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Assessing and Enhancing Environmental Sustainability: A Conceptual Review

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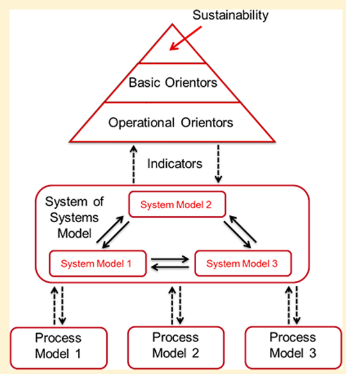
ABSTRACT: While sustainability is an essential concept to ensure the future of humanity and the integrity of the resources and ecosystems on which we depend, identifying a comprehensive yet realistic way to assess and enhance sustainability may be one of the most difficult challenges of our time. We review the primary environmental sustainability assessment approaches, categorizing them as either being design-based or those that employ computational frameworks and/or indicators. We also briefly review approaches used for assessing economic and social sustainability because sustainability necessitates integrating environmental, economic, and social elements. We identify the collective limitations of the existing assessment approaches, showing that there is not a consistent definition of sustainability, that the approaches are generally not comprehensive and are subject to unintended consequences, that there is little to no connection between bottom-up and top-down approaches, and that the field of sustainability is largely fragmented, with a range of academic disciplines and professional organizations pursuing similar goals, but without much formal coordination. We conclude by emphasizing the need for a comprehensive definition of sustainability (that integrates environmental, economic, and social aspects) with a unified system-of-systems approach that is causal, modular, tiered, and scalable, as well as new educational and organizational structures to improve systems-level interdisciplinary integration.



■ INTRODUCTION AND OBJECTIVES

In recent decades, there have been numerous reviews focusing on sustainability and sustainable development (e.g., refs 1−15), including those that analyze the development of sustainability as a discipline (e.g., refs 16−18) and those that evaluate the various frameworks, indicators, tools, approaches, methods, and schemes (which we collectively refer to as approaches) used to assess sustainability (e.g., refs 19−30). To our knowledge, however, there has been no overarching review that evaluates the range of assessment approaches and compares these to the nature of the sustainability problem to establish whether the available approaches are appropriate for the task. Thus, our goal in this conceptual review is to survey the field of sustainability and to identify and categorize the main approaches, which, as we will show, can be roughly divided into those that are design-based (and generally follow principles or guidelines) and those that employ computational frameworks and/or indicators. In addition, we focus our review on approaches that are primarily used to assess and enhance environmental sustainability, but briefly consider economic and social sustainability because the solution to the sustainability problem requires integrating environmental, economic, and social elements. Our specific objectives are therefore to

- Briefly review early assessment approaches as well as design-based approaches that relate to sustainability but that do not conform to the framework and indicator concept;
- Review the environmental sustainability assessment approaches that do conform to the framework and indicator concept, roughly categorizing them on a continuum from pure indicators, to integrated indicators, to indicators that are integrated within assessment frameworks, to pure frameworks;
- Briefly review approaches that are used to assess economic and social elements of sustainability to provide context for our more focused review of environmental sustainability; and
- Collectively evaluate the suite of approaches, establish whether they are appropriate for the task of assessing and enhancing sustainability, and highlight gaps in their collective ability to effectively guide real solutions to the sustainability problem.

We emphasize that many of the individual approaches could themselves be the subject of detailed reviews, and that it is not possible in this short overview of a vast field to be completely comprehensive. Indeed, one of the primary challenges associated with the field of sustainability is that many people have acquired their own limited understanding of the concept without having developed an appreciation of the full scope of the field. This conceptual review thus also serves as an

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introductory overview in which we endeavor to make the concept accessible and intelligible to a wide range of readers, therefore promoting an improved understanding of the concept across many knowledge domains and disciplines.

SUSTAINABILITY: EARLY APPROACHES

The Brundtland Report,[31] which was published in 1987, is most frequently cited as initiating the quest for sustainable development. However, the essence of the concept of sustainability may be found earlier in the National Environmental Policy Act (NEPA), which was enacted by the U.S. Congress in 1969. NEPA requires[32] that "all agencies of the Federal Government shall ··· include in every recommendation for major Federal actions significantly affecting the quality of the human environment, a detailed statement on ··· the environmental impact of the proposed action." Environmental impact assessment thus contains the seed of the idea of sustainability because NEPA declares[32] that "it is the continuing policy of the Federal Government ··· to use all practicable means and measures ··· to create and maintain conditions under which man and nature can exist in productive harmony, and fulfil the social, economic, and other requirements of present and future generations."

Environmental impacts are usually quantified by means of exposure and risk assessment, which can be applied to both ecosystems[33,34] and humans.[35,36] The concept of exposure and risk assessment has been extended to include environmental justice,[37−39] which is concerned with the potential for minority, low-income or otherwise disadvantaged and susceptible neighborhoods to be disproportionally exposed to environmental hazards.[37] Environmental impact assessment may result in legislation, and the impact that environmental legislation has on the economy may in turn lead to the adoption of benefit-cost analysis, which is an economic tool for comparing the desirable and undesirable impacts of future policies,[40,41] with 16 principles proposed for the appropriate use of benefit-cost analysis.[40] These early approaches (environmental impact assessment, exposure and risk assessment, environmental justice, and benefit-cost analysis) may be thought of as forerunners to the current suite of sustainability assessment approaches.

The Brundtland Report's definition of sustainable development is "development that meets the needs of the present without compromising the ability of future generations to meet their own needs".[31] The report highlighted three fundamental components of sustainable development: environmental protection, economic growth, and social equity, which are sometimes referred to as the three pillars of sustainability, and which are closely interrelated, as shown in Figure 1. Herman Daly provided more detail specific to environmental sustainability by outlining three operational rules:[12] (1) Renewable resources such as fish, soil, and groundwater must be used no faster than the rate at which they regenerate; (2) Nonrenewable resources such as minerals and fossil fuels must be used no faster than renewable substitutes for them can be put into place; and (3) Pollution and wastes must be emitted no faster than natural systems can absorb them, recycle them, or render them harmless. Although these early definitions provide useful context and broad guidelines for achieving sustainability, they lack specificity and are not explicitly quantitative.

