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Why Life Cycle Assessment Does Not Work for Synthetic Biology

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One of the triumphs of environmental sustainability has been the rapid adoption and application of *life cycle assessment* (LCA) to the analysis and management of risks related to chemical pollution.[1] Specifically, LCA provides a systematic accounting of resource use and environmental risks related to *industrial ecology*, that is, the material and energy exchanges between the economy and environment during raw materials extraction, manufacture, use, and disposal of products (Figure 1, left side).[2] Underlying LCA is the unstated supposition that industrial systems can be contained within an imaginary control volume that allows an unambiguous accounting of chemical exchanges across an industry-environment boundary. Nonetheless, production systems that are more complex than traditional manufacturing have tested the limits of the method.

The first challenge to LCA emerged when analysts began to study agricultural production, where the boundaries between industry and the environment are blurred. Although factory-based production is centralized and standardized, agricultural systems are decentralized, heterogeneous, and explicitly open to the environment. Thus, agricultural-LCA must confront issues related to geospatial and intertemporal variability of system boundaries and environmental releases, ambiguity in definitions of resource use (e.g., water consumption), and extraordinary sensitivity to selection of a functional unit (e.g., dry mass, caloric, protein, or other nutritional content for food products). As a result, the first LCAs of ag-based biofuels were the focus of scientific controversy, and may have caused policy confusion.

Shortly after, the second challenge to LCA emerged in the form of engineered nanomaterials.[3] The myriad configurations that can be encoded at the nanoscale imbue these materials with high degrees of informational, in addition to chemical content. LCA is limited in this scenario because the concept of the thermodynamic control volume that undergirds the definition of the industrial/ecological systems boundary is not designed to accommodate or account for *information* exchanges, only material and energy. For example, a change in aspect ratio, surface area, or functionalization of an engineered nanomaterial may result in big differences in fate, transport, or toxicity in the environment without significant changes in the bulk chemical formulas that constitute life cycle inventories. Thus, LCA of nanotechnology requires additional caveats, work arounds, and management of high levels of uncertainty in the characterization factors that relate material emissions to environmental impact.

Finally, the challenges posed to LCA by the emerging technology of synthetic biology combines the two previous challenges of blurred system boundaries and informational (rather than just chemical) transfers, to overwhelm the capabilities of LCA to serve as a reliable analytical tool. Current applications of synthetic biology include genetically modified organisms that produce biofuels, food, medicine, perform environmental bioremediation, and disrupt disease vectors.[4] While self-reproducing engineered organisms have the advantage of multiplying in situ at low cost (Figure 1, right side), these same organisms enhance the potential for reproductive aberrations (e.g., mutations, horizontal gene transfer, manipulation of evolutionary processes) that are the most difficult to characterize with existing LCA.

Injecting novel genetic information directly into ecological reproductive cycles obliterates the imaginary control boundary between industrial and ecological production systems and renders the concept of the life cycle inventory meaningless. Thus, existing approaches of LCA are unable to characterize the complex, nonlinear and potentially surprising disruptions of these information transfers to the ecological reproductive cycle. With a limited understanding of the potential ecological impacts, regulators and key stakeholders in industry are challenged to identify best practices and safety requirements for various applications of synthetic biology research such as with the containment and safe disposal of engineered organisms

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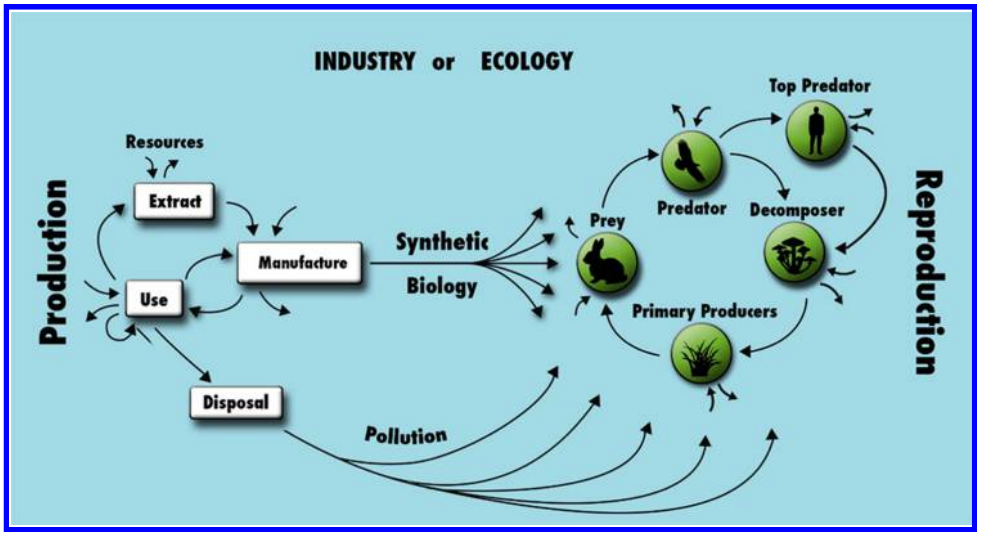

Figure 1. A representation of the blurred boundary between industrial and ecological processes.

without allowing such artificial information to proliferate in the natural environment.[5]

To date, LCA has succeeded as an analytic instrument for guiding the improvement of mature, well-characterized industrial technologies. Yet, for technologies like synthetic biology that fail to fit within the narrow frame of industrial production systems, new analytic methods are needed to manage early stage governance of both the *process* of development and the resulting *products*. These methods must be both anticipatory in the sense that they facilitate exploration of possibilities, and adaptive in the sense that they are continuously updated in response to the discovery of new hazards, risks, or other information.

To accomplish this, the life cycle metaphor may need to be reconceived and the traditional perspective of the *material* life cycle shifted toward the adoption of a *technological* life cycle model: from the research and development stage, toward early stage adoption, toward the exploitation of the product at commercial scales, and ultimately to retirement of the technology at obsolescence. Legal instruments (hard law) as well as voluntary best practices and codes of conduct (soft law) should be structured to incorporate emerging developments in the understanding of the technological risks to human and environmental health. While this sentiment applies to many uncertain and emerging technologies, this particularly applies to synthetic biology due to the limited regulatory guidance and best practices available to govern proper development, storage, and safe disposal of artificial genetic information that has the potential to mutate, proliferate, and impact the natural environment. In the absence of analytic instruments that can assess risks a priori, experience with technological analogs such as ag-bioengineering and nanotechnology may be more useful to inform adaptive governance of synthetic biology than fitting traditional models of LCA to technologies for which it is ill-suited.

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