A Landscape Approach for Sustainability Science

Jianguo (Jingle) Wu

Abstract The global life-support system for humans is in peril but no alternative to achieving sustainability is desirable. In response to this challenge, sustainability science has emerged in recent decades. In this chapter, I argue that to advance sustainability science a landscape approach is essential. Landscapes represent a pivotal "place" in the place-based research and practice of sustainability. Landscape ecology, as the science and art of studying and influencing the relationship between spatial pattern and ecological processes at different scales, can play a critically important role in the development of sustainability science. Global sustainability cannot be achieved without most, if not all, landscapes being sustainable. As landscapes are spatial units in which society and nature interact and co-evolve, it is more useful and practical to define landscape sustainability based on resilience rather than stability. Furthermore, the development of landscape sustainability measures can be facilitated by integrating landscape pattern metrics and sustainable development indicators.

Keywords Landscape sustainability • Sustainability science • Human–nature interactions • Sustainability metrics

Introduction

> This traditional dichotomy of humanity-vs.-nature is false and dangerous. On the one hand, it perpetuates our destructive mishandling of the biosphere. On the other hand, it scants the self-understanding that Homo sapiens needs to settle down on our home planet, hence as a

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> prerequisite to survival. Nature, to put the matter as succinctly as possible, is part of us, and we are part of nature
>
> E. O. Wilson (2007)

Human activities have transformed ecosystems and landscapes profoundly around the world, and the entire biosphere has been influenced in fundamental ways (Kareiva et al. 2007; Wu 2008). In search of solutions to a myriad of environmental and social problems, sustainability has become the defining theme of our time (Kidd 1992; Kates et al. 2005; Du Pisani 2006). Sustainability concerns our ability to maintain coupled human–environmental systems in a desirable state for multiple generations in the face of anthropogenic and environmental perturbations and uncertainties. To meet the needs and challenges of sustainability, a new kind of science has emerged in the past 2 decades—sustainability science—that focuses on the dynamic interactions between society and nature (Kates et al. 2001; Clark and Dickson 2003; Clark 2007; Weinstein 2010). The ultimate goal of sustainability science is not just to understand the human–environment relationship, but rather to improve it through producing knowledge and solutions for management, planning, and policy that are needed for a transition toward sustainability. Thus, sustainability science has to be integrative and pluralistic. As Reitan (2005) put it, sustainability science is "the cultivation, integration, and application of knowledge about Earth systems gained especially from the holistic and historical sciences (such as geology, ecology, climatology, oceanography) coordinated with knowledge about human interrelationships gained from the social sciences and humanities."

Three salient characteristics seem essential to sustainability science. First, sustainability science is multidimensional and transdisciplinary. This means that it deals with the nexus of environment, economy, and society, with integrative approaches cutting across natural and social sciences (Kates et al. 2001; Wu 2006). Second, sustainability is multiscaled and hierarchically linked in space and time. Sustainability can be defined at any scale from a local site (e.g., a household or a biological community) to the entire globe, although only the local, regional, and global scales have frequently appeared in the sustainability literature. Regardless of its specific definition, the sustainability of a system varies with scale in space and time and, as in other hierarchical systems, processes at different scales are linked in both bottom-up and top-down directions (O'Neill et al. 1986; Wu and Loucks 1995; Wu 1999). So, we not only need to ask the questions of what to sustain and what to develop, but also over what area and for how long. Third, sustainability science emphasizes use-inspired, placed-based research. Real-world problems occur in "places" and we must go "places" to understand and solve them. As Kates (2003) stated, "Sustainability science is regional and place based. …, 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." This does not simply mean that sustainability science is an "applied" discipline; it is a transdisciplinary enterprise that bridges the traditional divide between basic and applied research by focusing on use-inspired and place-based problems (Clark 2007).

If the "place" in sustainability science is essential, then what is the "place?" Kates (2003) asked the same question: "What constitutes an appropriate classification of place? In part, the distinction is surely one of scale, and a grand query of sustainability will be these scale relationships." So, defining "place" in sustainability research is critically important to effectively dealing with the issues of scale and hierarchical linkages as well as integrating the environmental, economic, and social dimensions. In this chapter, therefore, I argue that, although "place" can be defined at any scale, "landscape" represents the most pivotal scale for sustainability research. I will first discuss what landscape is and then present a landscape perspective on sustainability, including conceptual and practical considerations.