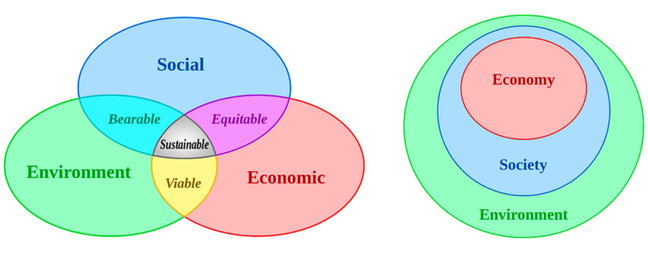

Figure 1. Two common representations of the three integrated pillars of sustainability. Although these visual representations capture the essence of sustainability, their deceptive simplicity may lead to the mistaken sense that sustainability is easy to assess.

SUSTAINABILITY: DESIGN-BASED APPROACHES

Several disciplines have added elements of sustainability to their traditional disciplinary field of emphasis, resulting in what may be classified as design-based approaches (which generally follow principles or guidelines) such as green accounting, green chemistry, and green engineering. We note here that several of the approaches included in our review were not necessarily conceived of as sustainability assessment tools, but can contribute to the assessment of sustainability and are often thought of as sustainability assessment approaches. For example, recent EPA[25] and NRC[9] reports consider green accounting, green chemistry, and green engineering to be sustainability assessment tools and approaches.

Green Accounting. Green accounting, which is an extension of benefit-cost analysis, "describes the efforts of academicians, accounting standard setters, professional organizations, and governmental agencies around the globe to induce corporations to participate proactively in cleaning and sustaining the environment and, moreover, to describe fully and forthrightly their environmental activities in either their annual reports or in stand-alone environmental disclosures".[42] In the 1980s, the focus was on health, safety, and environmental reporting, with environment as a junior partner to the other themes. By the 1990s, advances had been made on many health and safety issues, and environmentalism had become the dominant component. In 1994, Elkington coined the phrase *triple bottom line* to suggest that financial reporting should expand beyond traditional bottom-line net income as a measure of success to also include information about social and environmental performance, with a subsequent book titled *Cannibals with Forks*, which emphasized that the triple bottom line measured economic prosperity, environmental quality, and social justice.[43] A framework has also been proposed[44] for developing environmentally enlightened management and accounting information systems that include alternative environmental perspectives. More recently, it has been argued that acceptance of green accounting standards will induce unprecedented growth in the renewable energy sector, because it will make investment in renewable energy attractive for investors.[45]

Green Chemistry and Green Engineering. Green chemistry is the "design of chemical products and processes to reduce or eliminate the use and generation of hazardous substances" with the emphasis on the process of design. There are 12 principles or guidelines which provide the framework for sustainable design from a molecular point of view.[46] The approach has been extended to encompass green engineering, which has a further 12 principles which provide a framework for scientists and engineers to employ when designing new materials, products, processes, and systems that are benign to human health and the environment, and that move beyond

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baseline engineering quality and safety specifications to consider environmental, economic, and social factors.[47,48] The 24 principles are conveniently summarized in the form of two mnemonics.[49]

Whole System Design. Whole system design identifies 10 elements that can be mapped onto a traditional systems engineering approach. These elements enable sustainability thinking to be integrated into engineering design, particularly at the all-important conceptual and preliminary design stages.[50,51] This whole-system-design approach has recently been expanded, emphasizing the requirement for interdisciplinary skills and the need to identify relationships between parts of the system to ultimately optimize the whole.[52] Additional elements of sustainable whole systems design have been identified through a methodical review of sources from multiple design disciplines.[53]

ENVIRONMENTAL SUSTAINABILITY: FROM INDICATORS TO FRAMEWORKS

Many environmental sustainability assessment approaches use indicators, often within an assessment framework, to evaluate and compare alternative actions.[21,54] Here, we review the current suite of indicators and frameworks that are mainly relevant to environmental sustainability, and note that in several cases the approaches were developed for other purposes and only subsequently applied to assess sustainability, as previously mentioned. To illustrate the concepts presented in this section, we use the example of a river polluted during the manufacture and use of toxic chemicals.

Environmental sustainability indicators categorize and quantify the impact (which could be negative or positive) of human actions. In our example of river pollution, the toxic chemicals can affect both humans and organisms in the river as well as ecosystem function, with possible indicators including the mass of pollutant emitted and the concentration of the pollutant in the river water. In contrast, environmental sustainability frameworks conceptualize or quantify the scope of the human systems, actions, or influences that cause the impacts. This is done in a way that facilitates the use of indicators, with example human actions including resource extraction, manufacturing, and the distribution of goods or services. Thus, frameworks are used to examine the factors causing impacts, whereas indicators are used to assess the effects of the impacts. There is no clear distinction between an indicator and an assessment framework, but rather, as shown in Figure 2, there is a continuum between pure indicators that exist independently of frameworks and pure frameworks that exist independently of indicators. In our river pollution example, a framework would need to represent what industries, organizations, or consumers, use the toxic chemical, and possibly why, how, or where those chemicals are used. But frameworks also need to include natural systems, because natural systems often mediate, modify, or transform human impacts. In our example, the river transports pollutants downstream from their sources, geographically separating sources and impacts and thus altering our ability to assess the interaction between the human systems that caused the chemical pollution and the effects of the pollution on the ecosystem and humans that use the river.

Pure Indicators. A pure indicator is a metric that quantifies human impacts. By themselves, pure indicators are not specific to any particular human activity or system. An example is water use (also known as water footprint; for example, www.waterfootprint.org), which quantifies the water used in human activities, but can be applied to any human activity by different demographic groups in any geographic region over different time scales. In other words, water use is a potentially useful indicator whether we are comparing annual water consumption by a certain industrial sector at the national level or a person watering a lawn on a particular day. A variety of other pure indicators exist, including energy use and other footprints, but each focus on only a single type of impact.[28,29,55−57]

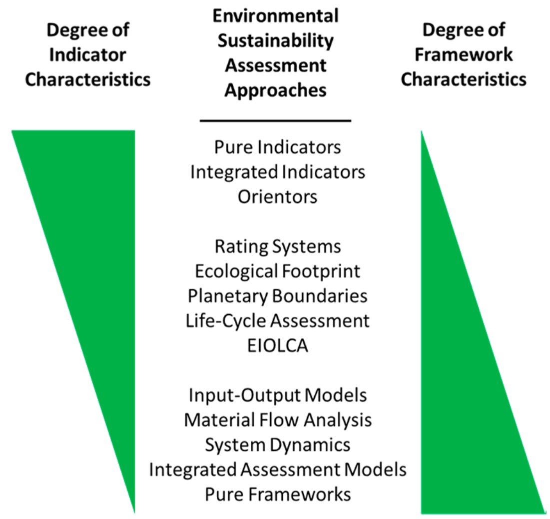

Figure 2. Continuum of environmental sustainability assessment approaches from pure indicators to pure frameworks.

