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RESEARCH ARTICLE

Landscape sustainability science: ecosystem services and human well-being in changing landscapes

Jianguo Wu

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Abstract The future of humanity depends on whether or not we have a vision to guide our transition toward sustainability, on scales ranging from local landscapes to the planet as a whole. Sustainability science is at the core of this vision, and landscapes and regions represent a pivotal scale domain. The main objectives of this paper are: (1) to elucidate key definitions and concepts of sustainability, including the Brundtland definition, the triple bottom line, weak and strong sustainability, resilience, human well-being, and ecosystem services; (2) to examine key definitions and concepts of landscape sustainability, including those derived from general concepts and those developed for specific landscapes; and (3) to propose a framework for developing a science of landscape sustainability. Landscape sustainability is defined as the capacity of a landscape to consistently provide long-term, landscape-specific ecosystem services essential for maintaining and improving human well-being. Fundamentally, well-being is a journey, not a destination. Landscape sustainability science is a place-based, use-inspired science of understanding and improving the dynamic relationship between ecosystem services and human well-being in changing landscapes under uncertainties arising from internal feedbacks and external disturbances. While landscape sustainability science emphasizes place-based research on landscape and regional scales, significant between landscape interactions and hierarchical linkages to both finer and broader scales (or externalities) must not be ignored. To advance landscape sustainability science, spatially explicit methods are essential, especially experimental approaches that take advantage of designed landscapes and multi-scaled simulation models that couple the dynamics of landscape services (ecosystem services provided by multiple landscape elements in combination as emergent properties) and human well-being.

Keywords Sustainability · Landscape sustainability science · Landscape sustainability spectrum · Ecosystem services · Human well-being · Key research questions and approaches

J. Wu (✉)
School of Life Sciences & Global Institute of Sustainability, Arizona State University, Tempe, AZ 85287-4501, USA
e-mail: jingle.wu@asu.edu

J. Wu
Center for Human-Environment System Sustainability (CHESS), State Key Laboratory of Earth Surface Processes and Resource Ecology (ESPRE), Beijing Normal University, Beijing 100875, China

J. Wu
Sino-US Center for Conservation, Energy, and Sustainability Science (SUCCESS), Inner Mongolia University, Hohhot 010021, China

Introduction

The earth system is entering a new epoch—the Anthropocene—which is characterized by significant global environmental impacts mainly driven by human activities (Steffen et al. 2011; Vince 2011). Since the advent of the industrial revolution approximately two centuries ago, the world population has increased exponentially, technological advances have mushroomed, and the overall material well-being (one dimension of human well-being) has improved substantially. Human ingenuity has proven exuberant, indeed. However, it is this spectacular success that has, perhaps unnecessarily, resulted in the many pressing environmental problems troubling the world today—biodiversity loss, ecosystem degradation, and climate change, to name a few. Abundant evidence suggests that the world and its constituent landscapes are on an unsustainable trajectory. Sustainability or sustainable development is a necessity, not a choice. It is widely recognized that sustainability is the theme of our times and represents the greatest challenge in the Anthropocene, this "Age of Man." To meet this challenge, sustainability science (NRC 1999; Kates et al. 2001)—a transdisciplinary science focusing on the dynamic relationship between society and nature at the local, regional, and global scales—has quickly established itself during the past decade, rapidly becoming a worldwide intellectual enterprise (NRC 1999; Kates et al. 2001; Clark and Dickson 2003; Bettencourt and Kaur 2011; Kates 2011).

While all spatial scales, from individuals and local ecosystems to the global society and the biosphere, are relevant to the understanding and practice of sustainability, some scales are more operational than others. For example, local ecosystem-based studies tend to be too small in spatial extent to incorporate the environmental, economic, and social patterns and processes most relevant to sustainable development, whereas at the global scale, it is often impossible to assess essential mechanistic details necessary for guiding local policies. A landscape or region, consisting of multiple ecosystems over a watershed or a geopolitically-defined area, represents a pivotal scale domain for the research and application of sustainability (Forman 1990; Wu 2006; Forman 2008; Wu 2012). In particular, landscapes are the scale at which people and nature mesh and interact most acutely, and thus the composition and configuration of a landscape both profoundly affect, and are affected by, human activities. By considering these human–environment interactions at the landscape scale in a spatially explicit way, we are more likely to link local and global sustainability realistically and effectively. Thus, the science of landscape sustainability constitutes an essential part of sustainability science (Wu 2006; Musacchio 2009; Wu 2012; Turner et al. 2013a, b).

Indeed, terms such as "sustainable landscapes," "landscape sustainability," and "landscape resilience" have entered into increasingly common usage among landscape ecologists, geographers, environmental planners, and landscape architects in recent years (Wu and Hobbs 2002; Wu 2013). While the scientific and moral necessity of sustainability is convincing, the meaning of sustainability differs widely among researchers in diverse fields. This is especially true at the landscape scale, because while research in landscape sustainability is burgeoning, it remains at a formative stage. Its relationship to sustainability science and landscape ecology, for instance, has yet to be rigorously explored. In this shortcoming, however, there is an opportunity to further the intellectual bounds and applicability of a transdisciplinary approach to human–environment interactions. The main objectives of this article are: to elucidate key definitions and concepts of sustainability, to examine key definitions and concepts of landscape sustainability, and to propose a framework for advancing landscape sustainability science.

Key definitions and concepts of sustainability

Before discussing landscape sustainability, it is useful to first understand what is meant by "sustainability." The literature on sustainable development or sustainability has been expanding exponentially since the 1980s. While more than one hundred definitions of sustainability exist (Marshall and Toffel 2005), most of them are irrelevant to the purpose of this paper. The proliferation of the term has caused it to be frequently employed as a vague gesture to the need for environmental conservation (e.g., its frequent occurrence in corporate advertisements and political slogans). Here I focus on a rigorous subset of the most fundamental concepts of sustainability, the ones that have been vetted through the years in the academic literature and have, consequently, gained scientific currency: the Brundtland definition, the triple bottom line, weak versus strong sustainability, human well-being, and ecosystem services (used here as a synonym of ecological services or environmental services). They are essential for the discussion of landscape sustainability in later sections.

Etymology and popularity

According to Online Etymology Dictionary (http://www.etymonline.com/), the word "sustainable" first appeared in the 1610s, meaning "bearable" or "defensible," and only acquired the connotation of "capable of being continued at a certain level" in 1965. The word "sustainability" emerged later in 1907, used in reference to a legal objection, and it did not acquire its contemporary meaning of the ability to sustain or to be sustained until 1972 (http://www.etymonline.com/). As a term that encompasses environmental, economic, and social dimensions, sustainability was first used in the United Kingdom in 1972, in the United States in 1974, and in a United Nations document in 1978 (Kidd 1992). Today, sustainability has become a buzzword in the political arena, the public media, as well as the scientific literature. In most cases, sustainability is used as a synonym of sustainable development.

The popularity of sustainability has increased rapidly since the 1970s for several reasons, including concerns with population growth, increasing resource consumption, depletion of crucial resources (e.g., wood, coal, and oil), and the widespread deterioration of ecological conditions (Du Pisani 2006). Kidd (1992) identified six different but related conceptual roots of sustainability: the ecological or carrying capacity root (biophysical capacity of ecosystems), the resources and environment root (adequacy of resources and environmental quality), the biosphere root (global-scale impacts of human activities), the critique of technology root (technology regarded as having "predominantly dehumanizing and disorganizing effects"), the "no growth" and "slow growth" root (emphasizing limits to growth and promoting a steady state economy), and the eco-development root ("harmonizing social and economic objectives with ecologically sound management"). Several milestones are commonly recognized in the literature, including:

- The 1987 report by the United Nations' World Commission on Environment and Development, which defined sustainable develop formally for the first time;
- The 1992 United Nations Conference on Environment and Development in Rio de Janeiro (the Rio Summit), which proposed the fundamental principles and the program of action for achieving sustainable development, endorsed by more than 170 national governments;
- The 1999 report by the United States National Research Council (NRC), which coined the term, "sustainability science;"
- The publication of the seminal paper, entitled "Sustainability science," authored by Kates et al. (2001);
- The 2002 World Summit on Sustainable Development (the 2nd Earth Summit), convened by the United Nations in Johannesburg, South Africa, which reaffirmed the UN's commitment to the Rio principles and implementation of Agenda 21.

The Brundtland definition

The most widely cited definition of sustainability is the one given in the now famous report "Our Common Future," released in 1987 by the United Nations' World Commission on Environment and Development (WCED). The report defined sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED 1987). It further emphasized that "sustainable development is a process of change in which the exploitation of resources, the direction of investments, the orientation of technological development; and institutional change are all in harmony and enhance both current and future potential to meet human needs and aspirations" (WCED 1987). As WCED was chaired by the former Prime Minister of Norway Gro Harlem Brundtland, the report is frequently referred to as the Brundtland Report, and the definition of sustainability therein the Brundtland definition.

The Brundtland definition emphasizes the dynamic balance between human development and environmental protection, as well as intra- and intergenerational equity. In the same spirit, the US National Research Council's (NRC) sustainability report—one of the most important milestones in the development of sustainability science—described sustainable development as "the reconciliation of society's developmental goals with its environmental limits over the long term" (NRC 1999). Both emphasize, quite explicitly, the long-run imperatives of contemporary policy, and tie the well-being of future peoples with the environmental conditions that will be bequeathed to them.

The popularity of the Brundtland definition may be attributed to two primary factors. First, it captures the essential elements in a definition of sustainability (i.e., balance between society and nature and equity between generations), although it does so in a rather general and vague fashion. Second, being general in scope and vague in detail has actually helped the definition be adopted by a number of fields for various purposes, as it allows for various, and sometimes incompatible, interpretations. In defending the concept of sustainable development, the pioneering ecological economist Daly (1995) put it eloquently: "All important concepts are dialectically vague at the margins." Terms of great importance to humanity, such as freedom, justice, and democracy, all seem vague, but convey fundamental principles for modern societies which guide our current actions and shape our visions for the future. Crow (2010) argued that sustainability is such a guiding principle for citizens, societies, and the world as a whole in the Anthropocene. To operationalize sustainability in research and practice, however, the system properties, their interrelationships, and spatial and temporal scales must be further specified.

