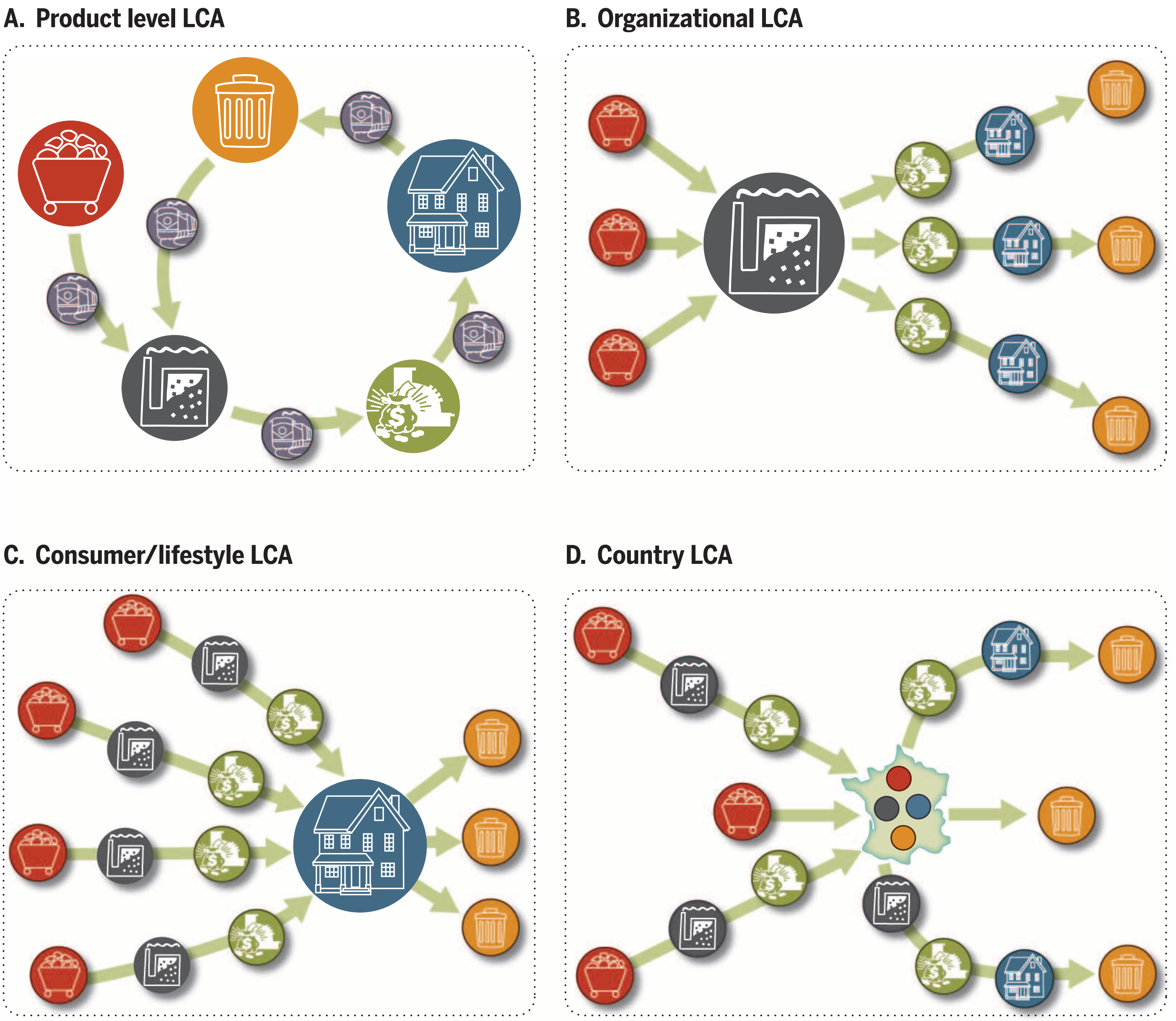

Fig. 2. The expanding nature of LCA applications. (**A**) Original product-based scope. (**B**) Organizational company LCA. (**C**) Consumer LCA (analyzing consumption patterns and lifestyles). (**D**) National-level assessments. One of the main goals in all of these application levels is the identification of environmental hotspots, which may then guide decisions on product improvement, corporate sustainability strategy (including supplier selection), consumer lifestyle and procurement options, or national sustainable consumption and production policy-setting.