Integrated Indicators. Integrated indicators are created when multiple pure indicators are combined into a single composite indicator.[21] For example, the pure indicators of water use, energy use, and pollutant emission could be combined into a single integrated indicator. Other examples include ecosystem services, which are valued with a common currency,[58] and various measures of resilience.[59−61] Note that integration involves combining multiple types of impacts, rather than combining different aspects of human actions that create the impact (e.g., such as what human group is involved, where the impact occurs, or when the impact occurs). There are many approaches for integrating indicators (e.g., refs 21,62−66). These typically involve assigning weights to, and then summing, more specific indicators. This often involves summation of impacts that are measured in different units, thereby requiring unit conversions that can be facilitated by common currencies[20] such as monetary valuation, energy, and risk.

Higher-level indicators, such as the human development index[67] and the environmental performance index,[63] are examples of highly integrated indicators. As with pure indicators, integrated indicators are focused on quantifying impact, but they incorporate or "integrate" multiple different impacts into one value. Integrated indicators can be of more value than individual (pure) indicators, because they combine more aspects of sustainability. However, the act of integrating multiple pure indicators requires judgments about which impacts are more important. This incorporates elements of a framework into the resulting integrated indicator because determining which impacts are more important requires understanding what human activities are causing the impact and/or when or where they are occurring. In other words, the integration process is in essence a framework, given the influence it has on the nature of the resulting integrated

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indicator. For our river example, we would need to know which industry or type of consumer is using the toxic chemicals, and in what watershed those chemicals are being used to predict which toxic chemicals will be discharged into which river.

Orientors. Combining multiple pure indicators is a bottom-up approach to creating integrated indicators. However, integrated indicators can also be generated in a top-down approach. Indicators derived in a top-down fashion start with an overarching goal or concept and may therefore be thought of as orientors.[68] For example, as shown in Table 1, Bossel[68−70] proposed that the sustainability of autonomous, self-organizing systems (which include both ecosystems and human systems) can be completely determined by several basic orientors, including existence, effectiveness, security, adaptability, coexistence, and in the case of human systems, freedom of action, and psychological needs. Focusing on humans, Max-Neef et al.[71] developed a similar list which includes subsistence, protection, affection, understanding, participation, leisure, creation, identity, and freedom. According to Bossel[69,70] the basic sustainability orientors are independent of one another, but are abstract in nature and need to be translated into more pragmatic operational orientors before they can be used to guide or orient the assessment of sustainability. An example operational orientor would be human water needs for survival, which would fall under the basic orientors of existence or security. Orientors may create conflicting pressures; for example, when human water needs must be balanced against ecosystem water needs (e.g., ref 72). Ecosystem water need is therefore another operational orientor falling under coexistence and existence.

Table 1. Basic Orientors May Be Used to Determine the Sustainability of Autonomous, Self-Organizing Systems[69,70] (which Include both Ecosystems and Human Systems)

basic orientor	definition
existence	requirements necessary to enable the system to function within its natural environment
effectiveness	capabilities of the system necessary to ensure that the system successfully functions within the environment
freedom of action	human systems must have the ability to make decisions that maintain system sustainability
security	system must be protected, or be able to protect itself, from harmful elements in the environment
adaptability	system must be able to adapt to a changing environment
coexistence	system must be able to interact and function sustainably with other systems in the environment
psychological needs	human systems have emotional satisfaction requirements that are required to achieve or maintain system sustainability

Sustainability is assessed by comparing the operational orientors (which reflect the desired state of the system) to specific indicators or integrated indicators (which reflect the actual state of the system) and evaluating the extent of orientor satisfaction, with each orientor requiring a minimum level of satisfaction for the system to be considered sustainable. Generally, the indicators are normalized by the minimum acceptable value to facilitate weighting and summing. When the normalized value is greater than or equal to 1.0, the orientor is satisfied. When the normalized value is less than 1.0, the orientor is not satisfied and action needs to be taken. Some orientors and indicators are inherently more important than others and relative weights are assigned to account for these differences. The normalized and weighted indicators are then summed, resulting in a quantitative extent of overall orientor satisfaction and, therefore, sustainability. Normalizing also eliminates the problem of integrating a wide range of impacts with multiple types of units. Sustainability is therefore achieved when all operational orientors are satisfied, and may be enhanced by improving individual orientor satisfaction and by achieving the highest possible overall orientor satisfaction.[69,70] The process of deriving operational orientors and selecting suitable indicators, as well as specifying their weights, is guided by groups of stakeholders.[73,74] Assigning appropriate weights is not a simple objective process,[68−70] but one which requires value judgments. Values, also referred to as norms, may differ substantially from person to person and from culture to culture, making the process whereby a group of stakeholders must reach agreement more challenging. Furthermore, individual values may be related to the values of others in the community.[75]

Rating Systems. There are a variety of sustainability rating systems that are typically intended for widespread use by practitioners and governments and that are relatively simple and user-friendly. Perhaps the most well-known is the LEED (Leadership in Energy and Environmental Design) rating system developed by the U.S. Green Building Council (www.usgbc.org).[76,77] LEED currently uses five rating systems for different types of projects (building design and construction; interior design and construction; building operations and maintenance; neighborhood development; and homes). In addition, LEED uses a credit system to assess sustainability, assigning points based on several categories including integrative process; location and transportation; materials and resources; water efficiency; energy and atmosphere; sustainable sites; indoor environmental quality; innovation; regional priority credits; smart location and linkage; neighborhood pattern and design; and green infrastructure and building. The total number of points determines the level of LEED certification. Similarly, the Envision rating system was developed by the Institute for Sustainable Infrastructure to rate the environmental and social sustainability of infrastructure (www.sustainableinfrastructure.org), while the AquaRating system (www.aquarating.org) under development by the Inter-American Development Bank and the International Water Association rates the performance of water and sanitation service providers. Similar to life-cycle assessment (see below), rating systems have built in indicators, and thus fall in the middle of the indicator-framework continuum (Figure 2).

