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Measuring sustainability

Planning for sustainability is high on many agendas, and tools to measure sustainability have been developed. Sustainable processes are those whose rates are maintained over time without exceeding the innate ability of its surroundings to support the process. We present the necessary conditions along with a new algorithm for measuring the sustainability of processes that integrates the laws of thermodynamics with laws for rate processes. The algorithm permits the assessment of the degree of sustainability of any process, whether ecological, economic, or social, as well as chemical or biological. It is a dynamic approach that applies at any scale and takes into consideration the spatial and temporal factors of processes, thus permitting empirical applications that correspond to real world (dynamic, complex, evolving) conditions across space and time. These characteristics make it especially suitable for applications in the field of spatial planning.

Keywords: sustainability, rate process, urban planning, development, industrial ecology, life cycle, performance measures, evaluation, assessment, indicators

Sustainability and planning

Sustainable development as a specific moniker has been high on numerous agendas for over a quarter century. Agreement has emerged about fundamental precepts: balancing environment and development; considering social, economic and ecological factors concurrently; and making an allowance for future generations (IPCC, 2014a; 2014b; UNCHS, 2009; UNWCED, 1987; Campbell, 1996). An early use of the term sustainable development goes back over three decades (IUCN, 1980). Earlier formulations of sustainable development date to the early 1970s. See, for example, Meadows et al. (1972) and Goldsmith et al. (1972).

In built environment professions, key thinkers and practitioners have contributed to the integration of measuring sustainable development into their practices (Cotgrave and Riley, 2013; Newton, 2012; Hack et al., 2011; Mostafavi and Doherty, 2010; Newman et al., 2009). Specialties within urban planning and design have created their own identities and denominations that reflect this: sustainable urbanism, green urbanism, ecological urbanism, landscape urbanism, compact cities, smart growth, fair growth, and new urbanism, among others. Sustainability figures explicitly in some of these movements, and increasingly, they exhibit synergies among allied fields, such as architecture and planning, and landscape architecture and planning (Black and Steiner, 2008; Farr, 2007).

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The principles underlying these different approaches possess certain commonalities: reduce consumption, reduce impacts, reduce distances, increase proximity, increase diversity, enhance equity, increase access, and so on. Yet numerous critiques found some of them to be insufficiently green in other aspects (Talen, 2005; Durack, 2001). Some have argued for a focus on flows and processes of urbanisation rather than urban form as a key to becoming sustainable (Hall and Hesse, 2012; Bagheri and Hjorth, 2007; Neuman, 2005).

Good city process

Sustainable urbanism in a global world is a fraught problematic. Can cities be green and just in splintering societies? Just as habitat fragmentation stresses ecosystems and biological species (Fahrig, 2003; Scholes and Biggs, 2005), globalisation and social fragmentation stress human settlements (urban ecosystems) and their inhabitants (Goldsmith and Blakely, 2011; Castells, 2009; 2010; Alberti, 2008; Graham and Marvin, 2001). Historically, the urban planning field, long identified with what we call today sustainability in its broadest sense, has focused on urban form – in history, theory, and practice – for example zoning codes, land use, and urban design. This focus on form is understandable as cities are places that take on form, their form evolving over time (Atkin and Rykwert, 2005). Moreover, the principal designers of urban form often have been architects and engineers, world-wide across centuries. Even in Anglo-Saxon countries, architects played seminal roles in the profession's founding. A list of iconic books attests to the tradition of form that permeates thinking and practice even today. Mumford's *The City in History*, Lynch's *Good City Form*, Kostof's *The City Shaped*, Morris's *The History of Urban Form*, and Jacobs's *Death and Life of Great American Cities* are just a few. Many more could be listed.

This paper suggests that process along with form are co-essential ingredients to plan cities, especially if they are to be sustainable. In nature and in cities, form flows from process. Process accretes into form. Canyons formed by river flows. Valleys carved by glacier flows. Sand dunes shaped by wave and wind flows. Buildings formed by flows of finance and concrete, lit by flows of electrons, heated by gas flows, populated by human flows. Transport infrastructure networks suffused by flows of vehicles. Flow and form is a bi-directional formulation that can be understood as a yin and yang that begets activities and the cities that contain them. Some of the earliest approaches to urban analysis using flow concepts include the 'city of flows' by Castells (1989), the city as 'transaction maximising system' (Meier, 1968), and regional econometric modelling (Klein, 1969).

Nonetheless, many of the different urbanisms and other modes of planning originally took the urban form approach to sustainability (Breheny, 1992). Other means to measure and identify sustainability in planning and in cities have been articulated as well. They can be grouped into two general categories: indicators that measure current conditions and the attainment of sustainability goals (Carmona and Sieh, 2004; UNCSD, 2007; Brandon and Lombardi, 2011; Dalal-Clayton and Sadler, 2011; Moldan et al., 2012), and best practices that illustrate what is being done to implement sustainable development (UNWSSD, 2002; Shen et al., 2011). Within these two categories are 'brands' of principles and techniques that underlie sustainability, each with its own goals, methods, criteria, and intent. They include, but as the next section serves as a sketch outline and not an exhaustive survey, are not limited to:

- balancing various factors (economy, ecology, society) pertaining to development;
- life cycle analysis to capture the long term service life of a system, place, or process;
- natural capital that values the benefits of ecosystems, habitats, and species in support of human activities;
- ecological services that values the benefits of natural processes in support of human activities;
- factor four for reducing consumption and more effectively using resources;
- industrial ecology and urban metabolism that performs input – output analyses of industrial processes and human settlements;
- ecological or environmental economics for evaluating resource consumption; and
- ecological footprint for measuring ecological impacts of urban development.

A common thread to each is that indicators of sustainability increasingly measure and assess the performance or function of a place or a system in terms of processes. Each will be sketched briefly, assessing their benefits and shortcomings regarding the measuring of sustainability in urban planning and development.

Existing approaches to measuring sustainability

Sustainability is not merely a matter of intergenerational equity, as the too-concise definition of the Brundtland Report implies (UNWCED, 1987). Nor is it just a qualitative enterprise that is invoked by the triad of environment, economy, and equity; effective as it is as a rhetorical device and as a motivating call for action. To measure sustainability meaningfully requires the assessment of a wide range of phenomena, as the following different approaches, when examined in their totality, suggest. It can never be done completely and comprehensively because the set of factors involved, at a range of scales from the microbe to the planet, are as inexhaustible as life itself. Each method offers its benefits and limitations, serving its applications' constrained purposes.

The use of *balancing* ranges from balancing environment and development in early formulations of sustainable development adopted by international institutions (UNWCED, 1987) and balancing the amount and forms of carbon, nitrogen, and other materials cycled through ecosystems (Cote et al., 2002; Newman and Jennings, 2008) to balancing adaptation and mitigation in urban planning (Newman et al., 2009, Hamin and Gurran, 2009).[1]

Balancing environment and development can be hard to specify, quantify, and translate into operational means. Sometimes balancing in this sense has been used in corporate and development jargon as 'triple bottom line', which in spite of best intentions, provides fuzzy metrics to determine the proper balance. At worst, it has been used at times to rationalise business as usual, or marginally better. A common planning-related tool for balancing in the context of sustainability – cost-benefit analysis, has been shown to mask theoretical and technical difficulties (Lave and Gruenspecht, 1991). They discredit cost-benefit analysis as a valid basis for decision-making for sustainability.[2]

Balancing techniques for energy and materials are possible to specify, quantify, and operationalise. They tend to focus on physical elements such as carbon or nitrogen, and more recently, phosphorus and water. Carbon balancing is a practice that seeks to neutralise carbon emissions by several means, including reducing carbon-producing energy sources, reducing carbon-based energy consumption, sequestering equivalent amounts in carbon sinks, and ensuring that enough vegetation exists to convert carbon dioxide to oxygen. Urbanised territories are estimated to produce about 96–98 per cent of anthropomorphic carbon emissions (IPCC, 2000, 691). This is astonishing, given urban areas only account for about two per cent of the earth's total land mass (UNCHS, 1996, 332).[3] Carbon balancing has promise for mitigating a variety of carbon producing processes. Research estimating 'the qualitative and quantitative contribution of urban territories and precisely of the process of urbanization to the Global Carbon Cycle' found that land conversion from non-urban (vegetated) to urbanised land is a significant factor (Svirijeva-Hopkins and Schellnhuber, 2006, 1).