are rarely used in practice. One of the key questions is, how much uncertainty is acceptable, depending on the application? In some cases, rough estimates of input values can be enough to identify supply-chain hotspots (*39*), but for other applications, such as product comparisons (*37*), the demands for more accurate values are higher. For some impact categories such as toxicity, very large differences in inventory results are needed to statistically differentiate product systems, whereas for other categories, differences of a factor of two or less may be enough (*40*). LCA practitioners should always attempt to manage the decision-maker's expectations and clarify that LCA is not always a tool to provide a single answer, but rather one that permits comprehensive understanding of a problem and its possible solutions.

Recent studies have aimed at reducing uncertainties in LCA by mapping and assessing value chains and impacts in a regionalized manner. Regionalized assessments increase the accuracy by considering site-specific production conditions as well as differences in transport and the sensitivity of ecosystems. However, acquiring spatial data constitutes a challenge. Companies may know their immediate suppliers, but only in exceptional cases do they know the whole supply chain and consumer (or post-consumer) phase. When spatial details have not been available, average market mixes have been used as an approximation. Global production mixes and trade are well known and documented for some products, such as electricity (*34*), but unfortunately, this is not the case for many other products. However, international production and trade data are becoming readily available on an industrial-sector level. Recent studies combine national production data with data on international trade flows (*41*, *42*) and are thus able to analyze the overall footprints of consuming nations, including the impacts occurring outside the national boundaries. To compare the environmental impacts between different locations of resource extraction or emission, regionalized impact-assessment methods need to be applied. Operational methods with global coverage became recently available for land-use impacts (*43*–*46*), water consumption (*47*–*50*), eutrophication (*51*, *52*), and noise (*53*). The use of Geographic Information Systems (GIS) has helped in the implementation of regionalization in LCA. An assessment of electricity generation, for example, shows that regionalization can indeed be important (Fig. 3) (*54*) and should be considered, for example, when redesigning the electricity supply mix.

Regionalization makes LCA more relevant, but matching the regionalized impact-assessment methods to regionalized emissions and resource flows is still very much a challenge. Although pilot research software systems are capable of doing this (*54*), it has yet to be implemented in commercial LCA software. An open question is, which is the most appropriate spatial (and temporal) resolution of data (*54*)? Inventory data are mostly available on the country level, with only some exceptions of finer geographical resolution [such as for agricultural processes (*55*)]. Impact-assessment methods often need a different geographical resolution, embracing the nature of the impact rather than political