Ecological Footprint. Ecological footprint is an accounting tool that quantifies how much of the Earth's surface a human population requires (or appropriates) to produce the resources it consumes and to absorb its wastes using prevailing technology, and compares this to the available biocapacity of the earth.[54,78] Ecological footprint measures the appropriated biocapacity across distinct land use types (cropland for the provision of plant-based food and fiber products; grazing land and cropland for animal products; fishing grounds (marine and inland) for fish products; forests for timber and other forest products; carbon uptake land to accommodate the absorption of anthropogenic carbon dioxide emissions; and built-up areas for shelter and other infrastructure).[79] Since the end of the 1940s, humanity has experienced a *great acceleration*, with a ∼15-fold increase in global economic output.[80,81] This explosion in economic activity is coupled to an exponential increase in population and a corresponding increase in natural resource extraction and consumption. As a result, humans are using

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more resources than can sustainably be replaced, with a current ecological footprint equivalent to about 1.5 earths.[79] Because ecological footprint considers the impact of a human population in a specific area, it is a framework (Figure 2). On the other hand, ecological footprint has a very specific and rather unique concept of impact (area of land needed) built in, and therefore may also be thought of as an indicator.

Planetary Boundaries. The planetary boundaries framework[82,83] defines a safe operating space for humans based on the intrinsic biophysical processes that regulate the stability of the Earth System. The current list of boundaries encompasses biogeochemical flows, freshwater use, land-system change, biodiversity loss (also referred to as biosphere integrity), climate change, stratospheric ozone depletion, atmospheric aerosol loading, and ocean acidification. Two core boundaries, biodiversity loss, and biogeochemical flows, may have already been crossed.[83] Both of these boundaries on their own have the potential to drive the Earth System into a new state should they be substantially and persistently transgressed. The planetary boundary approach does not suggest how to maneuver within the safe operating space to ensure sustainability. For example, the framework does not take into account the regional distribution of the impact, nor of its historical patterns, nor does it take into account the deeper issues of equity and causation.[83] Similar to ecological footprint, planetary boundaries can be viewed as a framework, or as a series of integrated indicators, or both.

Process Life-Cycle Assessment. Process life-cycle assessment (LCA) evaluates the environmental impact of a human activity, typically considering steady-state flows of material and energy required for the manufacture, distribution, and consumption of goods or the provision of services.[84−88] LCA assesses impacts in a cradle-to-grave manner, considering the entire process of production, use, and consumption/disposal. The four main stages of LCA include (1) definition of goal and scope to set the system boundary and level of detail; (2) inventory analysis which compiles detailed input and output data for the system; (3) impact assessment in which environmental significance is assessed; and (4) interpretation in which results are summarized for use in decision making.[89] The impact assessment stage typically evaluates a range of impact categories, each of which includes one or more indicators of sustainability,[90] although these are generally aggregated impacts which are neither spatially nor temporally explicit. These lumped impacts can include, for example, ozone depletion, global warming potential, smog formation, acidification, criteria air pollutants, eutrophication, human health, eco-toxicity, fossil fuel depletion, and water use.[91] These different impacts are then integrated via a process of normalization that is similar to that described above for indicators. Following our river example, LCA would track the raw materials used to synthesize the toxic chemicals, their production, distribution, and use, and the pathways by which they are disposed. LCA generally relates these environmental impacts to a functional unit which could be a product, process, or service.

Because LCA is organized around particular human activities, it is very much a framework, yet its range of built-in indicators (ozone depletion, global warming, etc.) means that it exists partway along the indicator-framework continuum (Figure 2). LCAs have focused on a wide range of products and processes[92−94] with a recent review focusing on urban water systems.[95] Although steady state is usually assumed, dynamic LCA has been proposed.[96] LCA has been extended[97] from the more traditional *attributional* LCA, which describes the flows within a chosen system attributed to the delivery of a specified amount of the functional unit, to what is known as *consequential* LCA, which estimates how flows within a system change in response to a change in output of the functional unit.[98] LCA has also been extended to include social life-cycle assessment, as well as life-cycle sustainability assessment,[99−104] although the inclusion of social sustainability has met with limited success.[105,106] In addition, eco-efficiency analysis,[107,108] which quantifies the relationship between economic value and environmental impacts,[109] combines LCA and benefit-cost analysis.

Economic Input-Output Life-Cycle Assessment. Economic input-output models track flows of goods and services through an economy, together with their unit prices.[110,111] Basic input-output models assume that facilities producing all the goods and services in an economy can be aggregated into a number of sectors, based on standard industrial classification or SIC (www.siccode.com) codes, and that input-output flows among all sectors are linearly related and at steady state. These simplifications enable governments to produce input-output tables of economic data at different economic scales. For example, input-output studies have been carried out for the global economy, nations, and subregions of countries.[112−116] If the flows of goods and services are expressed instead as flows of material and energy, and if data on resource requirements and environmental impacts are appended to the input-output table,[110] the resulting economic input-output life-cycle assessment (EIOLCA) models (www.lcatextbook.com) can then be used to make economy-wide life-cycle assessments for any of the goods and services.[117] Similar to process LCA, EIOLCA typically evaluates several lumped or aggregated impact categories each of which includes one or more indicators.[118−120] It is important to note that the key simplifying assumptions of steady-state conditions and linear relationships can be relaxed,[111] allowing flows to accumulate or deplete in stocks, and relationships between inputs and outputs to be nonlinear. Economic input-output models are pure frameworks, but once resource requirements and environmental impacts are incorporated, the resulting EIOLCA models are similar to LCA, and fall in the middle of the indicator-framework continuum (Figure 2).