Balancing methods do not typically integrate the processes that they balance with the place (environment) in which they are balanced. One approach that attempts to integrate the two in terms of sustainability is the EcoBalance method of the Center for Maximum Potential Building Systems (Fisk, 2008).

In this context, balancing refers to not taking more from the planet than is returned in terms of quantity and quality (more on this below), or not returning to the planet less than extracted or of lower quality (that is, not polluting or toxic). Nonetheless, while carbon balancing and eco-balancing offer powerful approaches, they are not

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[1] Earlier approaches were often based on limits, even if they did not explicitly adopt the term 'sustainable development' or 'sustainability' (Meadows, et al., 1972; Goldsmith et al., 1972).

[2] Reflecting a long line of thinking. See for example, Tribe (1972).

[3] Urban areas account for a large percentage of CO_2 emissions, yet they account for a smaller percentage of greenhouse gases overall, since methane and nitrous oxide emissions have primarily rural sources.

comprehensive planning tools in that they do not deal with critical and long standing planning concerns such as equity, health, and social issues.

Life cycle analysis, originally developed in engineering and accounting, offers promising leads to city planning. As applied in their own disciplines, they tend to be limited to the service life of the facility or network in engineering, or the costing of that service life in accounting (Collinge et al., 2013). Neither considers the full life cycle of assessment, planning, design, costing, budgeting, financing, operations, maintenance, repair and rehabilitation, recycling, reuse, and evaluation (Neuman and Whittington, 2000). In other words, balancing and life cycle costing are not fully comprehensive and long term in the urban planning sense. As practised, they do not take into account attendant impacts, embodied energy, or the complete planning life cycle from assessment to evaluation. Nonetheless, current methods of life cycle analysis could be expanded to include these and other concerns. Doing so would implicate extensive computing resources, staff time, and massive data sets; a set of conditions which should not deter researchers and analysts, or planners and policy makers in an era of big data and analytics. An early use of life cycle methods in comprehensive planning was pioneered by the New Jersey Office of State Planning (1991).

Natural capital refers to a concept that values the benefits of ecosystems in support of human activities. This valuation or accounting method does not calculate sustainability *per se*. Rather, as currently used, it measures the capital, or fixed value of a natural asset such as an ecosystem, habitat, or species; much as an accountant measures the fixed capital value of land, plant, or equipment in a corporate annual report (World Bank, 2010). Increasingly, methods using natural capital are evaluating services (including ecological processes that perform services – see 'ecological services' immediately below) in addition to place-based capital stock (Kareiva et al., 2011). This work continues to evolve as a promising methodology to calculate ecosystem wide assessments, and has promise for urban ecosystems as well. For example, Rees and colleagues (Farley et al., 2007) have introduced the use of the ecological footprint to measure natural capital to good effect.

Ecological services refers to the benefits of natural processes in support of human activities, and is related to natural capital. Sometimes called nature services, 'ecosystem services are generated by a complex of natural cycles, driven by solar energy, that constitute the workings of the biosphere' (Daily, 1997, 4). They constitute not only life's processes, but as the seminal text's subtitle 'societal dependence on natural systems' acknowledges, this view reflects human use of and dependence upon nature, which can be out of mind in highly urbanised settings. Nature's services range from bacteria digesting organic matter in the soil through biodiversity conservation (Hussein and Tschirhart, 2013) to entire ecosystems serving as habitats for countless species and bio-geo-chemical cycles (Schroter et al., 2005) to an evaluation of all of the earth's ecosystems ($33 trillion, in Costanza et al., 1997). An example is a forest filtering pollution, storing runoff, cycling carbon, providing shelter and nourishment, etc.

Factor four is shorthand for a powerful and simple idea that says we can double our production even as we cut in half our consumption of materials and energy, and our production of wastes and pollutants. It is a good admonishing device, elementary as it is. Factor four is the product of a collaboration between the Wuppertal Institute in Germany and the Rocky Mountain Institute in Colorado. It derives its essence from the Factor Ten notion put forth by Wolfgang Sachs and his collaborators at the Wuppertal Institute (von Weizsäcker et al., 1997, Sachs et al., 1998). While it does suggest ways to measure *improvements* in net resource productivity in relation to existing activities, as an approximation toward more sustainable economies, it does not, however, provide a theory or analytical model for how to measure in any absolute sense the sustainability of places or processes.

Industrial ecology and urban metabolism began as a holistic perspective on industrial processes that performs input – output analyses of their components (Linden, 1994). It applies regional economic and other social and ecological quantitative assessment methods to evaluate the overall costs, benefits, and impacts of the production of a good or service (Suh, 2009). Ayres and Ayres (1996) present the classic approach to industrial ecology as connecting material and energy cycles so that the outputs from one process become the inputs to others, as in nature itself. Recently, this approach has been attempted at the scale of human settlements, where the energy and associated pollution costs of urban living (Arvesen et al., 2010) and the material solid flows (Lehmann, 2012) were estimated. Assessing a wide range of factors for the entire city of Hong Kong, Warren-Rhodes and Koenig (2001) demonstrate the empirical nature and value of urban metabolism methods, in finding an increase in all throughputs as the city's population and consumption levels both increased.

Industrial ecology draws its inspiration from nature, which is seen to be its intellectual and analogical core (Ruth and Davidsdottir, 2009). A biological analogy to ecological systems is instructive in the overall architecture or topology of the ecosystems or urban networks under analysis. Pascuale and Dunne, for example, have analysed food web structures (2006). Others using this approach found that networked structures of ecosystems and institutional systems helped 'reconcile complexity with persistence or stability' (Haldane and May, 2011). This is important for planning in the design of urban (i.e., social) ecological networks whose stability is linked to resilience and sustainability. The economic and life cycle methods employed by industrial ecology, implemented using place-based and process-based approaches, when linked to ecological theory that serves as its basis, goes a good distance in integrating quantitative assessment methods that hold promise in evaluating urban places.

Urban metabolism is an extension of the industrial ecology model into the urban realm. It addresses larger scales and more complexity, including more throughputs (Decker et al., 2000). A review of urban metabolism in the context of overall integrated assessment methods for urban sustainability is made by Ravetz (2000). Many new urban sustainability models are emerging, and have been reviewed by Kissinger and Rees, (2010). These apply at multiple scales, and begin to account for inter-regional effects. Some are beginning to incorporate rate/process based measures, including Materials Flow Analysis (National Research Council, 2004) and Environmental Input Output Analysis (Miller and Blair, 2009).

Like industrial ecology, *ecological economics* has been addressing sustainability by incorporating ecological throughput approaches since the 1970s (Daly, 1973; Howarth and Norgaard, 1992; Capello and Nijkamp, 2002; Pearson, 2013). Herman Daly's text, for example, summarises this perspective:

> [as] the economy in fact grows into and encroaches upon the finite and non-growing ecosystem, there *is* an opportunity cost to growth in scale, as well as a benefit. The costs arise from the fact that the physical economy, like an animal, is a 'dissipative structure' sustained by a metabolic flow from and back to the environment. This flow, which we have called throughput (adopting the term from engineers) begins with the depletion of low-entropy useful resources from the environment, is followed by the processes of production and consumption, which, despite the connotations of the words, are only physical transformations, and ends with the return of an equal quantity of high-entropy polluting wastes. (Daly and Farley, 2004, 477)

Their analysis owes to thinkers such as Ilya Prigogine and his work on thermodynamic systems, dissipative structures, and self-organising systems (Nicolis and Prigogine, 1977; Prigogine, 1955; 1981; Prigogine and Stengers, 1984). Related work has been done in urban planning by William Rees and Peter Nijkamp, among others (Rees, 1992; 2003; Newman and Jennings, 2008; Nijkamp, 2004; Lakshmanan and Nijkamp, 1983).

The *ecological footprint* indicates how big an impact a person, household, or place (such as a city) has on its surroundings. It calculates this footprint by measuring the total use of resources and energy by the entity making the footprint. It also measures the acreage needed to absorb wastes. This total amount is then converted mathematically to an equivalent area of land that would be needed to produce all the goods, services, power consumed and impacts absorbed. Partial footprint analyses specific to a single factor, such as carbon dioxide emissions, have led to the emergence of carbon footprint analyses and the like (Carbon Disclosure Project, 2012; Wiedmann and Minx, 2008). The ecological footprint enables us to compare overall urban consumption and waste production among cities and other entities that can be discretely bounded and defined (Rees and Wackernagel, 1994). It deftly incorporates processes into the footprint equation, even as it converts their values into units of land area per capita.