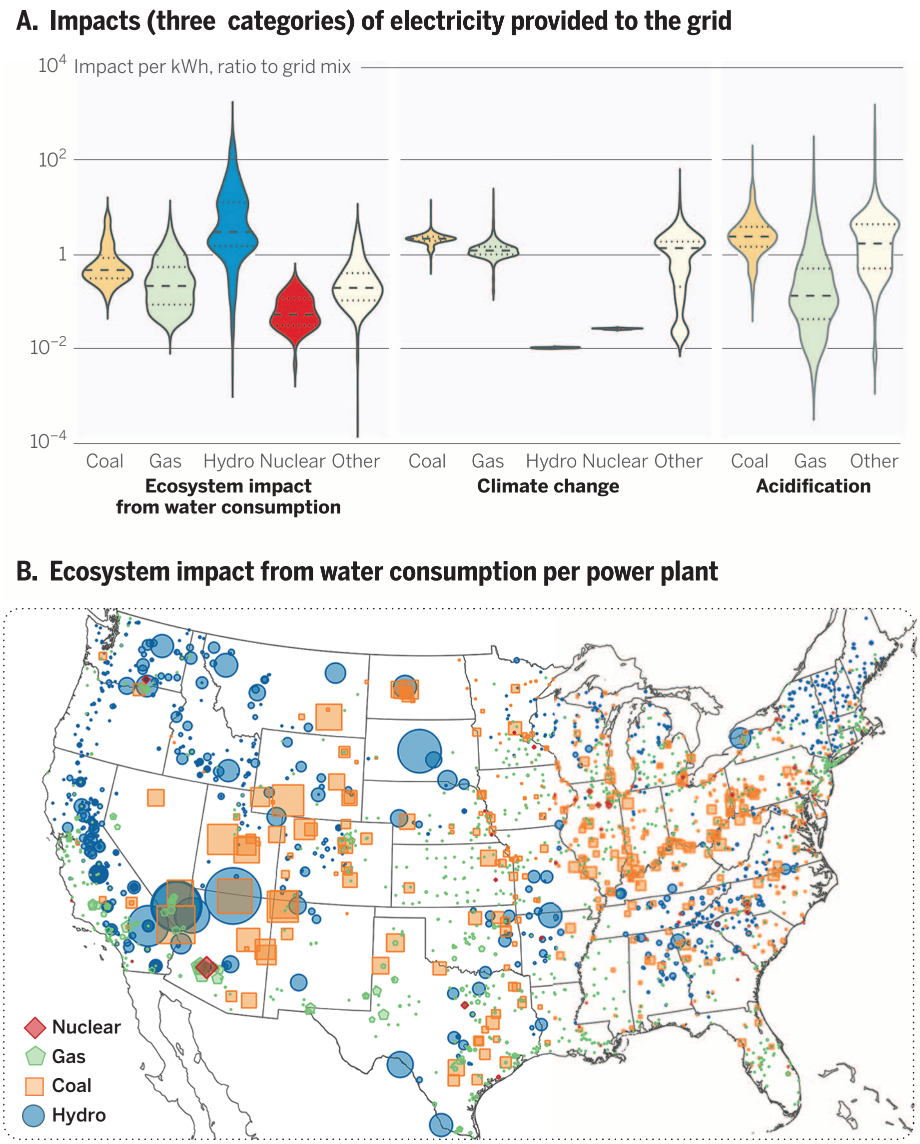

Fig. 3. Illustration of regionalized LCA of 4457 U.S. power plants. (**A**) Impact for 1 kilowatt-hour (kWh) electricity provided to the grid for three impact categories, normalized to the average impact of U.S. power production. The breadth of the "violins" reflects the frequency of data points. For impacts of climate change, differences in the technology explain the variation in impact within each power-plant type. For the other impact categories, regionalized impact assessment adds to the variability between power plants in addition to technology differences. This is illustrated by (**B**) the map, which shows total ecosystem impact from water consumption per power plant (total annual production). Impacts mainly occur in water-scarce regions with large ecosystem sensitivity. Acidification impacts of hydro and nuclear are not shown because they were negligible. Further details are available in the supplementary materials. All data are from (*54*).

boundaries. For instance, for the impacts of water consumption watersheds seem to be a logical choice. Adjusting the geographic resolution of data to a scale that warrants an appropriate assessment, without making the application too complex, is one of the challenges that remains to be confronted.

There are also new developments for global impact categories. The use of biomass for bioenergy, for example, leads to a temporary increase of carbon in the atmosphere, which acts as a greenhouse gas until it is sequestered again. Therefore, "carbon-neutral" biomass systems are not per se "climate neutral" (*56*). The importance of biogenic CO_2-emissions relative to fossil emissions depends on the rotation time as well as the temporal system boundary chosen (*56*). Discussions are also ongoing about how to model carbon storage (*57*).