Material Flow Analysis and Industrial Metabolism. Material flow analysis (MFA) tracks flows of material or energy moving through various processes.[121] Following our river example, MFA would trace the flows and fates of the chemical pollutants within industrial or environmental compartments.[122,123] MFA is simpler than life-cycle assessment and tends to be less complete, often focusing on only a few chemicals and neglecting impacts outside the region or time period studied. MFA is considered a framework because its essence is the pathways through a human or natural process, so its overall structure mimics the scope of actions of interest. Furthermore, the specific material to be tracked is not particularly constrained, so MFA does not have a strong indicator component. For these reasons, MFA is closer to the framework end of the continuum (Figure 2). Industrial metabolism, the integrated collection of physical processes that convert raw materials and energy, plus labor, into finished products and wastes,[124] can be viewed as MFA applied to industry. Extensions have been proposed linking decisions regarding industrial processes to their political and social

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context.[125] Similarly, urban metabolism is MFA applied to a city or metropolitan area.[126,127] Interestingly, Golubiewski[128] has questioned the concept of urban metabolism, suggesting instead that cities should be thought of as ecosystems, an idea echoed by Xu et al.[129]

System Dynamics. System dynamics is a generic programming language based on stocks and flows that was developed by Forrester[130] and originally applied to model global and social systems.[131,132] System dynamics was one of the first sustainability assessment approaches when it was employed in the 1970s to assess *The Limits to Growth*.[133] The resulting World3 model has been used to simulate scenarios that varied population growth, available resources, agricultural productivity, and environmental degradation. In a 30 year update,[134] the authors showed that the original models remain surprisingly accurate, as verified by Turner.[135,136] While many disciplines loosely use the term *system dynamics*, we note that we are specifically referring here to the system dynamics programming language.

The system dynamics language is flexible and can explicitly represent time and space, capturing elements of dynamic complexity[137] such as feedbacks, time delays, accumulations, and nonlinearities.[138] The visual nature of the influence diagrams helps system dynamics to be understood across disciplinary and organizational boundaries.[139] System dynamics can simulate complex processes[140] including social and economic phenomena, provided that appropriate equations and input data to quantify the relevant phenomena are available. Following the river example, a system dynamics model could examine the production of the toxic chemical and its disposal into the river as a function of several factors and feedbacks. For example, if the concentration of the toxic chemical in the river exceeded a threshold at which health impacts became a concern, the model could include the effects of new legislation regulating nonpoint and point source pollutants, which would ultimately lower the amount of chemical discharged into the river. However, depending on the behavior of the polluters and the residence time of the chemicals in the environment, there may be a substantial time lag between the enactment of legislation and resulting improvements in water quality.

An example of the use of system dynamics is the GUMBO model,[141−143] which includes dynamic feedbacks among human technology, economic production and welfare, and ecosystem goods and services within the dynamic earth system. System dynamics has been used to model watersheds,[144−146] climate,[140] electric equipment supply chains,[147] electric power systems,[148,149] ecosystems,[150] business systems,[138] public health,[151−153] social systems,[154,155] and socio-technical systems such as energy, transportation, and communications systems.[156,157] System dynamics models[139] have no size restriction and are essentially only limited by what is computationally feasible. System dynamics is flexible in terms of how indicators can be incorporated and is therefore a pure framework on the continuum (Figure 2).

Integrated Assessment. In contrast to the traditional planning process, which assumes that a combination of professional expertise, scientific methods, and well-defined goals will be efficient and effective, planning for sustainable development is far more complex, requiring new approaches and new tools.[158] Integrated assessment is a well-established approach for evaluating environmental science, technology, and policy problems,[159−161] having been used extensively for climate change,[160,162,163] and more recently for sustainability.[164] Kelly et al.[165] identified at least five uses of the term "integration," including integrated treatment of issues, integration with stakeholders, integration of disciplines, integration of processes and models, and integration of scales of consideration. They also identified five main purposes for integrated assessment models, including prediction, forecasting, management and decision-making under uncertainty, social learning, and the need to develop system understanding. Integrated assessment often employs scenarios and a process of adaptive management and can be qualitative or quantitative, in which case it is usually based on predictive models. When scenarios, adaptive management and integrated assessment are qualitative, they may be thought of as design-based approaches, while integrated assessment modeling clearly conforms to the framework and indicator concept (Figure 2), although both qualitative and quantitative integrated assessment approaches are by definition broadening environmental sustainability to include economic and social elements.

Integrated assessment employs scenarios to characterize hypothetical future pathways. Although there are many definitions, scenarios typically describe sequences of events over a period of time, and consist of states, driving forces, events, consequences, and actions which are causally related.[158] Although there have been several attempts to classify the many types of scenarios,[166−168] there is no consensus.[169] Simple examples[158] include forecasting scenarios, which explore future consequences of a sequence of assumptions, and backcasting scenarios, which start from an assumed final state, and explore the preconditions that could lead to this state. There are also descriptive scenarios, which describe an ordered set of possible events irrespective of their desirability, and normative scenarios, which take values and interests into account. Quantitative scenarios are usually based on models, while qualitative scenarios are based on narratives. Participatory scenarios involve stakeholders, including decision-makers, business people and lay people, while expert scenarios are developed by a small group of technical experts. Good examples of complex scenarios include those developed for climate change research and assessment.[170,171]

Adaptive management, which may be a part of the integrated assessment process, views policies as if they were experiments, with results from one generation of study informing subsequent decisions.[172] The way in which participation is arranged within the adaptive management cycle is itself a subject of research,[173] with a range of participatory mechanisms that can be employed at different stages of the adaptive management cycle to create favorable outcomes for diverse stakeholders. For example, a second generation of backcasting scenarios has been proposed[174,175] where the desired future is not determined in advance of the analysis but is an emergent property of the process of engaging with stakeholders that engenders social learning about possible and desirable futures.

Other Frameworks. Numerous other frameworks have been proposed for assessing systems that are related to sustainability (e.g., refs 176−183), including several that focus specifically on water resources (e.g., refs 184−193). A notable example is the multilevel, nested framework proposed by Ostrom[180] for analyzing outcomes achieved in social-ecological systems, which identified ten subsystem variables that affect the ability of users of a resource to self-organize themselves, investing time and energy to avert a tragedy of the commons. All of these frameworks are consistent with the concept of

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computational frameworks and indicators, and several include connections with economic and social systems.