The triple bottom line definition

From the Brundtland definition it is clear that sustainability is about achieving the balance between human needs and environmental integrity, which is increasingly difficult in conditions of resource scarcity, and between intra-generational and inter-generational equity, which is only realizable when the first condition is met. Meeting human needs in a particular place requires economic (increase in material goods and services) and social development (protecting and increasing collective values such as justice, trust, and liberty), which influences, and is influenced by, nature. Thus, sustainability has frequently been described as having three pillars or dimensions: environment, economy, and society (i.e., the triple bottom line, TBL; Fig. 1a). In this case, to achieve sustainability is to simultaneously achieve environmental, economic, and social sustainability.

The triple bottom line (also known as people, planet, and profit) was coined in 1994 by John Elkington, Co-founder and Chair of SustainAbility, a British business consultancy founded in 1987 (Elkington 2004). Inspired by the Brundtland Report, TBL was proposed as a catchy term to emphasize that economic activities have important social and environmental consequences for which corporations must assume responsibility (Elkington 2004). With the rising popularity of sustainability in the business world, the political arena, and academia during the past two decades, TBL has been widely used as a conceptual standard for assessing and promoting corporate social responsibility in particular and sustainable development in general. For example, in 2001 the United Nations Commission on Sustainable Development (UNCSD) replaced the pressure-state-response (PSR) model with a theme-based model as its organizational framework for sustainable development indicators. This theme-based framework organizes themes and indicators based on four dimensions:

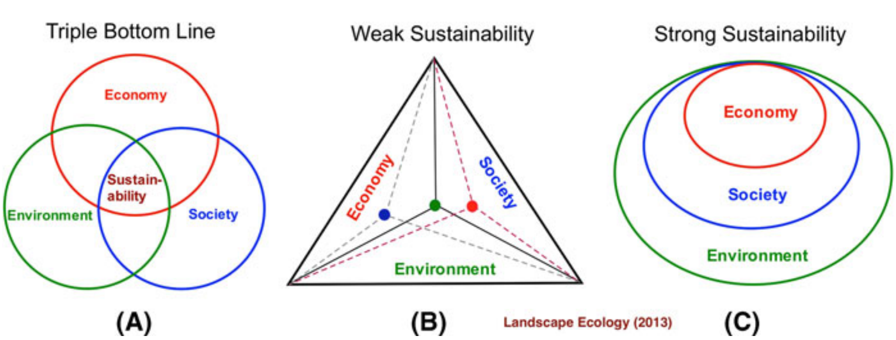

Fig. 1 Illustration of the triple bottom line definition of sustainability (**a**) and weak (**b**) versus strong sustainability (**c**). The three situations in **b** are equally sustainable because weak sustainability allows for substitutability as lone as the total capital (i.e., the sum of environmental, economic, and social capital) does not decrease

environmental, economic, social, and institutional. Having institutions as a separate dimension was intended to emphasize the unique and powerful influences of national and international laws, policies, and governance mechanisms (including science and technology), as UNCSD's sustainability indicators are targeted mainly at nation-states.

From the perspective of TBL, the grand challenge for sustainability is to understand and shape the relationship among the three dimensions, as well as the relationships among components within each dimension. For instance, how do the three dimensions interact with, and depend on, each other on local, regional, and global scales? Should economic development be allowed to substitute for environmental integrity, and if so, to what extent? Are there thresholds or tipping points in the substitution among the three types of capital? Substitutability between natural and human-made capital underlines the debate on "weak" versus "strong" sustainability, mainly among economists, as discussed in the following section.

Weak, strong, and absurdly strong sustainability

Weak sustainability permits mutual substitutability between natural capital (e.g., ecosystems and mineral wealth) and human-made or manufactured capital (e.g., factories and urban infrastructure) to the extent that a system is considered sustainable as long as its total capital increases or remains the same (Fig. 1b). According to this view, a region with rapid economic development and urban sprawl at the expense its environmental quality may still be considered as sustainable. Except those ardent neoclassical economists who believe otherwise, most natural and social scientists seem convinced that, without a healthy environment, long-term maintenance of economic and social development is impossible, much less economic growth (Daly 1997). On the other end of the spectrum of substitutability, the advocates of "absurdly strong sustainability" assert that "nature ought not to be substituted even where it can be substituted" (Holland 1997). In the words of Daly, this essentially means that "no species could ever go extinct, nor any nonrenewable resource should ever be taken from the ground, no matter how many people are starving;" in general, "'absurdly strong sustainability' is in fact absurd" (Daly 1995). Indeed, both views seem too extreme.

Meeting human needs while ensuring environmental integrity requires some form of strong sustainability that is not "absurd." Daly (1995) called this third view simply "strong sustainability." In general, strong sustainability means that economic activities are part of the social domain, and both economic and social actions are constrained by the environment (Fig. 1c). "Strong sustainability assumes that man-made and natural capital are basically complements" whereas "weak sustainability assumes that man-made and natural capital are basically substitutes" (Daly 1995). Apparently, absurdly strong sustainability regards the two forms of capital as completely incompatible or diametrically opposed. Daly (1995) further pointed out that complementarity, not substitutability, is the key to sustainability. Strong sustainability is consistent with the TBL definition because achieving a balance among the three dimensions of sustainability means creating so-called "win–win–win" situations, which must be based on the assumption that the different forms of capital are complementary and should be given commensurate emphasis. From an economic perspective, strong sustainability represents a precautionary expression of the Brundtland notion and the increasingly influential ecosystem services-centered paradigm of sustainability.

To some extent, the debate on weak versus strong sustainability resembles the SLOSS debate (i.e., whether a Single Large Or Several Small reserves would be a better strategy to protect biodiversity) in ecology and conservation biology, most heatedly, during the 1970s and the 1980s (Wu 2008). It is readily understandable from a landscape perspective that maximizing biodiversity conservation sustainably in a fragmented environment requires both strategies concurrently. Similarly, we may argue that, from a multi-scale perspective, Daly's strong sustainability at a broad scale may not be achieved without a proper combination of weak and absurdly strong sustainability on smaller scales. I will discuss this further in the section on landscape sustainability science.

Resilience, vulnerability, and sustainability

Human-dominated ecosystems and landscapes, as well as the biosphere, are coupled human–environment systems (CHES) or social–ecological systems (SES). These are quintessential examples of complex adaptive systems (CAS), which are characterized by a large number of nonlinearly interacting components, scale multiplicity in structure and dynamics, and self-organizing capacity (Levin 1999). Such systems are inherently unpredictable because of uncertainties arising from internal processes as well as nonlinear responses to external influences. Thus, the sustainability of CAS relies on resilience arising from the system's adaptive capability (Levin 1999; Holling 2001; Wu and Wu 2013).

Holling (1973) originally defined resilience as the ability of a system to absorb change and disturbance without changing its basic structure and function or shifting into a qualitatively different state. This "ecological resilience" or "ecosystem resilience" concept emphasizes persistence, change, and unpredictability, and differs fundamentally from the equilibrium-based "engineering resilience" idea that is characterized by efficiency, constancy, and predictability (Holling 1996). During the past three decades, resilience research has expanded from ecological systems to social and economic systems, and has emerged as a dominant paradigm in the study of coupled social–ecological systems. The definition of resilience in the context of sustainability focuses on the system's abilities to self-organize and adapt to change (Levin 1998; Holling 2001; Walker and Salt 2006). Key concepts in resilience theory includes alternate stable states (regimes, or domains of attraction), thresholds (tipping points), regime shifts (phase transitions), adaptive cycles, panarchy (a hierarchy of adaptive cycles), and transformability (Holling 2001; Folke et al. 2004; Walker and Salt 2006; Wu and Wu 2013). Recent studies have suggested that a high diversity of heterogeneous components, modular structures, and tight (but not too tight) feedback loops often characterize resilient complex adaptive systems (Levin 1999; Levin and Lubchenco 2008).

Sustainability and resilience are two different but closely related terms. Some authors have treated them as contrasting terms by describing the former as a concept of "stasis" or equilibrium state and the latter as a concept of promoting change and adaptability (or adaptive capacity). For example, Cumming et al. (2013) asserted that "the concept of sustainability emphasizes a 'business as usual' scenario that focuses on current rates of exploitation and growth, whereas the concept of resilience emphasizes more heavily the ability of the system to cope with perturbations (and the related topics of uncertainty, innovation, and adaptation)." Such dichotomization seems idiosyncratic, not representing the dominant view on the relationship between the two concepts (e.g., Holling 2004; Turner 2010). The recent literature on sustainability science suggests that adaptability is essential to both resilience and sustainability, and the past decade has seen an increasing integration of the two. Instead of seeking stasis, "Sustainability both conserves and creates" (Holling 2004). Resilience can thus be understood as an integral characteristic of social–ecological sustainability (Walker and Salt 2006). The close relationship between resilience and sustainability is aptly stated by Holling (2001):

> Sustainability is the capacity to create, test, and maintain adaptive capability. Development is the process of creating, testing, and maintaining opportunity… 'sustainable development,' thus refers to the goal of fostering adaptive capabilities and creating opportunities. It is therefore not an oxymoron but a term that describes a logical partnership… Sustainability requires both change and persistence. We propose that sustainability is maintained by relationships that can be interpreted as a nested set of adaptive cycles arranged as a dynamic hierarchy in space and time—the panarchy (Holling 2001, pp. 390, 402).

The concept of vulnerability is closely related to resilience (Turner et al. 2003; Adger 2006). According to Turner et al. (2003b), "Vulnerability is the degree to which a system, subsystem, or system component is likely to experience harm due to exposure to a hazard, either a perturbation or stress/stressor." Vulnerability and resilience are complementary concepts, but sometimes considered antonymous (Gallopin 2006). In general, highly resilient systems tend to be less vulnerable, and vice versa. However, this relationship is not exactly symmetric because a highly insensitive or resistant—and thus less vulnerable—system may also have low resilience (i.e., it has diminished scope for adaptation and innovation) (Gallopin 2006). Although the precise relationship between these closely related terms remains unclear, partly because each has been defined variously (Gallopin 2006), sustainability generally corresponds to low vulnerability and high resilience. All three concepts have been used in the study of human, environmental, and human–environment systems to describe the properties of the systems or the dynamic relationships between the systems and their environments. While they differ in origins and emphases, their common emphasis on adaptive capacity and their focus on CHES provide a common ground for increasing integration (Adger 2006; Turner 2010). Thus, resilience and vulnerability represent two essential perspectives on sustainability (Turner et al. 2003; Turner 2010).