The differences among these eight ways of addressing sustainable development lie in their approaches, as well as goals, scales of focus, and actions recommended. A gap appears in some ways of dealing with sustainability that relates to the fact that some of the indicators are static, of a place at a given time, and do not consider longitudinal variation. That is, they do not consider time/process. Yet as indicated above, others do consider time/process, especially industrial ecology, ecological services, and life cycle analysis. By using proxy measures, the balancing and footprint approaches can also incorporate processes into sustainability evaluations.

Other measures and models of aspects of sustainability have been proposed. These range from models of climate change and metabolic flow to biodiversity indicators, and assessments of ecosystems and cities (Pickett et al., 2001; Wigley, 2005; Meehl, 2005; Wang and Schimel, 2003; Luck et al., 2003; Scholes and Biggs, 2005; MEA, 2005). Increasingly, they address large scale, complex, and dynamic phenomena found in both nature and culture. Another approach, while not assessing sustainability, proposes a model to rank cities according to common characteristics of behavior. Its 'scaling laws provide the average baseline behavior and, by extension, the null model necessary for addressing the long-standing problem of how to rank specific cities' (Bettencourt et al., 2010). Their formulation explicitly excludes time and process measures, avoids any discussion of rates and thermodynamics, and does not address sustainability.

The rates of change, the processes on which these changes are based, and the multiple scales or levels of the activities they address are now of greater concern. Even so, there is only limited consensus across disparate disciplines, or even within individual ones (Wada et al., 2010; Balmford, 2005; Mace, 2005; Royal Society, 2003).

Clearly, measuring sustainability is complex and problematic (Bell and Morse, 2003). In urban contexts it is even more so (Shenet al., 2011; Alberti, 1996). No model or approach at this point claims to account for all factors and conditions in either nature or urban realms, or nature-human interactions (Alberti, 2008). The sections that follow present the necessary conditions that need to be addressed in order to construct an integrative and comprehensive theory that provides scientific and mathematical principles in order to comprehensively model and empirically assess the sustainability of physical, ecological, and social processes at any scale and in any context.

Sustainability, thermodynamics, and processes

The rest of this paper presents the major preconditions necessary to model and measure sustainability mathematically, using the scientific principles of thermodynamics and rate processes. First, sustainability is identified as a process, specifically as a rate process (Churchill, 1974). Second, sustainability is characterised precisely in theoretical and mathematical terms in which the rate of any process must be sustained over time without exceeding the innate ability of its surroundings to support the process. This includes the ability of the surroundings to absorb the impacts of the process – their resilience. Resilience has exploded as a complement to sustainability (Field et al., 2012). Finally, directions for future research, theoretical development, and other examples of practical applications are suggested. These include the relation of our approach to life cycle analysis, and the integration of spatial and rate process dimensions in analytical methods that support urban and environmental planning.

Understanding sustainability as a process takes full advantage of a resurgence in thermodynamics and its applications in numerous fields, including climate change, chaos, complexity, and ecology, among many others (Gutowski et al., 2011; Schneider and Sagan, 2005). In Schneider and Sagan's book *Into the Cool*, a fundamental precept of life holds that 'nature abhors a gradient'. In this case, gradient means difference between systemic parameters, or in other words, instability. Nature, by abhorring gradients, seeks stability of a dynamic kind. Over time, especially the long run, seeking stability means seeking to sustain processes of life. Sustaining processes of life entails the production, utilisation, and dissipation of energy over time; the prime factor among all others.

Thermodynamic laws govern processes that create and use energy. Originally developed as a set of laws to help explain physical systems (chemical, mechanical), thermodynamics is increasingly applied to life sciences (Prigogine 1955, Prigogine and Stengers 1984). As evolution on earth yielded more complex forms of life and ecosystems, increased energy flows processed more and more materials from nature. Recycling, in the broadest biological, ecological, and industrial senses, increased (Kleidon and Lorenz, 2005). Lenton and Watson expand these principles for human societies and settlements, finding that to increase productivity and population density, humans must increase rates of recycling (2011). Processes dealing with energy, when broadly understood, including embodied energy over the entire life cycle, comprise many of the processes of urbanisation, and of living in human settlements, including economic (the costs of energy) and social (the equity aspects of energy as embedded in access and opportunity). Thermodynamics, therefore, is vital to knowing urban sustainability.

A review article on urban sustainability examined how the relationship between compact urban form and sustainable development has been viewed and analysed, and found that compact cities are not necessarily sustainable. It further argued that compact cities are not even a necessary or sufficient condition for sustainable urban development and concluded that thinking about urban *form* provides only a partial basis for the creation and development of sustainable cities (Neuman, 2005). Beyond form we need to consider urban process – that is, all the economic, social, and ecological processes that occur in and through urban regions.

Among other research that furthered this thinking with specific applications to water supply planning in the urban context was that by Bagheri and Hjorth (2007). The authors concluded that sustainable development practices and their planning are dynamic and evolutionary, involving feedback loops and learning. This finding echoes, from a different context, that of Schön (1983) and Argyris and Schön (1978). ‘Sustainability cannot be considered as a defined end state of systems, but is an evolving ideal of development efforts with no end known in advance. Sustainable development is, then, an evolutionary process, which acknowledges change’ (Bagheri and Hjorth, 2007, 93).

Extending this line of reasoning to its logical conclusion results in examining all processes, not only of urban development, but processes of production and consumption in all realms and at all scales, the majority of which occur in city regions. Are we producing and consuming beyond some limits? While this question has been under consideration for quite some time (Malthus, 1798; McHarg, 1969; Meadows et al., 1972), its implications are again ripe in the realm of urban planning. Yet planning, a process itself, with its long term, comprehensive perspective that accounts for the inter-relatedness of impacts, has long been directed toward spatial factors. Planning is ideally suited to managing processes that change urban development practices and institutions so they are more sustainable by incorporating processual and spatial factors. Integrating sustainability into planning using a process-based approach unlocks a potential signaled two decades ago (Rees, 1992; McDonald, 1996). The question we now pose: if the path to sustainability lay in process, how are we to think about planning for sustainable urban development processes?

Sustainability as a way of life

Sustainability has to do with the way we live every day. It deals with our choices and actions in every realm, every endeavour. It is not just about the natural environment, nor even just the links between the environment and the economy. It concerns what is in our medicine cabinets and pantries, under our sinks and in our closets, garages, and workshops. It has to do with what we eat, how we clean, shop, get around, work, and get along with our neighbours. It is a way of being in the world. Sustainability is a way of life. For planners, it points to a new way of planning for urban development.

This recognition gathers increasing urgency, as the majority of the planet’s population now lives in urban areas. ‘Urban population will grow to 4.9 billion by 2030. In comparison, the world’s rural population is expected to decrease by some 28 million between 2005 and 2030. At the global level, all future population growth will thus be in towns and cities’ (UNFPA, 2007, 6, emphasis in original). A high percentage of consumption and production of all goods, services, wastes, pollution, and impacts occur in the world’s metropolitan regions.[4] If most of the planet’s human activities

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[4] This statement reflects the usual understanding, but a strict interpretation of the second law of thermodynamics

occur in urban areas, then making cities and their enabling infrastructure sustainable goes a long way to making our economies and societies sustainable.

We define sustainable processes across two principal parameters. First, sustainable processes are ones in which the flows of matter, energy, and capital are replenished both in quality and in quantity at levels in which the outputs are at least equal to the inputs. Second, sustainable processes lessen, with the ultimate aim of minimising, if not eliminating, the equity gaps that exist in all societies and communities, in all facets of life. How are these ideas expressed in most (not all) leading expositions in the literature?

Typical measures and models of sustainability are based explicitly or implicitly on the first law of thermodynamics, which is the conservation of matter and energy. However, they are approximate, incomplete, and/or ambiguous for one or more of the following reasons:

1. They fail to define with precision the boundaries in space and time of the system(s) to which they are applied.
2. They fail to incorporate the second law of thermodynamics.
3. They fail to incorporate the limitations imposed by rate processes and the related carrying capacity of the environment.
4. They fail to account for all effects and fluxes in the system.