ECONOMIC AND SOCIAL SUSTAINABILITY: A BRIEF REVIEW

It is well established that sustainability requires that each of the environmental, economic, and social pillars be addressed. Inherent in that idea is that none of the three areas can truly be addressed without acknowledging and accounting for interdependencies with the others. Returning to our polluted river, for example, achieving a more sustainable river from a water quality perspective will require not only technical fixes such as source control or contaminant removal, but also a shift in values, awareness, and culture (e.g., ref 194). Indeed, we believe that the focus should be on sustainability as a single achievable goal, and not on environmental, economic, and social sustainability as individually achievable goals. The distinctions are semantically convenient, however, because they allow the approaches to be categorized.

One of the major difficulties in assessing sustainability is therefore deciding on the extent to which different environmental, economic, and social aspects should be taken into account. A useful perspective on the integration of economic and social consequences was provided by Bossel,[70] who suggested that any societal system can be roughly divided into broad sectors that are interrelated and that establish meaningful connections among the environmental, economic, and social systems, as shown in Figure 3. This simple representation is more instructive than Figure 1 because it reveals the inherent difficulty of simultaneously integrating environmental, economic, and social systems. Figure 3 also shows how the six societal sectors can be aggregated into the three traditional systems. In this section, we briefly review approaches that are used to assess economic and social elements of sustainability to provide context for our more focused review of environmental sustainability.

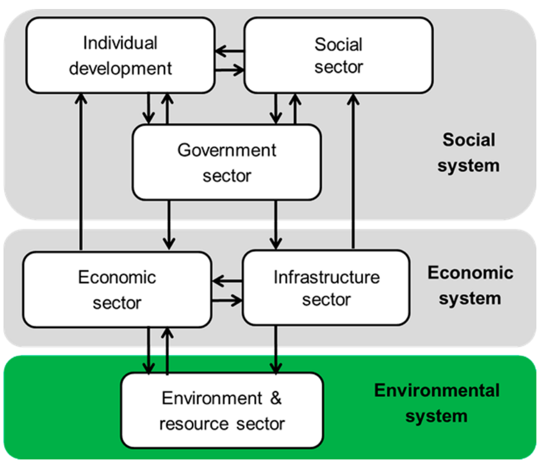

Figure 3. Societal systems can be divided into sectors that are interrelated and that establish meaningful connections among the environmental, economic and social systems.[70]

Sustainability economics may be thought of as the integration of resource economics and environmental economics,[195] with the competitive quest for scarce resources emphasized in *The Tragedy of the Commons*.[196] This classic paper led in turn to the idea of a stationary or steady-state economy[197,198] as well as *The Limits to Growth*.[133] While gross domestic product (GDP)[199] measures mainly market transactions, it is well-known that it ignores externalities such as social costs, environmental impacts, and income inequality.[200] In fact, in his first report on how to measure what is now known as GDP, Simon Kuznets stated clearly that "the welfare of a nation can, therefore, scarcely be inferred from a measurement of national income, as defined above".[201] To overcome the limitations of GDP as an indicator of human development, Arrow et al.[202] recently related sustainability to the temporal change in wealth, as opposed to income, proposing a quantitative framework that captures not only reproducible and human capital, but also natural capital,[203] health improvements, and technological change.

While intergenerational equity is a key aspect of sustainability, "efforts to define social sustainability and socially responsible investment cover a broad and unwieldy set of components, from the development assistance community's emphasis on poverty reduction to the international community's emphasis on human, labor, and indigenous rights, and the business community's orientation towards socially responsible investment and sustainable product life cycles".[106] The social component of sustainability is especially important for developing-world problems[204] including the provision of water, sanitation, and hygiene, all of which are key aspects of the 2030 Agenda for Sustainable Development.[15]

Although economic and social sustainability are difficult to define, many integrated indicators have been proposed that combine environmental, social, and economic aspects[205] and that could replace GDP as indicators of socio-economic development. These indicators may be divided into three categories.[206] First, GDP may be *adjusted* by including monetized environmental and social factors, an example being the genuine progress indicator.[207] Although world GDP has soared since the 1950s, the genuine progress indicator has remained flat since the 1970s.[200] Second, GDP may be *replaced* with indicators that try to assess sustainability or well-being more directly. An example is the Human Development Index, a product of the United Nations Development Program, which is used to measure a country's development. This composite indicator is a simple average of three indices: health and longevity, education, and living standard.[67] Third, GDP may be *supplemented* with additional social and environmental information. In this approach, several indicators are gathered together with the aim of providing a comprehensive, yet manageable assessment of sustainable socio-economic progress. A good example is the planetary dashboard developed to document the great acceleration,[81] which is based on 12 socio-economic indicators and 12 Earth System indicators.

More complex economic and social assessment approaches have been proposed. For example, in a review of the use of computable general equilibrium models (which are based to some extent on economic input-output data) for measuring the impacts of policy interference on policy-relevant economic, environmental, and social indicators, Böhringer and Löschel[208] found operational models to have good coverage of central economic indicators. Environmental indicators such as energy-related emissions with direct links to economic activities were widely covered, whereas indicators with a complex natural science background such as water stress or biodiversity loss were hardly represented. Social indicators were weakly covered, mainly because they are vaguely defined or incommensurable.[208] However, the legitimacy of employing computable general equilibrium models as a single integrating framework

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for a comprehensive evaluation of the multidimensional, dynamic and complex interactions between policy and sustainability has been seriously questioned.[209] A world trade model, which uses constrained optimization to determine world prices, scarcity rents, and international trade flows based on comparative advantage in a world economy with an arbitrary number of regions, goods, and factors, has been proposed as an alternative.[210] The model quantifies the sources of the gains from trade for the world as a whole, and for individual regions, and accounts for limitations to economic growth posed by environmental constraints, notably resource availability, making it useful for analyzing scenarios about sustainable development.[112,113,210]