Human well-being and the hierarchy of human needs

From the earlier discussion, it is clear that sustainability is far more comprehensive and interdisciplinary than the traditional notion of ecological or environmental carrying capacity, or the stability of ecological organizations and processes. Sustainability is evidently an anthropocentric concept—focusing on meeting human needs of the current and future generations within the limits of the environment. But humans have many needs that vary with socioeconomic status, cultural traditions, and individual lifestyle and preferences. What are these needs? Are they all equally important to human well-being? Theoretically, it is desirable, of course, to have all our needs met, but in reality this never happens. Then, what are the kinds of needs that we must meet in the context of sustainable development?

Addressing these questions often invokes the hierarchy of human needs (Fig. 2), developed by Maslow (1908–1970), one of the most influential psychologists of the 20th century (Haggbloom et al. 2002). Maslow's hierarchy groups human needs into six levels in a descending order of prepotency: physiology, safety, love and belonging, esteem, self-actualization, and self-transcendence (Maslow 1954; Koltko-Rivera 2006). High-level needs in Maslow's hierarchy are closely related to culture, values, and beliefs. While controversy abounds on the details, the hierarchy of needs has been widely used for understanding human motivations and behavior (Benson and Dundis 2003; Gorman 2010). As expected, its influences are also evident in the sustainability literature, particularly on assessing human well-being (Kofinas and Chapin 2009; Gorman 2010) and classifying ecosystem services (Wallace 2007; Dominati et al. 2010), both of which are inherently related to human needs and values. For example, Hagerty (1999) applied Maslow's hierarchy of needs in assessing national quality of life in which the individual-level needs were translated into corresponding measures at the national level (e.g., daily calories available per capita and GDP per capita for physiological needs; war rate, homicide rate, and life expectancy for safety needs). He concluded that the progression in quality of life for 88 countries from 1960 to 1994 followed the sequence of priority in Maslow's hierarchy (Hagerty 1999).

In a similar vein, Marshall and Toffel (2005) claimed that Maslow's hierarchy is equally applicable for individuals and societies, and proposed a "sustainability hierarchy" consisting of four sustainability issues with different degrees of urgency, severity, and uncertainty of consequences: human survival, life expectancy and basic health, species loss and human rights, and values, beliefs and aesthetics. But Marshall and Toffel (2005) went on to assert that the highest level in the sustainability hierarchy (i.e., values, beliefs, and aesthetic preferences) "should not be considered within the rubric of sustainability" because they represent a "moving target" that is "inherently an unobtainable goal." This is clearly at odds with Maslow's theory and most of the commonly quoted definitions of sustainability. Such a view is probably shared by many who seek precise and mechanistic solutions to sustainability problems. However, if meeting human needs is more than simply keeping people alive or physically content, key factors affecting "quality of life" should be considered. In reality, needs at different levels of Maslow's hierarchy are often interrelated, and cutting off the top undermines the goal of sustainability. As Kofinas and Chapin (2009) pointed out, opportunities for sustainability increase as more of Maslow's human needs are met. Also, being "objective" is different from being "accurate," and this is especially true when the matter at hand is inherently "subjective."

The Millennium Ecosystem Assessment (MEA) between 2001 and 2005, which provided the first global-scale scientific appraisal of the conditions and trends of the world's ecosystems and their services, was based on the assumption that human well-being depends on ecosystem services. Millennium Ecosystem Assessment (2005) recognized five dimensions of human well-being: (1) basic material for a good life (mainly, food, water, and shelter, adequate income, household assets), (2) freedom of choice (options a

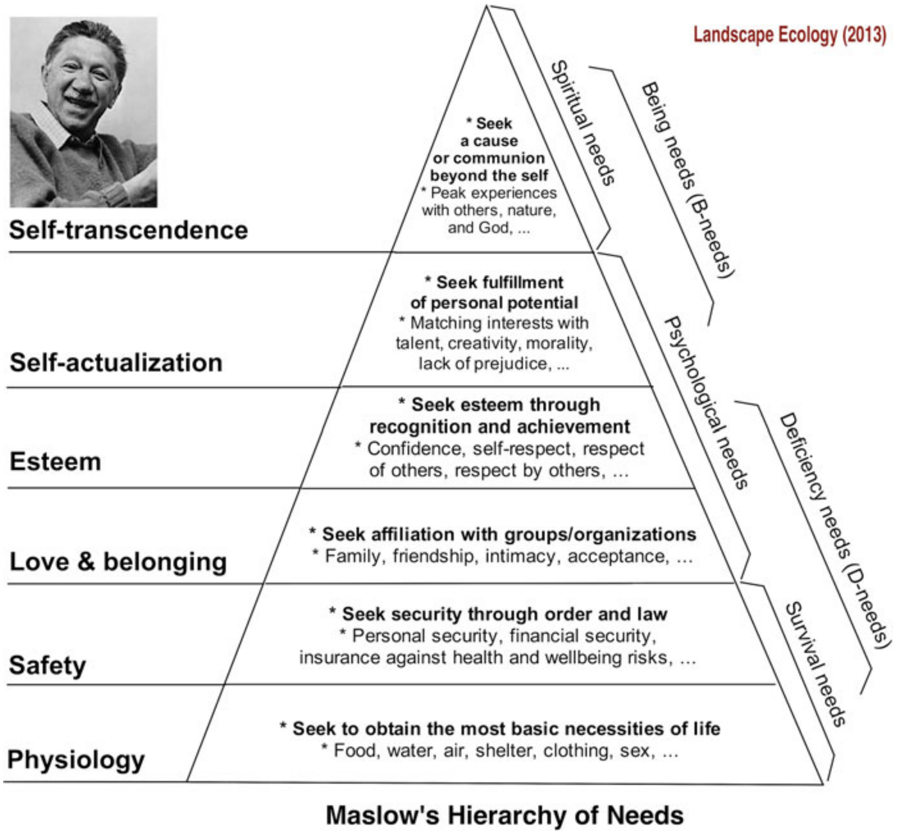

Fig. 2 Maslow's hierarchy of human needs (based on descriptions in Maslow 1954 and Koltko-Rivera 2006)

person has in deciding on and realizing the kind of life to lead), (3) health (life expectancy, infant mortality, and child mortality), (4) good social relations (being able to realize aesthetic and recreational values, express cultural and spiritual values, develop institutional linkages that create social capital, show mutual respect, have good gender and family relations, and have the ability to help others and provide for their children), and (5) security (not suffering abrupt threats to their well-being). The Commission on the Measurement of Economic Performance and Social Progress (also known as the Stiglitz-Sen-Fitoussi Commission) identified eight key dimensions that should be considered simultaneously when defining human well-being: (1) material living standards (income, consumption and wealth), (2) health, (3) education, (4) personal activities including work, (5) political voice and governance, (6) social connections and relationships, (7) social and physical environmental conditions (present and future), and (8) physical and economic insecurities (Stiglitz et al. 2009).

The above discussion suggests that it is possible to derive a set of universally essential constituents of human well-being, although some of them may be difficult to measure. Most of them can be related to the elements of Maslow's hierarchy, but are not necessarily organized hierarchically. Also, Maslow's hierarchy of needs focuses on the individual level, but the recent discussions on human well-being are relevant to organizational levels beyond the individual as well. It is evident that human well-being has both objective and subjective dimensions that are both essential (Stiglitz et al. 2009). Naveh (2007), an eminent landscape ecologist and premier proponent for landscape sustainability, stated: "We will have to consider not only the material and economic needs of the people, but also their spiritual needs, wants, and aspirations, their dignity and equity." All these key concepts and ideas of sustainability need to be integrated in a comprehensive and cohesive framework. Daly (1973) developed such framework 40 years ago, widely known as the "Daly Triangle" (Fig. 3), which was further refined by others (Meadows 1998). From a strong sustainability perspective, Daly's Triangle clarifies the relationship among the key sustainability dimensions and constituents, in which the natural environment is viewed as the "ultimate means" to achieve the "ultimate ends" of human well-being (including equity). Economy, technology, politics, and ethics are not "ends" themselves, but "intermediate means" to bridge the ultimate means and ends (Fig. 3) (Meadows 1998).

Ecosystem services

While the ultimate goal of sustainability is to improve and maintain human well-being, this goal cannot be achieved without simultaneously protecting the earth's life-support system. Levin (2012) pointed out that "Sustainability means many things … [it] includes the stability of financial markets and economic systems, of reliable sources of energy, as well as of biological and cultural diversity. At the core, though, it must mean the preservation of the services that we derive from ecosystems." Similarly, Perrings (2007) pointed out that "the main scientific challenge of sustainability is to learn the dynamics of complex coupled systems without compromising their ability to deliver the things that people value." This view is consistent with the 1987 Brundtland Report, the 1999 NRC report, and the 2005 Millennium Ecosystem Assessment report. What key elements and processes of the earth's life-support system does human well-being depend on, and should thus be a focus of sustainability research and practice? During the past two decades, the term "ecosystem services" has taken a central stage in this discourse, especially since the release of the MEA report in 2005, as ecosystem services have been considered, increasingly, as a crucial bridge between the environment and society, as well as forming a keystone concept in conservation, resource management, and ecological and environmental economics (Costanza et al. 1997; Daily 1997; Perrings 2005; Braat and de Groot 2012; de Groot et al. 2012). While the importance of ecosystem services to human well-being is evident, we also need to understand that nature's ecological patterns, processes and changes are as important in their own context, whether the human population is a billion, hundred, one, or zero (Forman 2013, *personal communication*).