One aspect that is gaining momentum in the LCA modeling community is the need to model rebound effects. Rebound effects are ones which offset the potential of a measure to reduce environmental impacts (*58*). For example, if the consumption of a good gets cheaper because of efficiency gains or if an activity becomes more time-efficient, households can use these newly available financial or temporal resources for additional consumption (*59*). Indirect effects may also occur. For example, an increased consumption of bio-based materials and energy can shift agricultural activities to rainforest areas, even if the biomass feedstock itself is not grown in rainforests. The modeling of such indirect land use requires traditional LCA modeling combined with other disciplines, such as general and partial equilibrium models from economic sciences (*60*). Although it is clear that for future-oriented decisions, it is desirable and sometimes essential to explicitly take into account the consequences of a change, including influences on the background economy and indirect effects (*61*, *62*) may compromise the transparency of the study and increase uncertainties (*32*, *63*).

Currently, LCA only addresses environmental impacts, but there is increasing demand for broader sustainability assessments covering the social and economic dimensions of sustainability (*64*). Methods for life-cycle costing exist (*65*), but methods for social assessment are still at an early development stage. A recently developed "social hotspot database" (*66*) contains country- and industrial-sector–based statistical data to screen potential hotspots at a macro level, in order to identify where more detailed social assessments about the value chain and the individual companies involved may be required. Furthermore, within the UNEP/SETAC Life Cycle Initiative, a guideline has been developed (*67*) that sets out the key elements and indicators for the assessment of the positive and negative social impacts of a product over its life cycle (for example, on human rights, working conditions, and health and safety), as well as the limitations in the approach. The point at which the environmental, economic, and social dimensions of sustainability can be assessed consistently and with sufficient detail lies at the end of a hurdled path. Such an accomplishment, however, would benefit science and society by facilitating a more thorough understanding of the impacts of human actions and identifying the proactive response required to achieve sustainability.