The human dimension is especially important when assessing and enhancing sustainability.[211,212] Using agent-based models, Pahl-Wostl[213] showed how adaptive management and social learning can more effectively lead to the required transformation in technological regimes and institutional settings. Agent-based models,[214] also known as individual-based models,[215] can capture the divergent behavior of individual humans exhibiting considerable variability in their decision-making across time and space.[157,215−217] As explained by Bonabeau,[218] agent-based models simulate the behavior of a system's constituent units (the agents) and their interactions. Emergent phenomena that result from the interactions of the agents can have properties that are decoupled from the properties of the agents. The whole is therefore more than the sum of its parts because of the interactions among the different agents. The resulting emergent phenomena can sometimes be difficult to understand and predict,[218] but agent-based models can be instructive in systems in which many agents operate individually according to stochastic processes, while the agents' actions aggregated as a group exhibit perceptible patterns. Such emergent population-level properties can provide critical insight into the traits of dominant agents, the agents as a group, and the conditions in which the agents are interacting. It should be noted that agent-based models consider a system at the level of the constituent units, and not at the aggregate level. Such bottom-up processes may involve describing the individual behavior of many agents, and can be computationally intensive depending on the model parametrization.[151,218]

■ GAPS IN EXISTING SUSTAINABILITY ASSESSMENT APPROACHES AND NEXT STEPS

Identifying a comprehensive yet realistic way to assess and enhance environmental sustainability is extremely difficult. Common approaches as reviewed above include adaptive management, eco-efficiency analysis, ecological footprint, economic input-output life-cycle assessment, green accounting, green chemistry, green engineering, indicators, industrial metabolism, input−output models, integrated assessment, integrated indicators, material flow analysis, orientors, process life-cycle assessment, planetary boundaries, rating systems, resilience, scenarios, and whole-system design. While recognizing that significant progress has been made in developing these approaches, we compare them to the nature of the sustainability problem to establish whether the available approaches are appropriate for the task.

The Sustainability Assessment Approaches Are Not Designed from a Systems Perspective. There is growing recognition of the need for a systems approach when dealing with sustainability (e.g., refs 179,181,212,219−221). Unfortunately, it is often the case that the complexity of the systems in which we are embedded overwhelms our ability to understand them.[139,222] This phenomenon, which is sometimes referred to as policy resistance, arises because complex systems are constantly changing, tightly coupled, governed by feedbacks, nonlinear, history-dependent, self-organizing, adaptive and evolving, characterized by trade-offs, and counterintuitive.[139] As a result, many seemingly obvious solutions to problems fail or actually worsen the situation,[139] causing what are more commonly known as unintended consequences. While mathematical models that are based on causal relationships may have substantial uncertainty, and may be subject to chaotic, nonlinear behavior, they represent the only feasible approach to understand complex systems so that we can attempt to enact appropriate management strategies.

The critical need for a coupled systems approach to understand causal relationships spanning environmental, economic and social systems is vividly illustrated with myriad examples of the unintended consequences of well-meaning policies. In the case of biofuels, for example, policy makers focusing only on the supply side of the problem overlooked the fact that policies that encourage the use of biofuels may lead to unsustainable subsidized burning of resources and food[223] or unsustainable use of water.[224] Another unintended consequence in a closely coupled system is the case of MTBE (methyl *tert*-butyl ether), which has been used as a gasoline additive to improve combustion and decrease air pollution. When gasoline containing MTBE leaked into aquifers, MTBE, being more soluble than the other constituents of gasoline, preferentially dissolved into the surrounding groundwater, incurring substantial cleanup costs. A final example is the so-called rebound effect[225−227] where improvements in energy efficiency make energy services cheaper, and may therefore encourage increased consumption of those services.[227] These unintended consequences can be hard to avoid when attempting to improve the sustainability of closely coupled, complex systems.

Approaches for evaluating sustainability, such as indicators, rating systems, and ecological footprint, are simple and easy to use, but do not capture the causal relationships that are needed to understand the behavior of complex systems. Design-based approaches such as green accounting and green engineering are valuable for introducing elements of sustainability into traditional areas of practice, but are not easily cast in terms of a generic computational framework. By contrast, LCA captures causal relationships for a specific product or process, but the aggregated nature of the environmental impacts, and the steady-state nature of the assessment, mean that spatially and temporally important criteria are lost. A major advantage of EIOLCA is the readily available economic data that capture important economic drivers, yet the highly aggregated nature of the economic data usually constrain the approach to top-down analyses. Although the current suite of environmental sustainability assessment approaches do provide crucial information required to evaluate sustainability, spatial and temporal explicitness is rare[20] and long-term trends are hard to incorporate because most assume steady state. In addition, existing approaches cannot easily be coupled with the social system in an interactive fashion, even though it is clear that accounting for and modifying human behavior will play a critical role in achieving sustainability.[211] Some frameworks, including LCA, have recently added social components,[105,106] but these new additions work in parallel with environmental

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LCA and not in a coupled fashion in which environmental, economic and social factors interact with one another.

Taken as a whole, the current approaches do not permit a comprehensive assessment of sustainability that spans a wide range of relevant systems. What is needed is a coupled, modular, system-of-systems approach with a causal computational framework that can be used together with orientors and indicators to assess and enhance sustainability.

There Is Not a Consistent Definition of Sustainability. Many authors have pointed out the difficulty of defining and quantifying sustainability and sustainable development (e.g., refs 1−4,10,14,23). While the Brundtland definition of sustainability is generally accepted,[228] the practical definition of sustainability tends to vary with the specific assessment approach, be it green chemistry or planetary boundaries or EIOLCA. To make things more difficult, sustainability is a normative notion prescribing the way humans should interact with nature, and how they are responsible toward one another and future generations.[229] Unfortunately, social and cultural norms vary significantly from one region to another and from one culture to another, making it difficult to agree on a definition of sustainability.

Indicators are used to evaluate and compare the sustainability of alternative actions. Although many indicators are in use, they are seldom related to basic orientors that capture the essence of sustainability, such as those proposed by Max-Neef[71] and Bossel.[70] The current approaches are haphazard and risk creating an incomplete picture of sustainability, leading to unintended consequences.[20] A comprehensive approach to sustainability assessment must start by deriving a suite of operational orientors and indicators from basic orientors in a systematic fashion. Because basic orientors are inherently abstract in nature, they are translated into a broad range of operational orientors that can be quantified. This is achieved by considering all aspects of a system that are necessary to satisfy the basic orientors.