Sustainability, when examined only in terms of the first law of thermodynamics is inadequate in two senses. First, environments and their living beings cannot be defined in terms of mass and energy only. Other qualities more difficult to quantify are essential to the survival of all species and habitats. Second, the limitations imposed by the second law of thermodynamics have often been overlooked in expositions of sustainability. All real processes are irreversible: over time entropy increases and exergy (the capacity of a system or body, whether living or inanimate, to do work) decreases. Irreversibility means that no process is wholly sustainable in a thermodynamic sense. Therefore the aim for sustainability is to minimise rather than eliminate the increase in entropy and the loss of exergy.

In order to apply thermodynamics to a closed or open system it is necessary to define the boundaries of the system. Different choices of a boundary (the measure of the extent of the system) are a major source of disagreement over the sustainability of various processes. This is because living systems are open systems, and processes are interconnected across many open systems occurring at and in different scales simultaneously. Another empirical limitation is the failure to account for all the inputs and outputs through the boundary(ies) of these interconnected and open systems. This limitation corresponds to the complexity of life and our incomplete

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shows that in terms of exergy or negentropy, much actual production and extraction occurs *outside* of cities. The urban economic 'production' process is really a consumption or transformation (*not* production) process that turns low-entropy energy and matter produced in the ecosphere into economic goods and services at the expense of nature by dissipating valuable resources and increasing global entropy (Rees 1992).

human understanding of it, notwithstanding our improving capacities to model and increasing computational capacities to calculate.

The greatest value of empirical assessments of sustainability is for decision makers to be able to compare the relative sustainability of various technical and/or policy options, in order to make the most informed judgment. To compare the sustainability of several processes, then their boundaries, all of the inputs and outputs through these boundaries, and all net changes within the boundaries must be identified. Thermodynamics indicates the limits of what can be done within any system or framework of space. On the other hand, the rate processes such as fluid flow, heat transfer, mass transfer, and material transport determine the time and/or space required to carry out the transformations both within and through any system or spatial framework. Basing the approach on the twin pillars of thermodynamics and rate processes enables it to be generalised across physical-metabolic and social-economic phenomena because it addresses processes within and outside of delineated system boundaries.

Sustainability as a process

Given that societies have become consumption-oriented, and thus production oriented to satisfy consumer demand, then processes of consumption and production need to be addressed in the quest for sustainability. Since consumption is important, any approach to sustainability should address all consumption and production processes. In urban planning this applies to the processes that produce space and place – urban development. However, classical and neoclassical modes of economics are insufficient to understand the new relation of production and consumption in a framework of sustainability. (A brief overview of some important advances of ecological economics over neoclassical economics, and their relation to our approach, is presented below.) The mathematical formulae presented here provide a new way to measure whether a given consumption and production process is sustainable.

These formulae measure sustainability using rate processes. A sustainable process is one whose rate is maintained over time without exceeding the innate ability of its surroundings to support the process, including the ability of the surroundings to absorb its impacts (Neuman and Churchill, 2011). Thus we can further specify our definition of a sustainable process. A sustainable process has rates of production and regeneration (replenishment) that equal or exceed rates of consumption plus depletion plus extraction plus by-product absorption. Moreover, in a sustainable process the rates of production of wastes or by-products are less than the rate in which the environs can absorb them and remain healthy and viable over the long term. This formulation thus integrates the concept of resilience in a specifiable, and thus quantifiable, manner.

Since material processes are governed by the first and second laws of thermodynamics and the theory of rate processes, any comprehensive approach to sustainability must be based on the same three concepts. This is a fundamental advance that overcomes the limitations of prior formulations.

The above comments are most often thought of in terms of 'natural resources' and material processes. Yet as we suggest below, they also can apply to social and economic processes. The distinction is important, in that 'natural' systems (human and biological ecosystems) import energy to stay alive, whereas strictly physical/material systems such as an urban metro system are not alive in the usual sense of the word. Nonetheless, material, social, and ecological systems all require inputs of energy to perform work that creates their own order. A perceived difference is that purely physical systems tend to dissipate when external sources of energy are removed, while living systems maintain their order when they are alive (Schneider and Sagan, 2005; Capra, 2002). Nonetheless, this distinction is not critical to the premise of our approach that we present below. What is important for the argument is that as society strives to undertake processes to produce urban development that is more sustainable, it does so at rates that are sustainable. Sustainable in this conception means a rate that does not exceed capacities or damage (cause to dissipate) the environs of all types (physical, ecological, social). We know that they will never be able to do so in a completely sustainable way, as equations (1) and (2) predict.

Sustainable processes replenish in a circular way, with the outputs of one process continuously forming the inputs of others. Waste disappears in a sustainable process. This dynamic and multi-scalar basis for this way of measuring sustainability overcomes limitations of static approaches that measure values at one point in time and/or one place in space. Moreover, some current conceptions of sustainability assume a completely closed system, which does not correspond to reality from a thermodynamic point of view.

We extend the rate process concept for sustainability to five categories: rates of consumption, rates of production, rates of accumulation, rates of depletion, and rates of assimilation. The formulae can be applied to any factor within these categories. For example, for consumption rates we can use energy and materials as a measure. For production rates we can use goods, services, and wastes. For accumulation – the buildup, saving, or stockpiling of a resource or waste (to use the conventional meanings of these last two terms) – we can use wealth and poverty, and debt and profit – whether personal, corporate, or governmental. Examples of accumulation rates also include nitrogen fixation, atmospheric carbon dioxide, and global climate change. For depletion rates we can use atmospheric ozone, aquifer recharge, desertification, biological diversity, habitat loss, and language and cultural loss. For assimilation rates – the extent to which a habitat or ecosystem can absorb the presence of a material, process, or living being – we can use water quality, atmospheric fluorocarbons, and the introduction of invasive and exotic species into an environment.

Our approach to sustainable processes is presented in the context of the new discourse on sustainability that is providing a normative framework for a variety of disciplines and organisations. The noun sustainability can thus be redefined to mean the degree to which an entity exists in a co-evolutionary process with its environment whose inherent condition (essence) enables it to continue evolving and developing without jeopardising its own life and livelihood, or the lives and livelihoods of those it affects, including the larger systems and networks in which the entity finds itself situated, now and in the foreseeable future. An entity may be an object (building), process (industrial production), place (city), organisation, or other living or territorial system. Sustainability refers to the ecology of human presence in place from a normative perspective – can humans inhabit a city, region, ecosystem, etc., sustainably, without damage and ill effects to others? The intellectual roots of sustainability and some of its theoretical consequences for sustainable development have been reviewed elsewhere (Owens and Cowell, 2002; Neuman, 2005).

A mathematical approach for sustainable rates of change

Two laws underlie the rate process concept. The first law of thermodynamics states that matter and energy are conserved. The second law of thermodynamics, in the context of sustainability, states that matter and energy consumed and then rejected into the environment is of equal or poorer quality than that acquired from the environment. The first law reveals that all resources, including energy, are finite and that their exploitation invokes inexorable tradeoffs. The second law reveals limitations and consequences of the possible tradeoffs. Both laws require the careful choice and scale of an envelope for the system, whether a single process, an entire industrial plant, a city, an ecosystem, or the entire earth and its atmosphere. All choices for the exploitation of resources invoke, in addition to the first and second laws of thermodynamics, the rates at which they can be carried out, and thereby introduce restrictions in terms of space and/or time.[5]

In more concrete terms, the second law – the entropy law – stipulates that all complex entities eventually die. Stated another way, entropy means that the universe becomes less ordered and less complex over time. The simpler the structure, however, the better its survival chances. A key implication for designing and planning is that simpler is more sustainable. It takes energy and information to sustain order and complexity. This applies to human artifacts, including a building, city, or infrastructure network. On the other hand, more complex means more energy means less

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[5] The value of information and knowledge added to a system or product in a process is one of a number of quantities that have not been considered in this exposition.

sustainable, if the energy is not renewable. Lenton and Watson (2011) postulate a corollary: for human societies to be sustainable while increasing energy and material throughput, they need to recycle more at higher *rates*.

The notion of rate dependence has been articulated by Daly and other ecological economists (Daly, 1991; 1992; Daly and Cobb, 1989). They posit three general material criteria for sustainability. Roughly speaking, they state that the human system cannot

1) degrade self-producing and replenishable natural capital faster than natural processes can renew it;
2) degrade essential non-renewable resources faster than they can be substituted by renewable alternatives; and
3) discharge waste into supportive ecosystems at rates in excess of the assimilative capacity of those systems.