Landscape as a Place for Sustainability

The term, "landscape," is a key concept in a number of fields, from social to geographical and ecological sciences. Because of the plurality of its origins and interpretations, landscape has acquired various connotations. The same word may refer to a natural landscape, a cultural landscape, a political landscape, an economic landscape, a mental landscape, an adaptive landscape, a landscape view, landscaping, or landscape painting (Fig. 1). "Landscape gives identity to place" and "landscape is where past and present meet" (Phillips 2007). Human geographers may think of landscape as "a work of human labor" or "an activity" of dynamic interactions between people and place (Mitchell 2000). As such, a landscape may also be

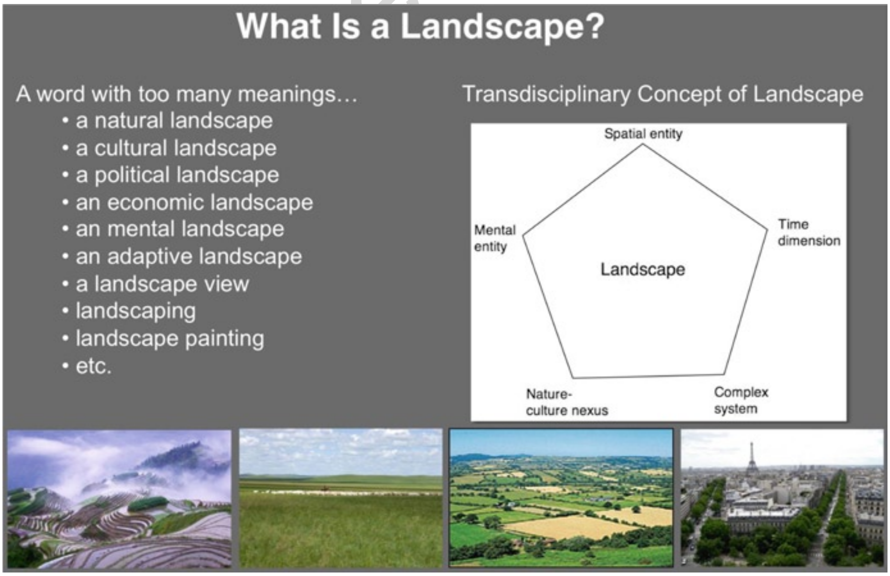

Fig. 1 A transdisciplinary concept of landscape based on discussion in Tress and Tress (2001)

considered as "a form of ideology" or "a way of carefully selecting and representing the world so as to give it a particular meaning," and thus it can be "an important ingredient in constructing consent and identity" (Mitchell 2000).

Geography has a long history of studying human–environment relationships, and a number of perspectives have been developed, with different research cores and methodologies that reflect a varying degree of affinity to either natural sciences or humanities (Turner 1997). The term, "cultural landscape," has been a fundamental concept in geography since its first use in Germany in the 1890s, referring to landscape modified by human activity as opposed to the primeval natural landscape. In his seminal publication, "The morphology of landscape," Sauer's (1925) defined cultural landscape as landscape "fashioned from a natural landscape by a cultural group." Since the 1960s, the concept of cultural landscape has been widely used in human geography (of which cultural geography is a part), anthropology, environmental management, and other related fields (Sauer 1925; Webb 1987). One of the major factors that contributed to the recent popularity of the term was the adoption of cultural landscapes in the International Convention for the Protection of the World's Cultural and Natural Heritage (or the World Heritage Convention) by the United Nations Educational, Scientific, and Cultural Organization (UNESCO) in 1992.

In the field of landscape ecology, the word "landscape" has different meanings. The main differences among various definitions reflect the different spatial scales at which a landscape is perceived and the different aspects of a landscape are emphasized (Wu and Hobbs 2007). For example, Forman and Godron (1986) defined landscapes as kilometers-wide geographic areas, which corresponds to the "human-perceived" landscape. This is the scale at which the field of landscape ecology was originally developed in Europe, and at which most landscape studies have been conducted ever since. This human-perceived landscape scale, in general, seems to coincide well with geographic units such as watersheds and urban regions (Forman 1995), as well as spatial domains of human perception (Gobster et al. 2007). Thus, it resonates with the public, the decision-makers, and researchers who are conscious about the environmental setting in which they live, work, and play.