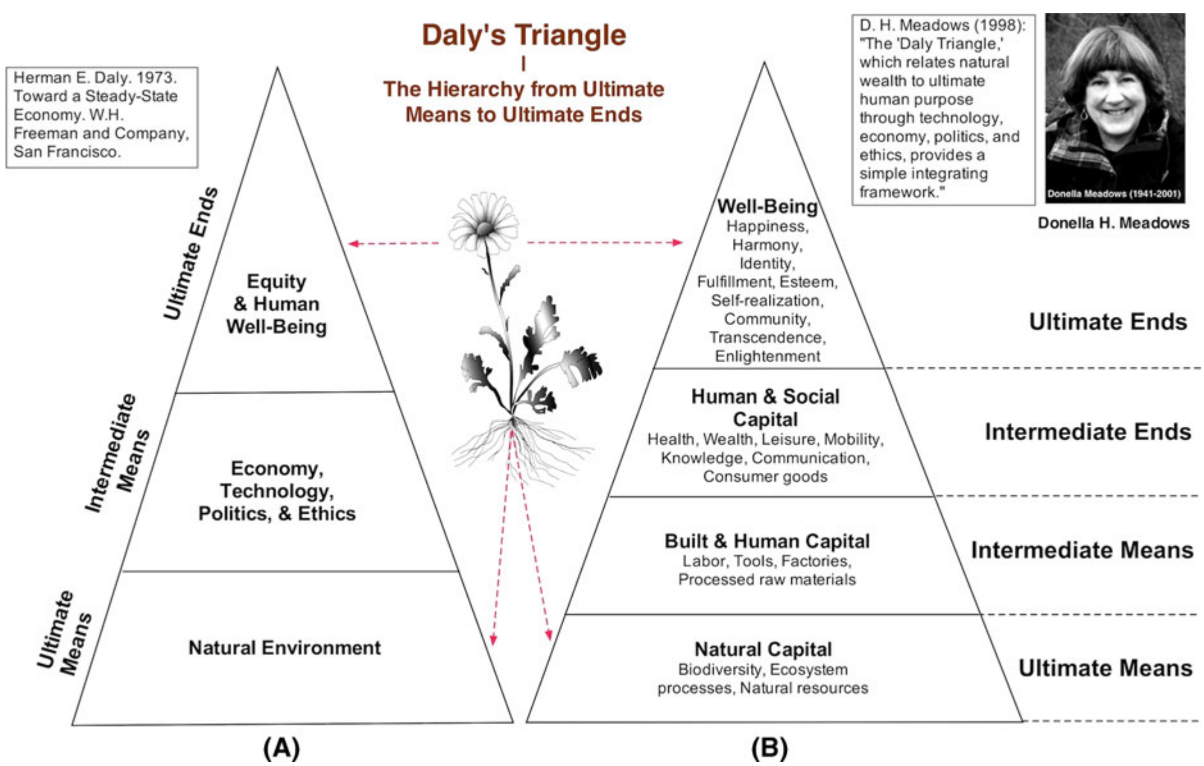

Fig. 3 The Daly Triangle, a strong sustainability framework that explicitly links the concepts of the triple bottom line, the hierarchy of human needs, and the different forms of capital. **a** The original version (redrawn from Daly 1973) and **b** the refined version (modified from Meadows 1998)

Currently, the most widely-cited definition of ecosystem services is from MEA (2005): "ecosystem services are the benefits people obtain from ecosystems" that are complex in structure and function, various in size, and dynamic in time. Although there are different ways of categorizing ecosystem services, much of the current literature follows MEA's (2005) classification that groups them into four types: (1) "provisioning services" (e.g., food, water, fiber), (2) "regulating services" (e.g., purification of air and water, regulation of climate, floods, diseases, hazard, and noise), (3) "cultural services" (e.g., recreational, spiritual, religious and other nonmaterial benefits), and (4) "supporting services" (e.g., soil formation, primary production, and nutrient cycling). Supporting services are the basis for all other ecosystem services (MEA 2005), and essentially refer to ecosystem processes and functions. In addition to the MEA classification, de Groot (2006) identified a variety of ecosystem services based on five groups of ecosystem functions that produce them: regulation functions, habitat functions, production functions, information functions, and carrier functions. In a recent study of valuating global ecosystems and their services, de Groot et al. (2012) further recognized four types of ecosystem services: provisioning, regulating, habitat, and cultural services. In the current usage of the term, ecosystem services clearly include both "goods" and "services" provided by ecosystems.

No matter how ecosystem services are classified, they depend on ecosystem structures and functions (i.e., roles of ecosystem processes) which are influenced by biodiversity (Kinzig et al. 2002; Naeem et al. 2009; Fu et al. 2013). Biodiversity, in general, increases ecosystem functions such as primary production, soil nutrient retention, and resilience against disturbances and invasions. Consequently, biodiversity and ecosystem functions together determine the natural capital stock and profoundly affect the flows of goods and services from nature to human societies (Costanza and Daly 1992; Costanza et al. 1997; De Groot et al. 2002; Perrings 2005; Wu and Kim 2013). Thus, ecosystem services make it clear how human needs (and thus well-being) depend on the environment. Natural capital, ecosystem services, and Maslow's hierarchy of needs are conceptually linked, and this relationship can be operationalized in practice (Fig. 4), as demonstrated by Dominati et al. (2010).

Key definitions and concepts of landscape sustainability

Although landscape sustainability was recognized as a key research topic in landscape ecology more than a decade ago (Wu and Hobbs 2002), a generally accepted definition of it has been lacking. In fact, the

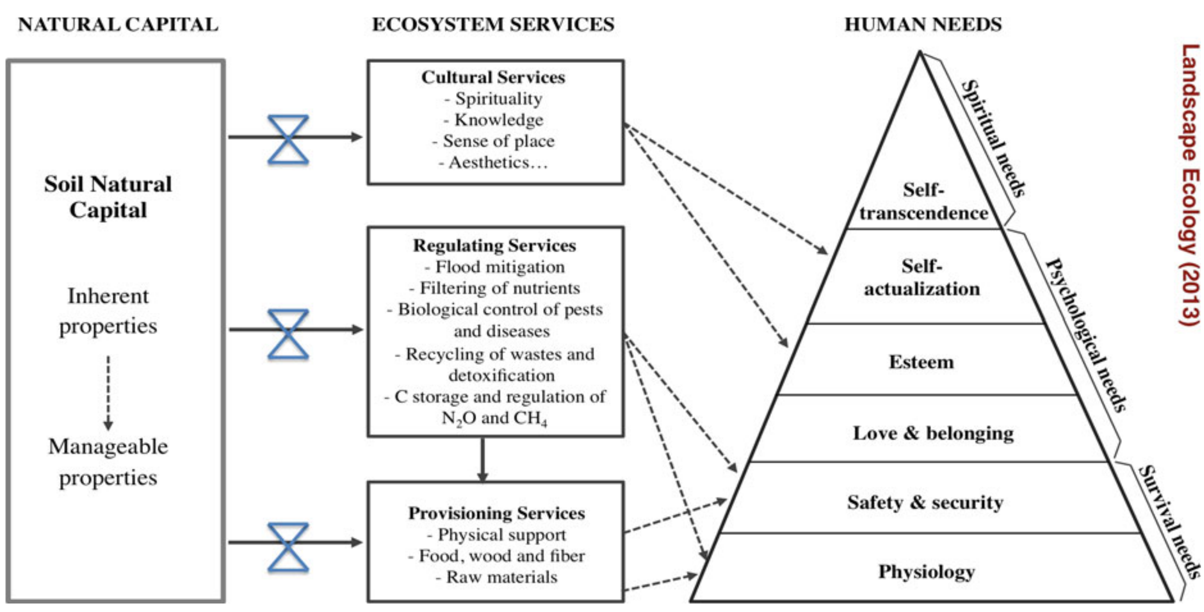

Fig. 4 The relationship among soil natural capital, ecosystem services, and human needs (modified from Dominati et al. 2010)

terms "sustainability," "sustainable landscapes," and "landscape sustainability" were not even commonly encountered in the mainstream ecology literature until several years ago (Wu 2013). These terms have occurred more frequently in the literature on landscaping, urban planning, and landscape architecture in general. As both "sustainability" and "landscape" have multiple connotations, the term landscape sustainability, not surprisingly, has acquired various definitions which differ in the dimensions of sustainability they emphasize as well as in the specific concepts they entail (Table 1). In the following sections, I discuss several existing definitions of landscape sustainability and related concepts.

What to sustain, what to develop, and for how long?

For a definition of sustainability to be meaningful, it needs to address four basic questions (NRC 1999; Kates et al. 2005): what is to be sustained, what is to be developed, how are these two aspects related to each other? On what scales should all these be considered? While most definitions of sustainability share a common concern for the future of the world, they differ substantially in how these questions are addressed. An increasingly dominant view is that biodiversity, ecosystem processes, and ecosystem services are to be sustained, human well-being (including economy) are to be developed, and that these two kinds of processes should be closely linked. For example, the US National Research Council defined "meeting human needs" as "providing food and nutrition, nurturing children, finding shelter, providing an education, and finding employment." To meet these basic human needs sustainably, "the quality and supply of fresh water, controlling emissions into the atmosphere, protecting the oceans, and maintaining species and ecosystems" must be ensured (NRC 1999). This view has become increasingly accepted as a fundamental principle of sustainability in the past decade.

Sustainability is inherently context-dependent, and the context is multifaceted—cultural, social, political, and, most ubiquitously, spatial. The landscape integrates all these facets into one holistic context—the landscape context. For the sustainability of a landscape, therefore, what is to be sustained, what is to be developed, and their interactions must be considered explicitly in relation to the biophysical and sociocultural composition and configuration of the landscape. Indeed, one may argue that the most effective spatial scale at which such placed-based, spatially explicit exploration can be done is the landscape (Forman 1990; Wu 2006, 2012).