REFERENCES AND NOTES

1. International Organization for Standardization (ISO), *The New International Standards for Life Cycle Assessment: ISO 14040 and ISO 14044* (ISO, Geneva, Switzerland, 2006).
2. R. K. Rosenbaum *et al*., *Int. J. Life Cycle Assess.* **16**, 710–727 (2011).
3. O. Jolliet *et al*., *Int. J. Life Cycle Assess.*, 10.1007/s11367 (2014).
4. M. Z. Hauschild *et al*., *Int. J. Life Cycle Assess.* **18**, 683–697 (2013).
5. L. Milà i Canals *et al*., *Int. J. Life Cycle Assess.* **16**, 50–58 (2011).
6. T. Mattila, S. Lehtoranta, L. Sokka, M. Melanen, A. Nissinen, *J. Ind. Ecol.* **16**, 51–60 (2012).
7. A. Koehler, C. Wildbolz, *Environ. Sci. Technol.* **43**, 8643–8651 (2009).
8. A. Tukker, B. Jansen, *J. Ind. Ecol.* **10**, 159–182 (2006).
9. T. Garnett, *Cooking Up a Storm. Food, Greenhouse Gas Emissions and Our Changing Climate* (Food Climate Research Network, University of Surrey, Surrey, UK, 2008).
10. European Parliament and Council, "Directive 2005/32/EC Energy-using Products" (2005).
11. C. Cros, E. Fourdrin, O. Rethore, *Int. J. Life Cycle Assess.* **15**, 537–539 (2010).
12. European Commission, *Regulation COM/2013/0196 final* (2013); available at http://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:52013DC0196.
13. M. Curran, S. Hellweg, J. Beck, *Ecol. Appl.* (2013).
14. Worldwatch Institute, "Wal-Mart Scrutinizes Supply-Chain Sustainability" (2014); available at http://www.worldwatch.org/node/6200#.Uvekg3nXdAk.email.
15. F. Stoessel, R. Juraske, S. Pfister, S. Hellweg, *Environ. Sci. Technol.* **46**, 3253–3262 (2012).
16. BSI, *BS EN 15804:2012 + A1:2013 Sustainability of Construction Works* (2012); available at http://shop.bsigroup.com/ProductDetail/?pid=000000000030279721.
17. L. F. Cabeza, L. Rincón, V. Vilariño, G. Pérez, A. Castell, *Renew. Sustain. Energy Rev.* **29**, 394–416 (2014).
18. D. Saner, N. Heeren, B. Jäggi, R. A. Waraich, S. Hellweg, *Environ. Sci. Technol.* **47**, 5988–5997 (2013).
19. S. Pauliuk, K. Sjostrand, D. B. Muller, *J. Ind. Ecol.* **17**, 542–554 (2013).
20. T. Ramesh, R. Prakash, K. K. Shukla, *Energy Build.* **42**, 1592–1600 (2010).
21. K. Steemers, G. Y. Yun, *Build. Res. Inform.* **37**, 625–637 (2009).
22. European Parliament and Council, *Directive European Commission 2008/98/EC* (2008); available at http://ec.europa.eu/environment/waste/framework.
23. C. Riber, G. S. Bhander, T. H. Christensen, *Waste Manag. Res.* **26**, 96–103 (2008).
24. T. H. Christensen, F. Simion, D. Tonini, J. Møller, *Waste Manag. Res.* **27**, 871–884 (2009).
25. J. P. W. Scharlemann, W. F. Laurance, *Science* **319**, 43–44 (2008).
26. Federal Department of the Environment Transport Energy and Communications, *regulation 641.611.21* (2009) http://www.admin.ch/opc/de/classified-compilation/20080562/index.html.
27. D. Saner, thesis 20970, ETH Zurich, Switzerland (2013).
28. R. Frischknecht, in *Der Systemblick auf Innovation*, M. Decker, A. Grunwald, M. Knapp, Eds. (edition sigma, Berlin, 2012), vol. 16.
29. W. Klöpffer *et al*., *Nanotechnology and Life Cycle Assessment: A Systems Approach to Nanotechnology and the Environment* (U.S. EPA and European Commission, 2007).
30. R. Hischier, T. Walser, *Sci. Total Environ.* **425**, 271–282 (2012).
31. M. Caduff, M. A. J. Huijbregts, H.-J. Althaus, A. J. Hendriks, *Environ. Sci. Technol.* **45**, 751–754 (2011).
32. T. E. McKone *et al*., *Environ. Sci. Technol.* **45**, 1751–1756 (2011).
33. J. Cooper, M. Noon, C. Jones, E. Kahn, P. Arbuckle, *J. Ind. Ecol.* **17**, 796–799 (2013).
34. Swiss Centre for Life Cycle Inventories (Ecoinvent Centre, 2012); www.ecoinvent.ch.