Below, we take the additional step of formalising parts of this by using differential calculus.

The first and second laws of thermodynamics, as generalised for open as well as closed systems and for dynamic (time-dependent) as well as stationary conditions, constitute a necessary constraint for a mathematical calculation of sustainability. The rate process concept provides a necessary complement; expressions for the rate of change of energy, mass, and chemical species can be derived from the first law but not for rate processes in general (Churchill, 1974). Individually, the first and second laws and rate concepts comprise an insufficient basis for sustainability because of the difficulty in quantifying such factors as the quality of life, and of system-wide phenomena.

The generalised treatment of rate processes will be described briefly. The rate process concept was developed by Churchill in the context of process design and was generalised with respect to chemical reactions, fluid flow, heat transfer, mass transfer, and bulk transport (Churchill, 1974). For example, for a batch (confined, unsteady-state, and one-step) process

$$\frac{1}{L}\frac{dx}{dt} = \sum r_i \tag{1}$$

Here, x represents some extensive quantity such as mass or other measure of inputs and outputs to the process, t time, and L a measure of the extent of the system (implying boundary enclosure), while r_i represents various rate mechanisms, which may be positive (inputs) or negative (outputs). A positive value for the right-hand side of Equation (1), namely $(dx/dt)/L$, represents the rate of accumulation of the quantity x and a negative value its rate of depletion, in both cases by the sum of the rate mechanisms r_i.

In either event, a finite value of $(dx/dt)/L$ indicates a deviation from sustainability. A positive value of r signifies sustainable, if the accumulation of x is beneficial; or not sustainable, if the accumulation of x is harmful. The converse of both cases also holds, so that a negative value of r means not sustainable if the accumulation of x is beneficial, and so on. Thus, Equation (1) is only one component of an expression for sustainability.

In nature and culture, and their interactions, many processes are periodic or continuous, rather than batch, and moreover occur in open and coupled systems. Therefore, we need an analogue to Equation 1 for these situations.

The analogue of Equation 1 for a process carried out in continuous flow through a conduit or place of cross-sectional area A is

$$\frac{1}{A}\frac{d(wX)}{dz}=\sum r_i \tag{2}$$

Here z is the distance along the conduit (length), w is the mass rate of flow through the tube or place, and X is the extensive quantity of concern per unit mass.

The term on the left-hand side of Equations (1) and (2) represents the deviation from sustainability resulting from this process when considered in isolation. Changes that occur outside the boundaries of the chosen system(s), including the net flows through the boundaries into or out of that portion of the environment not encompassed by these systems, must also be considered in these calculations.[6]

Equations (1) and (2) may also be derived by reducing the general partial differential equation for the conservation of a species, in accordance with restrictions imposed (Bird et al, 2002). In this restricted sense, Equations. (1) and (2) are special cases of the first law of thermodynamics. However, by incorporating the second law and rate processes, their applicability extends beyond thermodynamics into ecology, economics, and urban and regional processes.

Thus, this approach has the advantage of being applicable to a wide range of factors that make a place or process sustainable. Moreover, it answers what until now has been the most intractable barrier in the search for a general approach to sustainability – what are we trying to sustain, where are we trying to sustain it, and over what time span? The planet? An ecosystem? A city? A business? A way of life? Life itself? This decade, this century, this millennium, or indefinitely? Combining rate processes with thermodynamics enables the formulae to be applied to dynamic, non-linear, non-equilibrium systems as well as equilibrium systems. This makes it applicable to complex urban, social, and ecological phenomena such as cities, organisations, and ecosystems as well as to single, simple processes such as aquifer recharge, carbon dioxide accumulation, and energy consumption.

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[6] One of the contributions of the rate process concept was the distinction between rates of change, as represented by the terms on the left-hand-sides of Equations (1) and (2), from process rates, as represented by the terms on their right-hand-sides (Kabel, 1992; 1981).

To illustrate we use a simple example, for aquifer recharge, aquifer recharge rate by comparing the inflow rates into the aquifer against the withdrawal rates of water from the aquifer, in terms of volume per time. A per capita measure can also be incorporated for inter-aquifer/inter-jurisdictional comparison. Moreover, the extent of the aquifer system, L in Equation 1, can be identified by hydrogeologists, though not always with absolute precision.

Rate processes form an essential component of sustainability because the rate of any process must be able to be sustained over time without exceeding the innate and 'natural' ability of its surroundings to support it. This goes beyond existing carrying-capacity formulations in urban and environmental planning pioneered in the sixties and seventies by Ian McHarg, and by Donella Meadows and her colleagues in The Club of Rome report (McHarg, 1969; Meadows et al., 1972). These traditional views of carrying capacity dealt with a specific place at a specific point in time. Neither was rate process oriented, and consequently did not account fully for the dynamic nature of the systems they modelled. They did not consider the co-evolutionary character of human interaction with ecosystems. Another limitation in applying these two carrying-capacity approaches and their derivatives is that they did not pay close attention to the environs and the definition of the boundary between the activity system under study and its surroundings. The rate process approach with its mathematical formulation adds the dimension of time to the dimensions of space that the carrying-capacity approaches employed. The equations presented herein provide a basis for more complete modelling of particular problems of a high degree of ecological and social complexity. When coupled with spatial analytical tools such as GIS, they represent a new way of determining the sustainability of a place and its processes.

Directions for the future

1 Indicators

The rate process approach to sustainability has implications for practices in sustainable development and related fields such as urban and environmental planning and design, engineering, economics, finance, and accounting, as well as in manufacturing. An important implication is the use of indicators. Environmental indicators, economic indicators, quality of life indicators, and sustainability indicators all can be expressed using rate processes (UNCSD, 2007). There is no limit to the indicators that can be devised using these generalised rate equations.

2 Environmental accounting

Environmental and life cycle accounting techniques currently employed by the International Standards Organization (ISO) and national standards organisations such as the US National Institute of Standards and Technology (NIST) are being converted to process-based measures. They also can adapt the generalised rate equations contained here. The United Nations in partnership with other leading international agencies has revised environmental reporting and accounting standards to measure flows instead of static measures (UN et al., 2014). These organisations should consider in the course of future revisions to these standards the extent to which rate process approaches presented herein may augment current thinking on energy, water, and material flows that these new standards cover, the most common flows addressed in systems of national accounts apart from economic flows.

3 Life cycle assessment

Not only do joint environmental and economic accounting systems account have the capacity to be converted to a rate process basis. Rate process methods may also be linked effectively to another, and increasingly common, suite of approaches to measuring sustainability – life cycle methods. Life cycle analysis, life cycle costing, life cycle accounting, and life cycle planning are emerging as baseline techniques in sustainable management and development practices. The National Institute for Standards and Technology of the United States, for example, has developed a multi-attribute sustainable building evaluation programme titled Building for Environmental and Economic Sustainability (BEES) (NIST, 2010), which measures the environmental performance of building products and materials using the life-cycle assessment approach specified in ISO 14040 standards (International Standards Organization). While BEES is used increasingly in practice, and has developed life cycle environmental-economic performance measures for over 230 building products, its adoption of the rate process approach may afford it greater coherence and meaning.

4 Built environment rating systems

Another application of the rate process approach is in the fields of spatial planning, design, and construction. Sustainable development in cities results from the design of a human environment that is adaptable to its surroundings without exceeding their capacities at all scales to support the development and to absorb its impacts (resilience), both now and in the future. This is a necessary and sufficient definition of design as an evolutionary process that solves a problem by fitting (adapting) materials and processes to a function by creating a new form. The product of design, in this case a human environment, is also conceived as a process over the long term. This further reinforces the precept above that evaluation criteria for sustainable development – performance indicators – is best conceived in process terms, particularly rate processes.

One application of this thinking is to the scoring system of Leadership in Energy and Environmental Design for Neighborhood Development (LEED – ND) for sustainable neighborhood planning. Currently, the United States Green Building Council's LEED system is a checklist for designers and planners to follow as they develop a project. The checklist indicates the presence or absence of a factor that is considered to make a project more sustainable. Points are tallied to determine which level of attainment in the LEED system is achieved: silver, gold, platinum, etc. The checklist can be modified to include process-based factors along the lines established by this approach, in lieu of or in addition to the static form- or technology-based factors currently used by LEED.[7] For example, is the rate of replenishment of the local water supply (aquifer, for example) of the structure the same after construction as before? Can the rate of waste production (carbon dioxide, trash, construction debris, etc.) be assimilated by the environment without harming it? Is the waste production converted to resource production, by using the wastes as inputs to other processes?