On what time scale should sustainability be defined? Sustaining anything eternally is impossible. As Costanza and Patten (1995) put it, "nothing lasts forever, not even the universe as a whole." Consistent with hierarchy theory (Simon 1962; Wu and Loucks 1995; Wu 1999), the lifespan of a system should be commensurable with its time and space scale within the nested hierarchy of the world, so evolutionary and adaptive changes can operate (Costanza and Patten 1995). In the natural world, larger systems tend to have slower dynamics and greater longevity than smaller ones; in the artificial world, stable or resilient complex systems tend to have a modular structure that makes possible for order at a given organizational level to emerge out of disorder at lower levels (Levin 1999; Wu 1999). In the words of Costanza and Patten (1995), "Sustaining life requires death." Focusing on national and global scales and considering the feasibility for scientific and technological analysis, NRC (1999) suggested that an operational and realistic time scale for sustainability research and practice would be two generations (50 years). Kates (2011) seems to focus on sustainability issues within the period of a century.

In the current literature, however, the time scales for sustainability research range from one decade to several centuries. As discussed earlier, the time scales for sustainability research and practice should vary with the physical size and organizational level of the system, as well as the specific issues (e.g., ecological vs. evolutionary processes, micro- vs. macro-economic processes, and technological vs. cultural changes). For landscape sustainability, a scale domain of a few decades to a century seems sensible based on the characteristic scales of key processes supporting ecosystem services and human well-being. Beyond a century, uncertainties in environmental changes, technological breakthroughs, and shifts in human perceptions of a "good life" may render insurmountable barriers for any study to become more than just a fiction. Admittedly, some fictions may have useful insight into future possibilities.

Table 1 Definitions of landscape sustainability

Source	Definition	Key points
Forman (1995)	A sustainable landscape is "an area in which ecological integrity and basic human needs are concurrently maintained over generations. 'Sustainability' therefore is the condition where this is achieved or maintained. Adaptability, not constancy, is central to success"	In line with the Brundtland definition (WCED 1987); balance between ecological integrity and human needs; adaptability
Haines-Young (2000)	"A sustainable landscape is one in which the sum of the benefits (goods and services) people derive from the landscape area are maintained. It is also one in which our liabilities do not increase"	In line with MEA (2005); natural capital; ecosystem services; multiple alternative sustainable landscapes
Wu and Hobbs (2002)	A comprehensive definition of landscape sustainability should "incorporate the physical, ecological, socioeconomic, cultural, and political components of the landscape, with explicit expression of scale in time and space"	A holistic landscape ecology perspective; persistence of patterns and processes; landscapes as coupled human–environment systems
Odum and Barrett (2005)	A sustainable landscape is one that maintains "natural capital and resources to supply with necessities or nourishment to prevent falling below a given threshold of health or vitality"	Natural capital; thresholds
Potschin and Haines-Young (2006)	"A sustainable landscape is one in which the output of [ecosystem] goods and services is maintained, and the capacity of those systems to deliver benefits for future generations is not undermined…"	Natural capital; ecosystem goods and services; intergenerational equity
Dunnett and Clayden (2007)	Sustainable landscapes are "systems that are 'closed' i.e. to reduce direct energy or energy-demanding resource inputs and maximize internal cycling of materials and resources"	Maximize use of local resources; minimize imports; reduce, reuse, and recycle
Selman (2007)	"Landscape sustainability is characterized by 'ecological integrity' and 'cultural legibility', … sustainable cultural landscapes (unlike natural landscapes) will be characterized by a capacity to reproduce simultaneously their form, functions and meanings"	Self-regenerative capacity of landscapes; cultural legibility of landscape pattern; cultural identity and character
Nassauer and Opdam (2008)	A landscape that "sustainably providing ecosystem services while recognizably meeting societal needs and respecting societal values"	Ecosystem services, societal needs and values, landscape design
Selman (2008)	Five dimensions of landscape sustainability: environmental, economic, social, political, and aesthetic sustainability	Extension of the three-bottom line definition of sustainability; multiple ecosystem services; human wellbeing
Musacchio (2009)	"A sustainable landscape… represents a dynamic state of the system with multiple trajectories and outcomes and embodies multifunctionality, provides ecosystem services, and is resilient and adaptive." Landscape sustainability includes six dimensions: environment, economy, equity, aesthetics, experience, and ethics (six E's)	Extension of the three-bottom line definition of sustainability; landscape multifunctionality; design and planning
Power and Sekar (2011)	"A sustainable landscape is one that aspires to be resource self-sufficient and yield significant reductions in resource consumption and waste production while enabling the built landscape to support some natural ecological functions by protecting existing ecosystems and regenerating some ecological capacity where it has been lost"	Maximize self-sufficiency; minimize resource consumption; conservation and restoration; ecosystem services
Wu (2012)	Landscape sustainability is "the capacity of a landscape to maintain its basic structure and to provide ecosystem services in a changing world of environmental, economic, and social conditions"	Landscape resilience; landscape patterns and processes; ecosystem services
Cumming et al. (2013)	"Landscape sustainability can be viewed as the degree to which patterns and processes occurring within a landscape (and their interactions) can be expected to persist indefinitely into the future"	Persistence of landscape pattern and processes; spatial resilience

Table 1 continued

Source	Definition	Key points
Turner et al. (2013b)	"By sustainability, we mean use of the environment and resources to meet current needs without compromising the ability of system to provide for future generations; here, we deal specifically with the capacity of the system to deliver desired ecosystem services in the face of human land use and a fluctuating environment, now and in the future"	In line with the Brundtland definition (WCED 1987); ecosystem services; disturbances; resilience; spatial heterogeneity
Wu (2013)	Landscape sustainability is the capacity of a landscape to consistently provide long-term, landscape-specific ecosystem services essential for maintaining and improving human well-being in a regional context and despite environmental and sociocultural changes	Landscape-specific ecosystem services, human well-being, regional context, resilience, vulnerability

The Brundtland report-inspired definitions

A number of definitions of landscape sustainability have been derived from the Brundtland definition of sustainability for the landscape scale (e.g., Forman 1995; Odum and Barrett 2005; Turner et al. 2013b). Forman (1990) was among the first to recognize not only the importance of landscape sustainability but also the critical role that landscape pattern can play in achieving it. He stated that "for any landscape, or major portion of a landscape, there exists an optimal spatial configuration of ecosystems and land uses to maximize ecological integrity, achievement of human aspirations, or sustainability of an environment" (Forman 1990). In line with the Brundtland Report, Forman (1995) defined a sustainable landscape as "an area in which ecological integrity and basic human needs are concurrently maintained over generations." He further pointed out: "Adaptability, not constancy, is central to success" (Forman 1995), a viewpoint that is essential to resilience theory (Holling 1973, 2001; Cumming et al. 2013).

Dimensions of landscape sustainability

Landscape sustainability has also been defined on the basis of "sustainability dimensions" of the triple bottom line, with various derivations from interdisciplinary perspectives (e.g., Wu and Hobbs 2002; Selman 2008; Musacchio 2009, 2011). For example, Selman (2008) identified five dimensions of landscape sustainability: environment, economy, society, politics, and aesthetics. Selman (2007) also recognized "cultural legibility"—"retention and re-creation of typicity in land-based products—as being essential to landscape sustainability. Musacchio (2009) recognized six: environment, economy, equity, aesthetics, experience, and ethics (dubbed as 6 E's). She also defined a sustainable landscape as "a dynamic state of the system with multiple trajectories and outcomes and embodies multifunctionality, provides ecosystem services, and is resilient and adaptive" (Musacchio 2009). It makes sense to consider these additional dimensions when one attempts to translate the general TBL definition into a more specific one for landscapes. It is at the landscape scale that aesthetics and human experience with the land become undeniably important (Gobster et al. 2007; Barrett et al. 2009a, b). They are important components of cultural ecosystem services, and crucial for meeting human needs in the upper part of Maslow's hierarchy.

Definitions focusing on ecosystem services

A number of definitions of landscape sustainability have been centered on natural capital and ecosystem services (Haines-Young 2000; Odum and Barrett 2005; Potschin and Haines-Young 2006; Nassauer and Opdam 2008; Potschin and Haines-Young 2013; Turner et al. 2013b). Advocating that landscape ecology should be a society-centered science—a view that is in stark contrast with the prevailing paradigm in the field (Turner 2005)—Haines-Young (2000) argued that landscape sustainability is about maintaining the total amount of natural capital and associated ecosystem goods and services in a landscape without increasing people's liabilities (also see Potschin and Haines-Young 2006, 2013). This view may be seen as a derivation of the Daly Triangle (Fig. 3), and echoes some of the widely-cited studies on natural capital and ecosystem services (e.g., Costanza and Daly 1992; Costanza et al. 1997; Daily 1997). Haines-Young (2000) emphasized that "Sustainability should be measured or assessed by the change processes active in the landscape—not by the state the landscape is in at any one time," and that "a whole set" of spatial configurations of land cover are "more or less sustainable" for a given landscape. Furthermore, he noted that his view "counters" Forman's (1995) notion of optimal landscape pattern for sustainability. The existence of multiple stable states in complex systems, as well as focusing on change instead of equilibrium states for managing such systems, has long been recognized in the literature, particularly in terms of patch dynamics and the resilience of social–ecological systems (Holling 1973; Levin and Paine 1974; Wu and Loucks 1995).

Definitions focusing on "localization" and self-regenerative capacity

Some other definitions of landscape sustainability emphasize maximizing self-regenerative capacity and minimizing externalities (Dunnett and Clayden 2007; Selman 2007; Power and Sekar 2011). Loucks (1994) recognized that "Applying the ideas of sustainability … requires that we demonstrate and manage the regenerative capacity of the renewable elements in the city." Selman (2007) extended this idea explicitly to the landscape: "sustainable cultural landscapes (unlike natural landscapes) will be characterized by a capacity to reproduce simultaneously their form, functions and meanings." Dunnett and Clayden (2007) took this view to an extreme by defining sustainable landscapes as "systems that are 'closed' i.e. to reduce direct energy or energy-demanding resource inputs and maximize internal cycling of materials and resources." There is a large and expanding literature on minimizing ecological footprints, shrinking the size of urban metabolism, and reducing-reusing-recycling strategies for cities (Rees 2002; Newman et al. 2009; Weisz and Steinberger 2010), which is also relevant to landscape sustainability. Urban sustainability is not only related, but also essential, to the sustainability of landscapes and the planet as a whole (Rees 2002; Wu 2010).