However, most landscape ecologists consider landscape as a multiscale or hierarchical concept, meaning that a landscape is a spatially heterogeneous area of various sizes, depending on the subject of study and the research questions at hand (Urban et al. 1987; Wu and Levin 1994; Pickett and Cadenasso 1995; Turner et al. 2001). In this case, landscape is an "ecological criterion" (Pickett and Cadenasso 1995), and its essence does not lie in its absolute scale but in its internal heterogeneity. Different plant and animal species perceive, experience, and respond to spatial heterogeneity at different scales, and patterns and processes in landscapes tend to have different characteristic scales (Wu and Loucks 1995). Apparently, one does not need to consider a landscape of tens of square kilometers in order to study how the spatial patterning of grasses affects the movement of beetles (Wiens and Milne 1989) or is affected by gophers (Wu and Levin 1994).

Tress and Tress (2001) proposed a "transdisciplinary landscape concept" of landscape that encompasses five dimensions: (1) landscape as a spatial entity, (2) landscape as a mental entity, (3) landscape as a temporal dimension, (4) landscape as a nexus of nature and culture, and (5) landscape as a complex system (Fig. 1).

This is probably the most comprehensive of all landscape definitions. It is pertinent to cultural landscapes and implies a spatial scale that must be large enough to encompass key environmental, economic, and social processes that determine the sustainability of a place of interest. Following this notion, a landscape is more than just a geographic space as it has contents; a landscape is not merely a container as it shapes and is shaped by what it contains; a landscape is not just an environment modified by humans as it is a holistic system in which nature and culture co-evolve. Landscapes are endowed with and to foster the development of cultures, legacies, and stories. Today, most landscapes are "cultural landscapes" in which people interact or interfere with nature, whereas "natural landscapes" are found only as "islands" in an expanding sea of human land uses.

Scholars who study landscapes from either ecological or cultural perspectives seem to agree on the importance of landscape as an operational scale in sustainability research. For example, Forman (1990) argued that human-perceived landscapes, as a spatial scale for sustainable development, have significant advantages over broader scales such as the continent. Forman (1995) further pointed out that to deal with the "the paradox of management" (i.e., actions tend to be more effective at local scales whereas success often needs to be achieved at broader scales), "management and planning for sustainability at an intermediate scale, the landscape or region, appears optimum." The ordinary elements of human landscapes (e.g., forests, cropfields, urban land covers, residential areas, streams, and streets) also resonate well with human perception and thus facilitate decision-making (Nassauer 1997; Gobster et al. 2007). From a cultural geographer's perspective, Phillips (1998) commented that cultural landscapes are "places which can demonstrate that talk of sustainable development can be more than rhetoric."

In summary, the landscape represents a basic spatial unit of society–nature interactions and ought to be the primary "place" of study in sustainability science. It provides a multidimensional meeting ground for ecologists, geographers, social scientists, planners and designers, policy-makers who are all crucial to sustainability research. The landscape is large enough to incorporate key environmental, economic, and social processes and small enough to allow for in-depth and mechanistic studies that produce locally actionable solutions to sustainability problems.

Culture–Nature Relationship in Landscapes

As discussed in the previous section, landscapes, as commonly used in ecology and geography, represent a pivotal scale and place for sustainability. Beyond that, landscapes often shape, and are shaped by, the way we interact with nature. So, the structure and functionality of a particular landscape are reflective of the past and current relationships between humans and the environment in that region. As sustainability science is focused on the dynamic relationship between people and nature, landscapes have stories to tell, lessons to be learnt, and opportunities to offer.

Our perception and understanding of the relationship between people and nature in landscapes are often influenced by our philosophical roots and cultural traditions.