35. M. Baitz *et al*., *Int. J. Life Cycle Assess.* **18**, 5–13 (2013).
36. A. M. De Schryver, S. Humbert, M. A. J. Huijbregts, *Int. J. Life Cycle Assess.* **18**, 698–706 (2013).
37. J. R. Gregory, T. M. Montalbo, R. E. Kirchain, *Int. J. Life Cycle Assess.* **18**, 1605–1617 (2013).
38. S. M. Lloyd, R. Ries, *J. Ind. Ecol.* **11**, 161–179 (2007).
39. L. Milà i Canals *et al*., *J. Ind. Ecol.* **15**, 707–725 (2011).
40. M. A. J. Huijbregts, W. Gilijamse, A. M. J. Ragas, L. Reijnders, *Environ. Sci. Technol.* **37**, 2600–2608 (2003).
41. A. Tukker *et al*., *Econ. Syst. Res.* **25**, 50–70 (2013).
42. T. O. Wiedmann *et al*., *Proc. Natl. Acad. Sci. U.S.A.* 10.1073/pnas.1220362110 (2013).
43. L. de Baan, C. L. Mutel, M. Curran, S. Hellweg, T. Koellner, *Environ. Sci. Technol.* **47**, 9281–9290 (2013).
44. R. Saad, T. Koellner, M. Margni, *Int. J. Life Cycle Assess.* **18**, 1253–1264 (2013).
45. M. Brandão, L. Mila i Canals, *Int. J. Life Cycle Assess.* **18**, 1243–1252 (2013).
46. M. Núñez, A. Anton, P. Munoz, J. Rieradevall, *Int. J. Life Cycle Assess.* **18**, 755–767 (2013).
47. M. Motoshita, N. Itsubo, A. Inaba, *Int. J. Life Cycle Assess.* **16**, 65–73 (2011).
48. S. Pfister, A. Koehler, S. Hellweg, *Environ. Sci. Technol.* **43**, 4098–4104 (2009).
49. F. Verones *et al*., *Environ. Sci. Technol.* **47**, 12248–12257 (2013).
50. A. M. Boulay, C. Bulle, J. B. Bayart, L. Deschênes, M. Margni, *Environ. Sci. Technol.* **45**, 8948–8957 (2011).
51. L. B. Azevedo, A. D. Henderson, R. van Zelm, O. Jolliet, M. A. J. Huijbregts, *Environ. Sci. Technol.* **47**, 13565–13570 (2013).
52. R. J. K. Helmes, M. A. J. Huijbregts, A. D. Henderson, O. Jolliet, *Int. J. Life Cycle Assess.* **17**, 646–654 (2012).
53. S. Cucurachi, R. Heijungs, K. Ohlau, *Int. J. Life Cycle Assess.* **17**, 471–487 (2012).
54. C. L. Mutel, S. Pfister, S. Hellweg, *Environ. Sci. Technol.* **46**, 1096–1103 (2012).
55. S. Pfister, P. Bayer, A. Koehler, S. Hellweg, *Environ. Sci. Technol.* **45**, 5761–5768 (2011).
56. F. Cherubini, G. P. Peters, T. Berntsen, A. H. Stromman, E. Hertwich, *GCB Bioenergy* **3**, 413–426 (2011).
57. A. Levasseur *et al*., *Nature Clim. Change* **2**, 6–8 (2012).
58. E. G. Hertwich, *J. Ind. Ecol.* **9**, 85–98 (2005).
59. B. Girod, P. de Haan, R. W. Scholz, *Int. J. Life Cycle Assess.* **16**, 3–11 (2011).
60. J. Hedal Kløverpris, K. Baltzer, P. H. Nielsen, *Int. J. Life Cycle Assess.* **15**, 90 (2010).
61. G. Finnveden *et al*., *J. Environ. Manage.* **91**, 1–21 (2009).
62. T. Ekvall, B. P. Weidema, *Int. J. Life Cycle Assess.* **9**, 161–171 (2004).
63. A. Zamagni, J. Guinee, R. Heijungs, P. Masoni, A. Raggi, *Int. J. Life Cycle Assess.* **17**, 904–918 (2012).
64. J. B. Guinée *et al*., *Environ. Sci. Technol.* **45**, 90–96 (2011).
65. T. E. Swarr *et al*., *Int. J. Life Cycle Assess.* **16**, 389–391 (2011).
66. C. Benoit-Norris, D. A. Cavan, G. Norris, *Sustainability-Basel* **4**, 1946–1965 (2012).
67. C. Benoit, B. Mazijn, *Guidelines for Social Life Cycle Assessment of Products* (UNEP/SETAC Life Cycle Initiative, Paris, 2009).
68. N. Fries, S. Hellweg, *Int. J. Life Cycle Assess.* **19**, 546–557 (2014).

ACKNOWLEDGMENTS

We thank C. Mutel, S. Pfister, T. Colley, and C. Raptis for their helpful assistance with figures and comments on a draft version of this paper. The views expressed in this article are those of the author and do not necessarily reflect those of UNEP.

SUPPLEMENTARY MATERIALS

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Materials and Methods
References (*69–74*)

10.1126/science.1248361