Other applications of the rate process approach to sustainability include the design and management of infrastructural and social service delivery systems, and of natural landscapes. In Australia, for example, the Infrastructure Sustainability Council of Australia has developed its Infrastructure Sustainability Rating Tool that applies to the design, construction and operation of infrastructure systems (ISCA, 2014). In the United States, the Sustainable Sites Initiative has developed its SITES v2 Rating System, which measures the sustainability of designed landscapes (www.sustainablesites.org/rating-system).

5 Future research

For future research, the equations can serve as the basis for measuring the degree of sustainability that can be verified by empirical analyses. An important constraint that needs to be the subject of additional research is that the individual equations presented here do not necessarily deal with the complexities of the *inter-relationships* of processes in living systems, such as ecosystems and cities. These system effects are more than the sum of individual resources and the processes of their utilisation, transformation, and disposal. Future research can be devised to determine and assess the nature of these interrelationships and how they can be modelled to measure their degree of sustainability.

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[7] Many nations have been adapting and adopting the Green Building Council's LEED methodology, and/or have been developing their own. For the latter, see the BASIX methodology in New South Wales, Australia, and the Green Star rating system of the Green Building Council of Australia.

Conclusion

Thermodynamics and rate process concepts have been adapted to develop a process-oriented methodology for measuring sustainability. The approach permits the calculation of the sustainability of any process, whether chemical, biological, ecological, economic, or social. It is a dynamic and scale-independent (applies at any and all scales) approach that takes into consideration the spatial and temporal factors of processes, thus setting the stage for empirical applications that correspond more closely to actual (dynamic, complex, evolving) conditions. This formulation can underpin advances in emerging 'sustainability science' (Kates et al., 2001; Clark and Dickson, 2003). This approach reflects a new manifestation of human will that does not merely shape and subjugate nature and culture, and us along with them. Instead, sustainability embodies a new will to work with nature and culture, respecting them, and adhering to their capacities and limitations while still realising our own realistic hopes and dreams.

The contributions of a rate process approach to sustainability[8]

1. Enables the mathematical calculation of the degree to which any process is sustainable over the long term, using the scientific theories and methods of thermodynamics and rate processes.
2. Enables a comprehensive consideration of the relevant factors that impinge upon sustainability – economic, ecological, technological, and social.
3. Facilitates the determination of where in geographic space to draw the system boundary lines in the calculation of the degree of the long-term sustainability.
4. Enables a quantitative comparison of several processes to determine their relative degrees of sustainability to objectively inform technology and policy choices.
5. Places long-term sustainability alongside short-term efficiency in the cost-benefit calculus of choosing processes, technologies, and materials.

References

ALBERTI, M. (1996), 'Measuring urban sustainability', *Environmental Impact Assessment Review*, **16**, 381–424.

ALBERTI, M. (2008), *Advances in Urban Ecology: Integrating Human and Ecological Processes in Urban Ecosystems*, New York, Springer.

ARGYRIS, C. and SCHÖN, D. (1978), *Organizational Learning: A Theory of Action Perspective*, New York, Addison-Wesley.

ARVESEN, A., LIU, J., and HERTWICH, E. (2010), 'Energy cost of living and associated pollution for Beijing residents', *Journal of Industrial Ecology*, **14**, 890–901.

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[8] Adapted from Neuman and Churchill (2011).

ATKIN, T. and RYKWERT, J. (eds) (2005), *Structure and Meaning in Human Settlements*, Philadelphia, University of Pennsylvania Museum of Archeology and Anthropology.

AYRES, R. and AYRES, L. (1996), *Industrial Ecology: Closing the Materials Cycle*, Cheltenham, UK, Edward Elgar.

BAGHERI, A. and HJORTH, P. (2007), 'Planning for sustainable development: a paradigm shift towards a process-based approach', *Sustainable Development*, **15**, 83–96.

BALMFORD, A., BENNUN, L., TEN BRINK, B., COOPER, D., CÔTÉ, I. M., CRANE, P., ... & WALTHER, B. A. (2005), 'The convention on biological diversity's 2010 target', *Science*, **307**, 212–3.

BELL, S. and MORSE, S. (2003), *Measuring Sustainability*, London, Earthscan.

BETTENCOURT, L., LOBO, J., STRUMSKY, D., WEST, G. B. (2010), 'Urban scaling and its deviations: revealing the structure of wealth, innovation and crime across cities, *PLoS ONE*, **5**, e13541, DOI: 10.1371/journal.pone.0013541.

BIRD, R. B., STEWART, W. E., and LIGHTFOOT, E. N. (2002), *Transport Phenomena*, 2nd edition, New York, Wiley and Sons.

BLACK, S. and STEINER, F. (eds) (2008), *Emergent Urbanism: Evolution in Urban Form*, Austin, University of Texas School of Architecture.

BRANDON, P. and LOMBARDI, P. (2011), *Evaluating Sustainable Development in the Built Environment*, Chichester, UK, Wiley-Blackwell.

BREHENY, M. (ed.) (1992), *Sustainable Development and Urban Form*, London, Pion.

CAMPBELL, S. (1996), 'Green cities, growing cities, just cities? Urban planning and the contradictions of sustainable development', *Journal of the American Planning Association*, **62**, 296–312.

CAPELLO, R. and NIJKAMP, P. (2002), 'In search of sustainable human settlements', *Ecological Economics*, **40**, 151–55.

CAPRA, F. (2002), *The Hidden Connections: A Science for Sustainable Living*, New York, Doubleday.

CARBON DISCLOSURE PROJECT (2012), *Measurement for Management: CDP Cities 2012 Global Report*, London, Carbon Disclosure Project.

CARMONA, M., and SIEH, L. (2004), *Measuring Quality in Planning: Managing the Performance Process*, London, Spon Press.

CASTELLS, M. (1989), *The Informational City: Information Technology, Economic Restructuring, and the Urban–Regional Process*, New York, Blackwell.

CASTELLS, M. (2009), *Communication Power*, Oxford, UK, Oxford University Press.

CASTELLS, M. (2010), *The Power of Identity*, 2nd edition, Chichester, UK, Wiley Blackwell.

CHURCHILL, S. W. (1974), *The Interpretation and Use of Rate Data: The Rate Concept*, Washington DC, Hemisphere Publishing.

CLARK, W. and DICKSON, N. (2003), 'Sustainability science: the emerging research program', *Proceedings of the National Academy of Sciences*, **100**, 8058–61.

COLLINGE, W., LANDIS, A., JONES, A. SCHAEFER, L., BILEC, M. (2013), 'Dynamic life cycle assessment: framework and application to an institutional building', *International Journal of Life Cycle Assessment*, **18**, 538–52.

COSTANZA, R., D'ARGE, R., DE GROOT, R., FARBER, S., GRASSO, M., HANNON, B., LIMBURG, K. et al (1997), 'The value of the world's ecosystem services and natural capital', *Nature*, **387**, 253–60.

COTE, W. A., YOUNG, R. J., RISSE, K. B., COSTANZA, A. F., TONELLI, J. P., and LENOCKER, C. (2002), 'A carbon balance method for paper and wood products', *Environmental Pollution*, **116** (Supplement 1), 1–6.

COTGRAVE, A. and RILEY, M. 2013, *Total Sustainability in the Built Environment*, London, Palgrave MacMillan.

DAILY, G. (ed.) (1997), *Nature's Services: Societal Dependence on Natural Ecosystems*, Washington, DC, Island Press.

DALAL-CLAYTON, B. and SADLER, B. (2011), *Sustainability Appraisal: A Sourcebook and Reference Guide to International Experience*, London, Earthscan.

DALY, H. (1973), *Toward a Steady-State Economy*, San Francisco, Freeman.

DALY, H. (1991), *Steady-State Economics*, Washington, Island Press.

DALY, H. (1992), 'Allocation, distribution and scale: toward an economics that is efficient, just, and sustainable', *Ecological Economics*, **6**, 185–93.

DALY, H. and COBB, J., Jr. (1989), *For the Common wGood: Redirecting the Economy Toward Community, the Environment, and a Sustainable Future*, Boston, Beacon Press.