Fig. 2 Some key characteristics of sustainability science whose conceptual roots can be traced back to the ancient Chinese philosophy—the unity of man and nature. The focus of sustainability science is the dynamic relationship between nature and society, examined simultaneously from environmental, economic, and social dimensions at local, regional, and global scales. This transdisciplinary science is multiscale, multidimensional, and use-inspired and place-based. The unity of man and nature is its ultimate goal as well as its ancient philosophical root

These traditions represent the historical antecedent to the modern technocratic approach to social and economic development. As Phillips (1998) stated: "The separation of culture and nature—of people from the environment which surrounds them—which has been a feature of western attitudes and education over the centuries, has blinded us to many of the interactive associations which exist between the world of nature and the world of culture." In contrast, one of the most influential Asian philosophies on the relationship between culture and nature—the "Unity of Man and Nature" ("天人合一")—advocates that people should be in harmony [AU1] with the rhythms of nature (Chen and Wu 2009). Unity of Man and Nature was the quintessential theme shared by dominant ancient Asian cultures and has been described as the greatest contribution of Chinese culture to humanity (Ji 2007). While the contemporary roots of the concept of sustainability include the ideas of carrying capacity, biosphere conservation, and limits to growth (Kidd 1992), Unity of Man and Nature is one of its most relevant ancient philosophical roots (Fig. 2).

The theme of Unity of Man and Nature is evident in some seminal works by western environmental scientists and landscape architects. For example, in his landmark book, "A Sand County Almanac," the conservation ecologist Aldo Leopold (1949) advocated for "a state of harmony between man and land," and a new land ethic that "changes the role of *Homo sapiens* from conqueror of the land-community to plain member and citizen of it." The landscape architect Ian McHarg (1969) developed the "design with nature" approach, based on the premise: "Let us then abandon the simplicity of separation and give unity its due. Let us abandon the self-mutilation which has been our way and give expression to the potential harmony of man-nature." Tress et al. (2001) argue that "The perceived division between nature and culture has dominated the academic world," and "In the case of landscapes, this divide is counter-productive and must be overcome since all landscapes are multidimensional and multifunctional."

To unite culture with nature in landscapes and to advance a landscape-based science of sustainability, four principles articulated by Nassauer (1995) should be borne in mind when we formulate our research questions: (1) human perception, cognition, and values of the landscape directly affect, and are affected by, the landscape; (2) cultural conventions have profound influences on both human-dominated and apparently natural landscapes; (3) cultural concepts of nature may differ from scientific concepts of ecological function; and (4) the appearance of landscapes communicates cultural values. In our attempt to integrating culture and nature in landscapes, we need to fully recognize the necessity and opportunities of taking pluralistic and ecumenical approaches, as no single perspective or approach is sufficient to understanding human–environment relationships (Turner 1997).

Defining Landscape Sustainability

If landscapes are pivotal, then how should sustainability be defined? Before defining the sustainability of landscapes, some discussion on the conceptualization of the structure and organization of landscapes should be helpful. Everything is related to everything else, but some are much more related to each than most others; and complexity often takes the form of hierarchical or modular structure (Simon 1962; Wu and Loucks 1995). From this hierarchical perspective, the world is a nested hierarchical system, in which smaller spatial units (e.g., individuals and local populations) form larger spatial units (e.g., ecosystems and landscapes) that in turn make up even larger spatial units (e.g., biomes and the entire biosphere). Many ecological, as well as socioeconomic, systems may be viewed as hierarchical patch dynamic systems whose behavior is determined by pattern–process interactions at different scales (Simon 1962; Wu and Loucks 1995; Wu 1999; Wu and David 2002). Wu and Loucks (1995) articulated five key elements of hierarchical patch dynamics: (1) ecological systems are spatially nested patch hierarchies, (2) dynamics of an ecological system can be studied as the composite dynamics of individual patches and their interactions, (3) pattern and process are scale dependent, (4) nonequilibrium and random processes are essential to ecosystem structure and function, and (5) ecological (meta)stability is often achieved through structural and functional redundancy and spatial and temporal incorporation of dynamic patches.

Landscapes are spatially nested hierarchical patch systems as each landscape is composed of different kinds of patches that in turn comprise smaller patches. As such, the sustainability of landscapes is not only influenced by the interactions among environmental, economic, and social components, but also by their spatial configurations and cross-scale linkages. In a similar way but on broader scales, human-perceived landscapes or cultural landscapes form a pivotal level in the hierarchy of study objects in sustainability science, which may include local communities/ecosystems, landscapes, nations/regions, and the entire world. In this context, the sustainability of a landscape is influenced both by upper levels (constraints) and lower levels (initiating processes and driving forces). From a hierarchical patch dynamics perspective, landscape sustainability is similar to landscape metastability—a shifting mosaic steady state in which macro-level structural and functional patterns are maintained through constant micro-level changes (patch dynamics).