There Is No Connection between Bottom-up and Top-down Assessment Approaches. Another challenge to assessing sustainability is the vast gap between bottom-up and top-down approaches. For example, there are product- or process-specific life-cycle assessments on one hand, and high-level sustainable development indicators and planetary boundaries on the other. How can we ensure that process life-cycle assessments (bottom-up approaches that focus on environmental impacts) are consistent with indicators of sustainable development (top-down approaches that include economic and social impacts)? High-level sustainable development indicators may be useful for assessing the well-being of nations, or the state of the planet, but what specific actions do we take if the indicators inform us that change is needed? How do we know that actions we do take to improve sustainability will not result in unintended consequences? What is needed is a tiered framework with different levels of abstraction. Thus, as shown by Borschev and Filippov[230,231] we can imagine a lower micro level, which would have a low degree of abstraction and more detail (focusing, for example, on individual objects and exact sizes) as well as a higher macro level, with a high degree of abstraction and less detail (focusing, for example, on aggregates and feedback dynamics). There could be additional levels, including an intermediate meso level,[230] but for now, we simply consider two levels. If we refer to the lower level as the process level and the higher level as the systems level, then a consistent way of up-scaling from the process level to the systems level is needed, as well as a way of connecting the tiers or levels so that critical information can be passed among them.

The Sustainability Field Lacks Effective Interdisciplinary Integration. The field of sustainability is fragmented, with a wide range of professional and academic groups pursuing similar goals, but without effective interdisciplinary coordination. Many disciplines and professional societies have added elements of sustainability to their historical disciplinary approaches, resulting, for example, in green chemistry, green engineering and green accounting. The International Association of Hydrological Sciences recently launched a new initiative to improve the ability to make predictions of water resources dynamics to support sustainable societal development in a changing environment. Similarly, the International Water Association has several different specialist groups focusing on sustainability and resilience of water. In other cases, parts of disciplines have been merged, with examples including industrial ecology and ecological economics.[232] Progress is being made in many of these areas, but remains highly fragmented. In contrast, work on climate change has benefited substantially from the activities of the Intergovernmental Panel on Climate Change (IPCC) (www.ipcc.ch), which integrates experts in many different disciplines and has shown considerable progress in the area of integrated assessment.[170] New educational and organizational structures are needed to improve systems-level interdisciplinary integration in the broader area of sustainability, including, for example, organizational guidance similar to that provided by the IPCC.

■ TOWARD A COMMON INTERDISCIPLINARY FRAMEWORK TO ASSESS AND ENHANCE SUSTAINABILITY

A system-of-systems approach that couples a wide range of environmental, economic, and social systems is needed to assess and enhance sustainability. Interestingly, a simplified systems approach is already being implemented by the climate change community, with integrated assessment models that include key features of human systems, such as demography, energy use, technology, the economy, agriculture, forestry and land use.[170] These models incorporate simplified representations of the climate system and are calibrated against more complex climate models. The models are used to develop emissions scenarios, simulate feedbacks, estimate the potential economic impacts of climate change, evaluate the costs and benefits of mitigation, and evaluate uncertainties.[170] The development of these integrated assessment models involves two conceptual steps—the first being the creation of reduced-order models from more complex ones, also known as up scaling or emulation modeling,[233] and the second being the coupling of the up-scaled components using a common framework. If we have many process level models (water, energy, air, land, ocean, climate, agriculture, fishing, forestry, mining, transportation, urban environment, human health, natural ecosystems, as well as other economic and social systems, for example), it becomes essentially impossible to couple them all directly in their original form at the process level—there is simply too much detail and computational resources will be overwhelmed.[233] Thus, as shown in Figure 4, we envision a process level with process models that have a lower degree of abstraction and more detail, as well as a systems level with system models that have a higher degree of abstraction and less detail. In this way, a comprehensive definition of sustainability (imposed by means of basic

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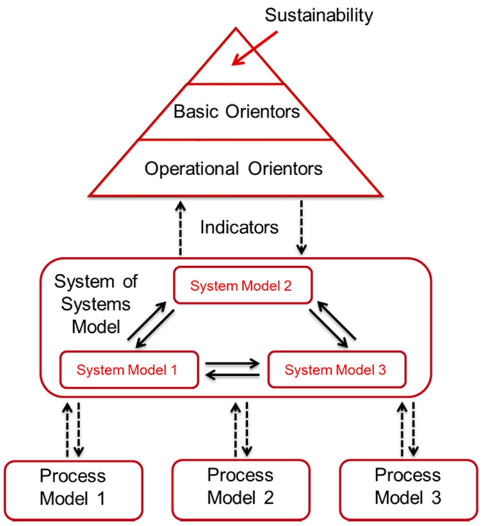

Figure 4. Tiered structure with process models up-scaled to the systems level where they are coupled. The system-of-systems model is combined with a comprehensive definition of sustainability (imposed by means of basic orientors, operational orientors, and indicators) and then used to assess and enhance sustainability.

orientors, operational orientors, and indicators) can be combined with a unified system-of-systems approach that is causal, modular, tiered, and scalable. This approach should prove useful even if the necessary fundamental knowledge, mechanistic understanding, and data are not yet available for all systems of interest. For example, current economic models are unable to accurately predict the trajectory of economic development, but simpler economic models (such as those based on input-output data) do capture important economic drivers and are therefore useful in scenario analysis.

Identifying a realistic way to assess and enhance sustainability may count as one of the most difficult challenges of our time. As emphasized by Sterman,[139] "the consequences of our actions spill out across time and space and across disciplinary boundaries, but our universities, corporations, and governments are organized in silos that focus on the short term and fragment knowledge." If we are serious about wanting to assess and enhance sustainability, we need a unified system-of-systems approach that is based on the computational framework and indicator concept and that is causal, modular, tiered and scalable. The approach will need a consistent definition of sustainability as well as new educational and organizational structures to improve systems-level interdisciplinary integration. We acknowledge that this represents a daunting challenge that may take decades, but argue that the goal of achieving sustainability will itself play out over several decades, and that much could be gained by working toward a common interdisciplinary assessment framework. We conclude by noting that such an approach is not only needed for sustainability, but also for resilience[234−236] and many other large-scale interdisciplinary problems involving coupled societal systems.

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Notes

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