DALY, H. and FARLEY, J. (2004), *Ecological Economics: Principles and Applications*, Washington, DC, Island Press.

DECKER, E. H., ELLIOT, S., SMITH, F., BLAKE, D. R. and SHERWOOD ROWLAND, F. (2000), 'Energy and material flow through the urban ecosystem', *Annual Review of Energy and the Environment*, **25**, 685–740.

DURACK, R. (2001), 'Village vices: the contradiction of new urbanism and sustainability', *Places*, **14**, 64–69.

FAHRIG, L. (2003), 'The effects of habitat fragmentation on biodiversity', *Annual Review of Ecology, Evolution, and Systematics*, **34**, 487–515.

FARLEY, E., GADDIS, B., REES, W.and VAN DIS, K. (2007), 'Managing our global footprint through restoration of natural capital', in J. Aronson, S. Miltonand J. Blignaut (2007), *Restoring Natural Capital: Science, Business, and Practice*, Washington, DC, Island Press, 275–85.

FARR, D. (2007), *Sustainable Urbanism*, New York, McGraw-Hill.

FIELD, C., BARROS, V., STOCKER, T., QIN, D., DOKKEN, D., EBI, K., MASTRANDREA, K., MACH, G.-K., PLATTNER, S., ALLEN, S., TIGNOR, M., and MIDGLEY (eds) (2012), *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation: A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC)*, Cambridge, UK and New York, Cambridge University Press.

FISK, P. (2008), 'The ecobalance approach to new urbanism and the smart code', in S. Black and F. Steiner (eds),*Emergent Urbanism: Evolution in Urban Form*, 125–27, Austin, University of Texas School of Architecture.

GOLDSMITH, E. and PRESCOTT-ALLEN, R. (1972), *Blueprint for Survival*, Boston, Houghton Mifflin.

GOLDSMITH, W. and BLAKELY, E. (2011), *Separate Societies: Poverty and Inequality in US Cities*, 2nd edition, Philadelphia, Temple University Press.

GRAHAM, S. and MARVIN, S. (2001), *Splintering Urbanism: Networked Infrastructures, Technological Mobilities, and the Urban Condition*, New York, Routledge.

GUTOWSKI, T., BAKSHI, B. and SEKULIC, D. (eds) (2011), *Thermodynamics and the Destruction of Resources*, Cambridge, Cambridge University Press.

HACK, G., BIRCH, E. and LAURENCE, P. (2011).,*The Penn Resolution: Educating Urban Designers for Post-Carbon Cities*, Philadelphia, Penn Design.

HALDANE, A. and MAY, R. (2011), 'Systematic risk in banking ecosystems', *Nature*, **469**, 351–55.

HALL, P. V. and Hesse, M. (eds) (2012), *Cities, Regions and Flows*, Oxford, Routledge.

HAMIN, E. and GURRAN, N. (2009), 'Urban form and climate change: balancing adaptation and mitigation in the US and Australia', *Habitat International*, **33**, 238–45.

HOWARTH, R. and NORGAARD, R. (1992), 'Environmental evaluation under sustainable development', *The American Economic Review*, **82**, 473–77.

HUSSEIN, A. M. T. and TSCHIRHART, J. (2013), 'Economic/ecological tradeoffs among ecosystem services and biodiversity conservation' *Ecological Economics*, **93**, 116–27.

IPCC (INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE) (2014a), *Fifth Assessment Report Climate Change 2014: Mitigation of Climate Change*, Geneva, IPCC.

IPCC (INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE) (2014b), *Fifth Assessment Report Climate Change 2014: Impacts, Adaptation and Vulnerability*, Geneva, IPCC.

ISCA (INFRASTRUCTURE SUSTAINABILITY COUNCIL OF AUSTRALIA) (2014), *IS Rating Tool*, Sydney, ISCA.

IUCN (INTERNATIONAL UNION FOR CONSERVATION OF NATURE) (1980), *World Conservation Strategy: Living Resource Conservation for Sustainable Development*, Gland, Switzerland, IUCN-UNEP-WWF.

KABEL, R. L. (1981), 'Rates', *Chemical Engineering Communications*, **9**, 15–17.

KABEL, R. L. (1992), 'Reflections on rates', *Industrial & Engineering Chemistry Research*, **31**, 641–43.

KAREIVA, P., TALLIS, H., RICKETTS, T., DAILY, G. and POLASKY, S. (2011), *Natural Capital: Theory and Practice of Mapping Ecosystem Services*, Oxford, Oxford University Press.

KATES, R., CLARK, W., HALL, J. H., JAEGER, C., LOWE, I., MCCARTHY, J., SCHELLNHUBER, H. et al (2001), 'Sustainability science', *Science*, **292**, 641–42.

KISSINGER, M. and REES, W. (2010), 'An interregional ecological approach for modeling sustainability in a globalizing world: Reviewing existing approaches and emerging directions', *Ecological Modelling*, **221**, 2615–23.

KLEIDON, A. and LORENZ, R. (eds) (2005), *Non-Equilibrium Thermodynamics and the Production of Entropy: Life, Earth, and Beyond*, New York, Springer.

KLEIN, L. (1969), 'The specification of regional econometric models', *Papers in Regional Science*, **23**, 105–16.

LAKSHMANAN, T. and NIJKAMP, P. (eds) (1983), *Systems and Models for Energy and Environmental Analysis*, Aldershot, UK, Gower.

LAVE, L. and GRUENSPECHT, H. (1991), 'Increasing the efficiency and effectiveness of environmental decisions: benefit-cost analysis and effluent fees: A critical review', *Journal of the Air & Waste Management Association*, **41**, 680–93.

LEHMANN, S. (2012), 'The metabolism of the city: optimizing urban material flow through principles of zero waste and sustainable consumption', in S. Lehmann and R. Crocker (eds), *Designing for Zero Waste: Consumption, Technologies and the Built Environment*, London and New York, Earthscan, 309–42.

LENTON, T. and WATSON, A. (2011), *Revolutions that Made the Earth*, Oxford, Oxford University Press.

LINDEN, H. (1994), 'Energy and industrial ecology', in B. Allenby and D. Richards (eds), *The Greening of Industrial Ecosystems*, Washington, DC, National Academy Press.

LUCK, G. W., DAILY, G. C. and EHRLICH, P. R. (2003), 'Population diversity and ecosystem services', *Trends in Ecology and Evolution*, **18**, 331–36.

MALTHUS, T. (1798), *An essay on the Principle of Population, as it Affects the Future Improvement of Society*, London, J. Johnson.

MCDONALD, G. T. (1996), 'Planning as sustainable development', *Journal of Planning Education and Research*, **15**, 225–36.

MCHARG, I. (1969), *Design with Nature*, New York, Natural History Press.

MACE, G. M. (2005), 'An index of intactness', *Nature*, **434**, 32–33.

MEA (MILLENNIUM ECOSYSTEM ASSESSMENT) (2005), *Millennium Ecosystem Assessment Synthesis Report*, New York, Millennium Ecosystem Assessment.

MEADOWS, D. H., MEADOWS, D. L., RANDERS, J. and BEHRENS, W. (1972), *The Llimits to Growth. A Report for the Club of Rome's Project on the Predicament for Mankind*, New York, Universe Books.

MEEHL, G. A., WASHINGTON, W. M., COLLINS, W. D., ARBLASTER, J. M. HU, A., BUJA, L., STRAND, W.G. and TENG, H. (2005), 'How much more global warming and sea level rise?', *Science*, **307**, 1769–72.

MEIER, R. (1968), 'The metropolis as a transaction-maximizing system', *Daedalus*, **97**, 1292–1313.

MILLER, R. and BLAIR, P. (2009), *Input-Output Analysis: Foundations and Extensions*, 2nd edition, Cambridge, Cambridge University Press.

MOLDAN, B., JANOUŠKOVÁ, S. and HÁK, T. (2012), 'How to understand and measure environmental indicators and targets', *Ecological Indicators*, **17**, 4–13.

MUSTAFAVI, M. and DOHERTY, G. (eds), (2010), *Ecological Urbanism*, Baden, Switzerland, Lars Muller.

NEUMAN, M. (2005), 'The compact city fallacy', *Journal of Planning Education and Research*, **25**, 11–26.