Landscape resilience

Landscape resilience necessitates the explicit consideration of the composition and spatial arrangement of landscape elements, and is closely related to "spatial resilience"—defined as "the ways in which spatial variation in relevant variables, both inside and outside the system of interest, influences (and is influenced by) system resilience across multiple spatial and temporal scales" (Cumming 2011). Cumming et al. (2013) further defined landscape resilience as "the resilience of an entire landscape, viewed as a spatially located complex adaptive system that includes both social and ecological components and their interactions." Turner et al. (2013b) discussed the importance of spatial heterogeneity for the resilience of forested landscapes, particularly with respect to the provision of ecosystem services in the face of changing disturbance regimes and climate change. These authors have defined resilience as "the capacity of a system to tolerate disturbance without shifting to a qualitatively different state," distinct from the concept of sustainability as the capacity of a system to provide, mainly, desired ecosystem services for current and future generations (Turner et al. 2013b).

Towards a science of landscape sustainability

To develop a mechanistic understanding of the dynamic relationship between society and nature, landscape ecology and place-based sustainability research are crucial (Kates 2003; Wu 2006; Turner 2010). In this section, I propose a working definition of landscape sustainability and a framework for moving toward a science of landscape sustainability. The framework, illustrated in Figs. 5 and 6, identifies system dimensions, core system constituents and their interactions, scales and cross-scale linkages, and key research topics.

A working definition of landscape sustainability

Following the discussions of the previous sections, a general yet operational definition of landscape sustainability should simultaneously capture the essence of sustainability and the key attributes of the landscape (Fig. 5). The essence of sustainability is to ensure meeting human needs now and in the future by continuously improving and balancing environmental

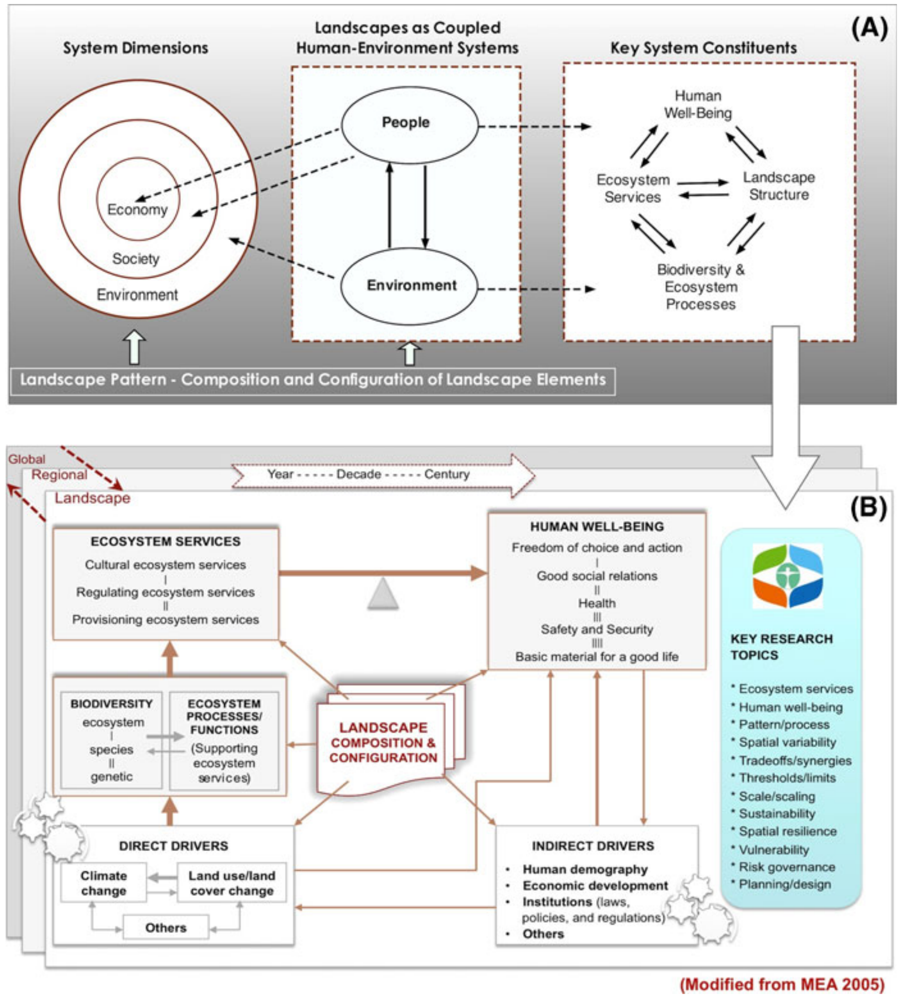

Fig. 5 A framework for landscape sustainability science, in which the landscape is conceptualized as a spatially heterogeneous, coupled human–environment system from a strong sustainability perspective, and with a focus on the nexus of ecosystem services and human well-being (**a**). Key components, interactions, drivers, and research topics are illustrated in **b**, which is modified from MEA (2005)

integrity, economic vitality, and social equity. The key attributes of a landscape include the composition (kinds and amounts), configuration (shape, connectivity, and spatial arrangement), and dynamics of the landscape mosaic. A common theme has rapidly emerged during the past decade that general sustainability goals can be translated into more specific operations by focusing on the dynamic relationship between ecosystem services and human well-being. As discussed above, major advances have been made in identifying the key constituents of these two reciprocal macro-variables of sustainability. But the quest for understanding the dynamic relationship between the two—the gist of sustainability science—has just begun.

A working definition of landscape sustainability may be stated as follows: landscape sustainability is the capacity of a landscape to consistently provide long-term, landscape-specific ecosystem services essential for maintaining and improving human well-being in a regional context and despite environmental and sociocultural changes (Fig. 5). This definition recognizes meeting human needs as the ultimate goal of landscape sustainability and focuses on essential ecosystem services by adopting a strong sustainability perspective. Sustainability here includes both enhancing resilience and reducing vulnerability—which are related but not always the same (Gallopin 2006; Turner 2010). "Landscape-specific" here has two meanings: (1) different types of landscapes provide different kinds and amounts of ecosystem services that demand different management strategies (Fig. 6), and (2) landscape pattern creates, mediates, and impedes ecosystem services. "Capacity" here includes adaptability, and "consistently" and implies that landscape sustainability requires not only resilience at the landscape level but also stability for certain key

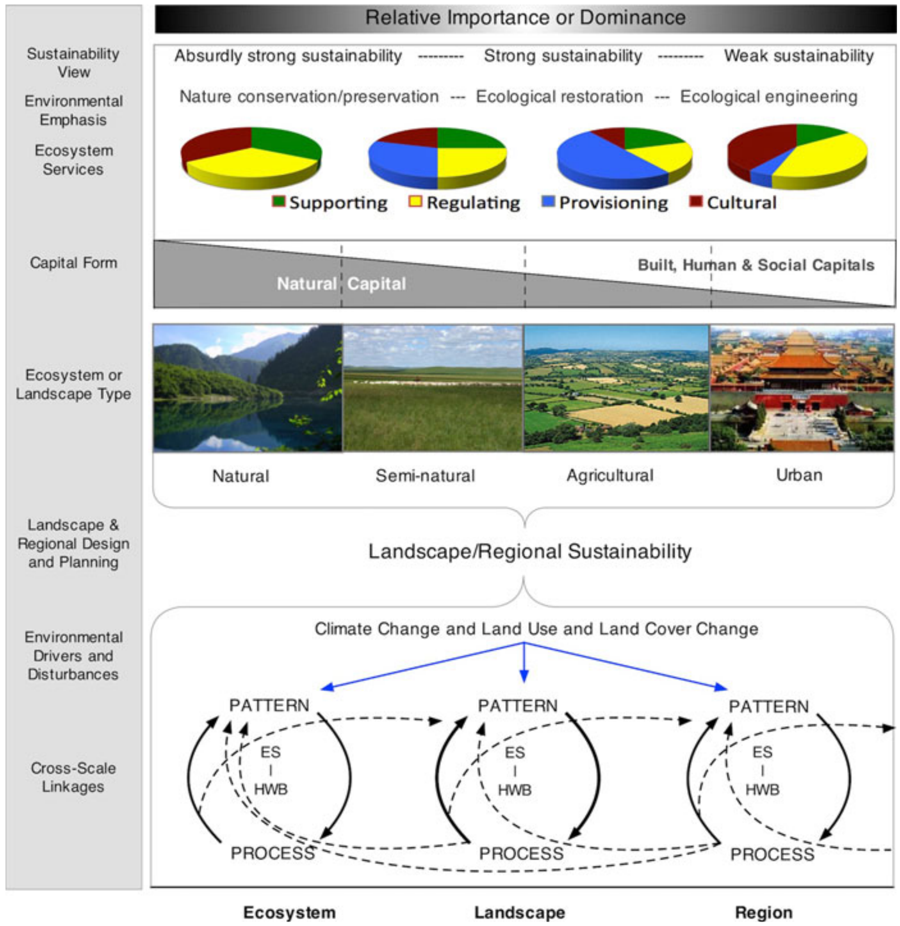

Fig. 6 Relative importance of different sustainability views (strong vs. weak), forms of capital, types of ecosystem services, and environmental actions among different landscapes (*up*), and the scale multiplicity of landscape and regional sustainability (*bottom*). Note that the proportions of the different ecosystem services for each landscape are not meant to be numerically precise, but rather illustrate their relative abundance across landscapes with various degrees of human modifications in a given geographic region. The illustration of cross-scale linkages is modified from Fig. 5.1 in Charles (2009), in which ES denotes Ecosystem Services and HWB stands for Human Well-Being

landscape elements (e.g., those providing food, water, and essential cultural services). "Long-term" encapsulates a timeframe of a few to several generations (decades to a century), in general. The "regional context" emphasizes that landscape sustainability affects, and is affected by, regional (and global) sustainability—landscape sustainability is inherently a multi-scale concept (Figs. 5, 6). From a hierarchical patch dynamics perspective, landscape sustainability is related to landscape metastability—a shifting mosaic steady state in which macro-level structural and functional patterns are maintained through constant micro-level changes (Wu and Loucks 1995).

A framework for landscape sustainability science

What is landscape sustainability science?

Landscape sustainability science (LSS) is a place-based, use-inspired science of understanding and improving the dynamic relationship between ecosystem services and human well-being with spatially explicit methods. It is the science of landscape sustainability as defined in the previous section. This definition is in line with Turner's (2010) recognition that CHES, ecosystem services, and services-human outcome tradeoffs are the three foundational pivots of sustainability science. LSS addresses core research questions in sustainability science in direct relation to landscape composition and configuration (Fig. 5). A background assumption in LSS is that the dynamic relationship between ecosystem services and human well-being is affected by, and affect, landscape pattern, no matter how this relationship or its components may be expressed (e.g., in terms of resilience, vulnerability, or sustainability). Casting sustainability research in the landscape perspective is essential because "it is in specific regions, with distinctive social, cultural, and ecological attributes, that the critical threats to sustainability emerge and in which a successful transition needs to be based" (Kates 2003). Complex adaptive systems, spatial resilience, and vulnerability (and robust) analysis provide an important theoretical and methodological foundation for advancing landscape sustainability science.

Relationship to landscape ecology

Landscape sustainability science is obviously related to landscape ecology (Potschin and Haines-Young 2006; Wu 2006; Naveh 2007; Turner et al. 2013a), but they are not the same. Potschin and Haines-Young (2006) advocated an "alternative paradigm for landscape ecology, based on the concept of ecosystem goods and services, or natural capital," and claimed that landscape ecology needs to "shift away from an ecological focus … to a more anthropocentric one." Naveh (2007) called for a "transformation of landscape ecology into a transdisciplinary science of landscape sustainability," partly by abandoning "chiefly outdated mechanistic and positivistic scientific paradigms" and focusing on "goal-oriented and mission-driven" projects. However, I wonder: What would landscape ecology be without an ecological focus? What kind of science would landscape ecology be if all mechanistic and hypothetico-deductive methods are intentionally kept out?

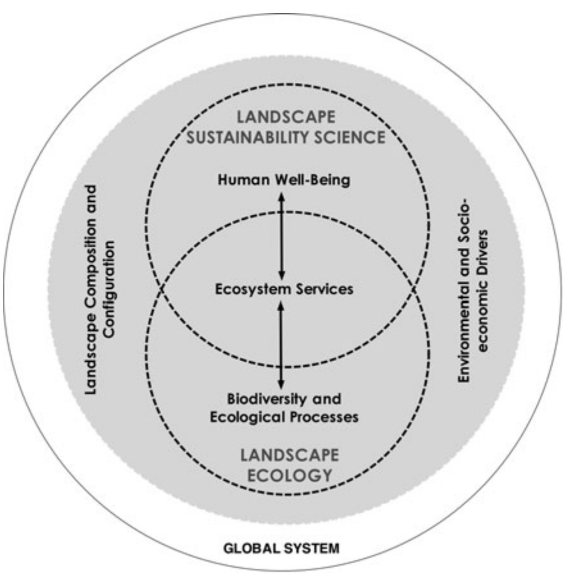

Fig. 7 Relationship between landscape sustainability science and landscape ecology

While I concur that landscape ecology needs to embrace sustainability as an essential part of its science and application (Wu 2006, 2010), I also believe that recognizing the distinction between landscape ecology and LSS is necessary and important. Landscape ecology is the science of studying and improving the relationship between spatial pattern and ecological processes, while landscape sustainability science focuses on the dynamic relationship between ecosystem (or landscape) services and human well-being in changing social, economic, and environmental conditions (Fig. 7). They overlap in research elements, especially for human-dominated landscapes, but differ in research emphasis and outcomes. Both fields emphasize the effects of spatial heterogeneity or landscape pattern, as well as environmental, socioeconomic, and cultural drivers and processes. Ecosystem services provide the primary nexus of the two research fields (Fig. 7). The past decade has seen increasing interactions between the two, and this trend will inevitably continue into the future. To move both fields forward, a hierarchical, pluralistic perspective that integrates reductionist and holistic approaches would help in theory and practice (Wu 2006).

Core research components and main theme

The core components of LSS are ecosystem services, human well-being, and landscape pattern (Fig. 5). The research focus of LSS should be the dynamic relationship among the three core components. In order to understand this dynamic relationship, biodiversity and ecosystem processes in the heterogeneous landscape, as well as climate change, land use change, and other socioeconomic drivers must be considered explicitly. Landscape pattern has pervasive influences on every aspect of landscape sustainability. Thus, the main theme of LSS in theory, methodology, and applications is the paramount emphasis on spatial heterogeneity, context-dependent relationships, and spatial tradeoffs and synergies of, and between, ecosystem services and human well-being. A central research question of LSS is how landscape pattern affects the long-term maintenance and improvement of the ecosystem services and human well-being relationship in the face of uncertainties arising from internal dynamics and external disturbances.

While it is widely accepted that ecosystem services are essential to human well-being, how ecosystem services affect the different aspects of human well-being remains poorly understood. For example, MEA (2005) showed that, at the global scale, the general level of human well-being, as measured by Human Development Index (HDI; consisting of three components: life expectancy, GDP per capita, and education), has steadily increased in spite of the well-documented declining trend in ecosystem services during the past several decades. Raudsepp-Hearne et al. (2010) termed this phenomenon as the "environmentalist's paradox" and attributed this seemingly contradictory trend to the prepotency of provisioning services to supporting, regulating, and cultural services, time lags, and separation of humans from nature due to technology and social innovation. However, "the link between ecosystem services and human well-being should occur at finer spatial scales, suggesting that using global statistics makes little sense" (Duraiappah 2011).

A better understanding of this so-called paradox requires scrutiny with more detailed data at local and regional scales. In fact, landscape features, including physical, social, and cultural environments and amenities, have been shown to influence the physical activities and health, as well as self-esteem and psychological health, of people living in the landscape (Macintyre et al. 1993, 2002). In addition, spatial heterogeneity is more than likely to affect the relationship ecosystem services and human well-being. Also, HDI measures mainly physical well-being, with psychological well-being largely ignored and, in general, ecosystem services do not provide for all human needs (Dominati et al. 2010; Duraiappah 2011). The provision of ecosystem services does not guarantee the satisfaction of human needs; furthermore, the latter does not necessarily lead to improved human well-being or happiness, neither. Placed-based landscape studies are essential to understanding the meanings of, and relationships among, these related but distinctive aspects of sustainability.

A central assumption behind a landscape approach is that spatial heterogeneity is important. The view that landscapes have "optimal" or more desirable patterns for promoting sustainability does not mean that we naively seek a "static" landscape state in sustainability research and practice. As Forman (1995) pointed out, "A sustainable condition or environment may be impossible… Therefore, it may be better to consider 'sustainability' as a direction or trajectory, rather than a specific end point." This perspective may be, and has been, interpreted as equating landscape sustainability to maintaining a static landscape structure (e.g., Haines-Young 2000; Potschin and Haines-Young 2006). Such interpretation may suggest that landscape sustainability is a "utopian goal" irrelevant to particular landscapes (Antrop 2006), an attempt to maintain landscape pattern and process "indefinitely into the future" or "business as usual" (Cumming et al. 2013), or simply a useless concept (Wiens 2013). However, if landscape pattern is important to biodiversity and ecological processes, which is a fundamental assumption for modern landscape ecology, it must also be important to the generation and delivery of ecosystem services across the landscape. Thus, it follows that there must be some landscape configurations that are more desirable than others for improving and maintaining ecosystem services and human well-being. Then, how to identify and design desirable landscape configurations has to be a central question in landscape sustainability research.

Landscape sustainability spectrum

While much of the discussion on sustainability implicitly assumes equal importance of the human and environmental (sub)systems, it is necessary to recognize that, at the landscape scale, the relative importance of sustainability components or criteria may vary with landscape types. All landscapes—natural, semi-natural (e.g., grazing lands), agricultural, and urban landscapes—provide ecosystem services, but they differ in the kind, amount, and quality of services provided (Fig. 6). In an already human-dominated world, natural landscapes are increasingly rare and precious as they are essential to maintaining biodiversity, ecosystem processes, and ecosystem services on the regional and global scales (e.g., the extensive landscapes from the Tibetan Plateau to the Arctic and the Antarctic, as well as numerous smaller ones scattered in the sea of other landscapes across the world). Many of these natural landscapes are under increasing stress from development. An absurdly strong sustainability view is needed to protect natural landscapes from development, and their non-substitutable role in providing supporting, regulating, and cultural ecosystem services should be valued at the landscape, regional, and global scales.

All non-natural landscapes are the quintessential examples of CHES, but the kinds, relative amounts, and interactions of ecosystem services also vary substantially among them (Fig. 5). From natural to semi-natural, agricultural, and urban landscapes, natural capital tends to decrease, but built, human, and social capital tend to increase (Fig. 6). In general, for a given region natural landscapes provide critically important supporting, regulating, and cultural services in large amounts; agricultural landscapes maximize in provisioning services (particularly food), with substantial proportions of other services; and urban landscapes are often dominated by cultural (e.g., recreation, positive psychological and mental effects) and regulating services (purifying air and water, mitigating urban heat island effects). Many semi-natural grazing landscapes around the world (e.g., the Mongolia grassland in Eurasia and the Serengeti in Africa) not only have important supporting, provisioning, and regulating services, but also provide unique and significant cultural services for the local (often minority) people. These general trends also apply to different ecosystems within a landscape (Fig. 6).