NEUMAN, M. and WHITTINGTON, J. (2000), *Building California's Future: Current Conditions in California's Infrastructure Planning*, Budgeting and Financing, San Francisco, Public Policy Institute of California.

NEUMAN, M. and CHURCHILL, S. (2011), 'A general process model of sustainability', *Industrial and Engineering Chemistry Research*, **50**, 8901–04.

NEW JERSEY OFFICE OF STATE PLANNING (1991), *The Resource Investment and Management System*,. Trenton, NJ, Department of Treasury.

NEWMAN, P., BEATLEY, T. and BOYER, H. (2009), *Resilient Cities: Responding to Peak Oil and Climate Change*, Washington, DC, Island Press.

NEWMAN, P. and JENNINGS, I. (2008), *Cities as Sustainable Ecosystems: Principles and Practices*, Washington, DC, Island Press.

NEWTON, P. (2012), 'Liveable and sustainable? Socio-technical challenges for twenty-first century cities', *Journal of Urban Technology*, **19**, 81–102.

NICOLIS, G. and PRIGOGINE, I. (1977), *Self-Organization in Nonequilibrium Systems:fFrom Dissipative Structures to Order through Fluctuations*, New York, Wiley.

NIJKAMP, P. (2004), *Environmental Economics and Evaluation*, Cheltenham, UK, Northampton, MA, Edward Elgar.

NIST (NATIONAL INSTITUTE FOR STANDARDS AND TECHNOLOGY OF THE UNITED STATES) (2010), *Building for Environmental and Economic Sustainability (BEES)*, available at http://www.nist.gov/el/economics/BEESSoftware.cfm, accessed 10 January, 2012.

NATIONAL RESEARCH COUNCIL, (2004), *Materials Count – The Case for Material Flows Analysis*, Washington, DC, The National Academies Press.

OWENS, S. and COWELL, R. (2002), *Land and Limits: Sustainability in the Planning Process*, London, Routledge.

PASCUALE, M. and DUNNE, J. (2006), *Ecological Networks: Linking Structure to Dynamics in Food Webs*, Oxford, Oxford University Press.

PEARSON, L. (2013), 'In search of resilient and sustainable cities: prefatory remarks (to the special issue on Sustainable Urbanisation: A Resilient Future)', *Ecological Economics*, **86**, 222–23.

PICKETT, S., CADENASSO, M., GROVE, J., NILON, C., POUYAT, R., ZIPPERER, W. and COSTANZA, R. (2001), 'Urban ecological systems: linking terrestrial ecological, physical, and socioeconomic components of metropolitan areas', *Annual Reviews of Ecology and Systematics*, **32**, 127–57.

PRIGOGINE, I. (1955), *Thermodynamics of Irreversible Processes*, New York, John Wiley and Sons.

PRIGOGINE, I. (1981), *From Being to Becoming: Time and Complexity in the Physical Sciences*, New York, W. H. Freeman and Co.

PRIGOGINE, I. and STENGERS, I. (1984), *Order out of Chaos: Man's New Dialogue with Nature*, New York, Bantam.

RAVETZ, J. (2000), 'Integrated assessment for sustainability appraisal in cities and regions', *Environmental Impact Assessment Review*, **20**, 31–64.

REES, W. (1992), 'Ecological footprints and appropriated carrying capacity: what urban economics leaves out', *Environment and Urbanization*, **4**, 121–30.

REES, W. (2003), 'Understanding urban ecosystems: an ecological economics perspective', in A. Berkowitz,, C. Nilon and K. Hollweg(eds) *Understanding Urban Ecosystems*, New York, Springer-Verlag.

REES, W. and WACKERNAGEL, M. (1994), 'Ecological footprints and appropriated carrying capacity: measuring the natural capital requirements of the human economy', in A.-M., Jansson, M., Hammer, C. Folke and R, Costanza (eds), *Investing in Natural Capital: the Ecological Economics Approach to Sustainability*, 362–90, Washington, DC, Island Press.

RUTH, M. and DAVIDSDOTTIR, B. (eds), (2009), *The Dynamics of Regions and Networks in Industrial Ecosystems*, Northampton, MA, Edward Elgar Publishing.

SACHS, W., LOSKE, R. and LINZ, M. (eds) (1998), *Greening the North: a Post-Industrial Blueprint for Ecology and Equity*, New York, St. Martin's Press.

SCHNEIDER, E. and SAGAN, D. (2005), *Into the Cool: Energy Flow, Thermodynamics, and Life*, Chicago, University of Chicago Press.

SCHOLES, R. J. and BIGGS, R. (2005), 'A biodiversity intactness index', *Nature*, **434**, 45–49.

SCHROTER, D., CRAMER, W., LEEMANS, R., PRENTICE, I. C., ARAÚJO, M. B., ARNELL, N. W., ... & ZIERL, B. (2005), 'Ecosystem service supply and vulnerability to global change in Europe', *Science*, **310**, 1333–37.

SCHÖN, D. (1983), *The Reflective Practitioner: How Professionals Think in Action*, New York, Basic Books.

SHEN, L-Y., OCHOA, J., SHAH, M. and ZHANG, X. (2011), 'The application of urban sustainability indicators: a comparison between various practices', *Habitat International*, **35**, 17–29.

SUH, S. (2009), *The Handbook of Input-Output Economics in Industrial Ecology*, New York, Springer.

SVIRIJEVA-HOPKINS, A. and SCHELLNHUBER, H-J. (2006), 'Modeling carbon dynamics from urban land conversion: fundamental model of city in relation to a local carbon cycle', *Carbon Balance and Management*, **1**, 1–9.

TALEN, E. (2005), *New Urbanism and American Planning: the Conflict of Cultures*, New York, Routledge.

THE ROYAL SOCIETY (2003), *Measuring Biodiversity for Conservation*, London, The Royal Society.

TRIBE, L. (1972), 'Policy science: analysis or ideology?' *Philosophy and public affairs*, **2**, 66–110.

UNCHS (HABITAT) (1996), *Global Report of Human Settlements,* Oxford, Oxford University Press.

UNCHS (HABITAT) (2009), *Planning Sustainable Cities: Global Report of Human Settlements,* London, Earthscan.

UNCSD (UNITED NATIONS CENTER FOR SUSTAINABLE DEVELOPMENT) (2007), *Indicators of Sustainable Development: Guidelines and Methodologies*, New York, United Nations, 3rd edition.

UNFPA (UNITED NATIONS POPULATION FUND) (2007), *State of World Population 2007: Unleashing the Potential of Urban Growth*, New York, United Nations Population Fund.

UNITED NATIONS, EUROPEAN UNION, WORLD BANK, INTERNATIONAL MONETARY FUND, AND THE ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT (2014), *The System of Environmental-Economic Accounting 2012, Central Framework*, New York, United Nations.

UNWCED (UNITED NATIONS WORLD COMMISSION ON ENVIRONMENT AND DEVELOPMENT) (1987), *Our Common Future,* Oxford, Oxford University Press.

UNWSSD (UNITED NATIONS WORLD SUMMIT ON SUSTAINABLE DEVELOPMENT) (2002), *Johannesburg Plan of Implementation,* New York, United Nations.

VON WEIZSÄCKER, E., LOVINS, A. and LOVINS, H. (1997), *Factor Four: Doubling Wealth, Halving Resource Use*, London, Earthscan.

WADA, Y., VAN BEEK, L., VAN KEMPEN, C., RECKMAN, J., VASAK, S. and BIERKENS, M. (2010), 'Global depletion of groundwater resources', *Geophysical Research Letters,* **37**, L20402, doi 10.1029/2010GL044571.

WANG, G. and SCHIMEL, D. (2003), 'Climate change, climate modes, and climate impacts', *Annual Review of Environment and Resources*, **28**, 1–23.

WARREN-RHODES, K. and KOENIG, A. (2001), 'Escalating trends in the urban metabolism of Hong Kong: 1971-1997', *Ambio*, **30**, 429–38.

WIEDMANN, T. and MINX, J. (2008), 'Definition of carbon footprint', in C. C. Pertsova (ed.), *Ecological Economic Research Trends*, Hauppauge, NY, Nova Science Publishers, 1–11.

WIGLEY, T. M. (2005), 'The climate change commitment', *Science,* **307**, 1766–69.

WORLD BANK (2010), *World Development Report 2010: Development and Climate Change*, Washington, DC, World Bank.