Thus, sustainability at the regional scale requires planning and design to "optimize" the spatial pattern of different landscape types. It is mathematically impossible to identify the best solution for a complex nonlinear system that usually has multiple solutions similarly effective or "optimal" in terms of system functionality. Thus, the word, optimize, here does not means to find "the best" solution, but rather to seek a set of solutions that lead to more desirable landscape outcomes than other alternatives. In this sense, meshing different types of landscape elements to optimize the ecosystem services portfolio for satisfying human needs is imperative for landscape sustainability. In Forman's (2008) words: "Mold the land so nature and people both thrive longterm." Landscape sustainability is enhanced by, or requires, localization of human demands for ecosystem services attuned to the particular landscape setting (Reitan 2005; Selman 2009). Landscape multi-functionality is key to the sustainability of many urban and agricultural landscapes (Lovell and Johnston 2009; Termorshuizen and Opdam 2009; O'farrell and Anderson 2010). While "localization" and "regionalization" are key to landscape and regional sustainability, we must be cognizant that "Local sustainable solutions often have externalities when considered within larger regions or the globe" (Verburg 2013, *personal communication*). For coupled human–environment systems to achieve strong sustainability at the landscape or regional scale, it is often necessary to allow for substitution among the different forms of capital (weak sustainability) at a lower scale. In general, patterns and processes from local ecosystems to the entire globe hierarchically influence the sustainability at the landscape and regional scales (Figs. 5, 6).

Key research questions

To move forward, it is useful to identify some of the key research questions of LSS. Because LSS is part of sustainability science, the core questions for LSS ought to be closely related to those for the latter. In a seminal paper, Kates et al. (2001) identified seven "core questions" for sustainability science, which has played an important role in advancing the filed. Similarly, Levin and Clark (2010) identified six "fundamental questions" for sustainability which highlight the importance of tradeoffs between human well-being and the environment, adaptability, long-term consequences of human–environmental interactions, theory and models, and sustainability assessment. Based on the seven core questions originally published in 2001 (Kates et al. 2001) and the six fundamental questions by Levin and Clark (2010), Kates (2011) provided a revised list:

(1) What shapes the long-term trends and transitions that provide the major directions for this century?
(2) What determines the adaptability, vulnerability, and resilience of human–environment systems?
(3) How can theory and models be formulated that better account for the variation in human–environment interactions?
(4) What are the principal tradeoffs between human well-being and the natural environment?
(5) Can scientifically meaningful "limits" be defined that would provide effective warning for human–environment systems?
(6) How can society most effectively guide or manage human–environment systems toward a sustainability transition?
(7) How can the "sustainability" of alternative pathways of environment and development be evaluated? (Kates 2011, p. 19450).

To make these questions directly relevant to LSS, one only needs to rephrase them in terms of ecosystem services and human well-being in dynamic heterogeneous landscapes. Along this line, Turner et al. (2013b) proposed "five general research questions" for landscape sustainability science, highlighting the importance of landscape heterogeneity in the production, tradeoffs and synergies, vulnerability, and resilience of ecosystem services, as well as landscape legacy effects on ecosystem services. The next decade, I am sure, will see a surge of efforts to address and further refine these important questions from the perspective of LSS.

Major research approaches

To answer these key questions, spatially explicit methods, especially experimental and spatial modeling approaches, are essential. Methods from various social and economic sciences must be part of the toolbox for advancing LSS. Spatial methods have been widely used in landscape ecology during the past 30 years (Turner and Gardner 1991; Turner et al. 2001; Wu 2013), but a major challenge is to use these methods innovatively and interactively to address questions involving both ecosystem services and human well-being.

In this case, bridging concepts and integrated models are often helpful and even necessary. For example, "landscape services" seems an extremely apt bridging concept that links landscape pattern, ecosystem services, aesthetics, values, and decision-making through a "structure–function–value chain," and thus it promotes participatory research and sustainable landscape planning (Termorshuizen and Opdam 2009). Compared to the concept of ecosystem services which focuses mainly on ecosystems individually without consideration of their spatial interactions, Termorshuizen and Opdam (2009) argued that landscape services better conveys the idea that ecosystem services are not only spatially heterogeneous but also interactive (resulting in tradeoffs and synergies), so that certain services (or "disservices") are generated by the spatial configuration of multiple ecosystems across a landscape (e.g., pest control, flood control, and urban heat island mitigation through properly placing landscape elements). In other words, these are "emergent" ecosystem services at the landscape scale. From the perspective of LSS, the term "landscape services" makes perfect sense. Even though it is unlikely to replace the term "ecosystem services," which now enjoys unprecedented popularity, the idea of landscape services is at the core of LSS.

Experimental approaches are indispensable for fully addressing key questions in LSS and, indeed, for its advance toward maturity. Despite their commonly recognized logistic and conceptual challenges, landscape ecological experiments have been widely and increasingly conducted in recent decades, and provided unparalleled mechanistic evidence for understanding pattern-process relations (Jenerette and Shen 2012). Such experimental studies are useful, especially when ecosystem services are explicitly incorporated, but landscape sustainability experiments must go beyond the traditional domain of thinking and doing with experimentation. In traditional experiments treatment, control, and replication are equally important, and common statistical methods are usually adequate for analyzing the results. However, landscape sustainability experiments need to hinge on, and to take advantage of, "design" because the criteria of control and replication can almost never be met in the sense of the classic experimentation.

"Design" here refers to the "intentional change of landscape pattern, for the purpose of sustainably providing ecosystem services while recognizably meeting societal needs and respecting societal values" (Nassauer and Opdam 2008). We need to consider designed landscapes as experiments, and treat "design" as part of the process of doing landscape sustainability science—creating, testing, and evaluating hypotheses (Golley and Bellot 1991; Nassauer and Opdam 2008; Ahern 2013; Swaffield 2013). This can be done by comparison between different designed landscapes as well as between designed and more natural landscapes. Longitudinal experiments for planned or designed landscapes, evaluated using Baysian or other advanced statistical methods should also be valuable. In addition, controlled experiments using spatially explicit simulation models have proven feasible and insightful, especially in combination with plausible planning and decision-making scenarios. Thus, while three types of research and design interactions in landscape architecture—"research for design," "research on design," and "research through design" (Lenzholzer et al. 2013)—are all relevant, it is the research through design perspective that needs to be greatly emphasized in LSS experiments. True landscape sustainability experiments may never reach the rigor of reductionist experiments, but with assistance of advanced statistical methods and simulation modeling they should play a crucial role in advancing LSS.

New mapping and modeling methods have emerged to "spatialize" ecosystem services research (Bohnet et al. 2011; Kareiva et al. 2011; Koniak et al. 2011; Bagstad et al. 2012; Johnson et al. 2012; Verburg et al. 2012; Wu and Kim 2013). For example, the Service Path Attribution Networks (SPANs), a group of agent-based models, provide a spatial framework for mapping and quantifying the sources, sinks, and flows of ecosystem services in a heterogeneous landscape, as well as exploring and testing different landscape-based scenarios for sustainability planning and decision-making (Bagstad et al. 2012; Johnson et al. 2012). Wu and Kim (2013) developed a capital-theoretic framework based on the "Inclusive Wealth" approach (Arrow et al. 2004; Dasgupta 2009) to quantify the economic relationship between ecosystem resilience and provisioning of ecosystem services. This framework integrates a number of key concepts in LSS, including ecosystem resilience, disturbances, natural capital, ecosystem services, ecosystem valuation, ecological restoration, and ecosystem management (Wu and Kim 2013). Also, developed originally in landscape and environmental planning, alternative futures analysis provides a powerful way of exploring the environmental and socioeconomic consequences of plausible future scenarios of land use and development (Steinitz et al. 1996; Neale et al. 2003; Baker et al. 2004; Bolte et al. 2006; Hulse et al. 2009; Bryan et al. 2011). Recently, Turner et al. (2013b) have proposed a so-called "land system architecture" approach which "expands the reach of landscape architecture beyond the urban/peri-urban 'built' environments and local environmental concerns of the planning communities, linking to the spatial dimensions of landscape ecology but with attention to human outcomes beyond the impacts of changes in ecosystem services per se." To achieve the ultimate goal of LSS, all these geospatial modeling approaches will be essential.

Finally, to gauge and guide landscape sustainability, it is necessary to develop reliable landscape sustainability indicators. Landscape pattern metrics are only useful when they have proven and reliable relationships to landscape functions and services or measures of human well-being. Thus, LSS indicators should incorporate knowledge of the variability, thresholds, drivers, mechanisms, and cross-scale linkages of landscape functions and services, and should also be relevant to human well-being and policy-making (Mander et al. 2005; Coelho et al. 2010; Morse et al. 2011; Palmer and Febria 2012; Wu 2012). Meeting all these criteria is a tall order. Landscape ecologists have much to offer from their experience with landscape pattern analysis and also much to learn from the enormous literature on sustainable development indicators (Wu 2012; Wu and Wu 2012). For example, it is worthwhile to explore how landscape metrics can be incorporated into sustainability assessment methods to produce landscape-specific indicators. For developing comprehensive yet operational indicators at the landscape level, the "inclusive wealth" framework that integrates manufactured with natural capital (Arrow et al. 2004; Dasgupta 2009; UNU-IHDP and UNEP 2012) may prove useful. As we move forward with LSS indicators, we should be mindful of Meadows' (2001) shrewd observation: "Not only do we measure what we value, we also come to value what we measure."

Concluding remarks

Landscapes are places where people live and work, and where ecosystems reside and provide services to people. Thus, landscapes represent, arguably, the most operational scale for understanding and shaping the relationship between society and the environment. Landscape sustainability links local actions to the regional and global context, and landscape sustainability science, although still in its infancy, will be an integral part of sustainability science. In the same time, landscape sustainability science is intrinsically related to landscape ecology, with ecosystem services as the key nexus. Focusing on human well-being and ecosystem services in changing landscapes, LSS should also recognize the values of ecosystems to nonhuman species; focusing on the landscape, LSS should also deal with between-landscape connections and continental and global linkages; focusing on use-inspired and placed-based studies, LSS should also emphasize fundamental research and well-established scientific methods whenever possible.

From hunters–gatherers to agrarians, and thence to urbanites, humans have profoundly transformed their landscapes, and greatly diversified and elevated their needs and wants. Consequently, the meanings of well-being and sustainability have changed and continue to change. Fundamentally, well-being is more of a journey than a destination, and accordingly sustainability is more of a process than a state. Thus, landscape sustainability is a constantly evolving goal. We cannot predict it precisely; we cannot fix it permanently; but we must, and we can, make our landscapes sustainable by continuously improving the human–environment relationship based on what we know and what we are learning. As Meadows (2001) said so elegantly, we cannot fully understand, predict, or control complex systems, but we can envision, design, and dance with them!

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