Ecosystems and the biosphere are the prototypical examples of complex adaptive systems (Levin 1999), and so are landscapes. Interactions between spatial patterns and ecological and socioeconomic processes at differing scales are keys to the behavior of such systems. Key to the sustainability of any complex adaptive systems, including landscapes, is resilience. Holling (1973) 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" stresses persistence, change, and unpredictability, and differs fundamentally from the equilibrium-based "engineering resilience" which focuses on efficiency, constancy, and predictability (Holling 1996).

More recent work has further refined Holling's (1973) definition by including the system's abilities to self-organize and adapt to changes, as well as expanding the concept to socioeconomic systems (Levin et al. 1998; Walker and Salt 2006). For example, social resilience is defined as the ability of a human community to withstand, and to recover from, external perturbations (Adger 2000). Resilience thinking frequently invokes the concepts of thresholds or tipping points, alternate stable states or regimes, regime shifts, complex adaptive systems, adaptive cycles, and transformability (Holling 2001; Walker and Salt 2006).

From a resilience perspective, landscape sustainability is not about maintaining the landscape at a steady state by reducing the variability in landscape dynamics or optimizing its performance, but rather focusing on the landscape's adaptive capabilities to cope with uncertainties. In the face of changing climatic conditions and intensifying land uses, the ability to self-organize and preserve system integrity is crucial to realizing landscape sustainability. Recent studies have suggested that high diversity of heterogeneous components, modular structures, and tight feedback loops often characterize resilient complex adaptive systems (Levin 1999; Levin and Lubchenco 2008). The hierarchical patch dynamics perspective corroborates this conclusion from complex adaptive systems theory and resilience research.

Based on the above discussion, it is tempting to define landscape sustainability as 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. To operationalize this rather general definition, different landscape types need to be distinguished because they each have different structural and functional characteristics. One common classification is the landscape modification gradient by Forman and Godron (1986): (1) natural landscape (without significant human impact), (2) managed landscape (where native species are managed and harvested), (3) cultivated landscape (with villages and patches of natural or managed ecosystems scattered), (4) suburban landscape (a town and country area with a heterogeneous patchy mixture of residential areas, commercial centers, cropland, managed vegetation, and natural areas), and (5) urban landscape (with remnant managed park areas scattered in a densely built-up matrix). Focusing more on characteristics related to system self-regenerative capacities, Naveh (1998) classified cultural landscapes into seminatural and managed multifunctional landscapes (e.g., protected areas, parks, recreation areas), traditional agricultural landscapes, rural and suburban landscapes, and urban landscapes. These landscapes are distinguished based on their energy inputs and self-organizing and regenerative capacities through the photosynthetic conversion of solar energy: (1) "solar-powered" seminatural and managed landscapes, ranging from protected areas, traditional agricultural landscapes, to contemporary organic farming systems, (2) "intensive agro-industrial" landscapes, including modern agricultural systems that are heavily subsidized by fossil energy, and (3) "technosphere" landscapes, including rural, suburban, and urban-industrial landscapes that are supported primarily by fossil energy, with all internal natural regenerative capacities lost.

Also, insight into landscape sustainability can be gained from examining traditional cultural landscapes, which are the products of long-term co-evolution between culture and nature. For example, based on a review of lessons from history, Forman (1995) observed that water problems, soil erosion, high population density, war, and a decline in exports are key attributes associated with decreased sustainability, whereas cultural cohesion, low population density, export–import trade, overall level and arrangement of the resource base, religious cohesion, varied linkages with adjacent areas, and a major irrigation or dike system are key attributes associated with increased sustainability. Selman (2007) suggested three propositions as a basis for assessing the sustainability of landscapes: (1) "cultural landscapes are sustainable if they are regenerative," (2) "landscape sustainability is characterized by ecological integrity and cultural legibility," and (3) "regenerative landscapes are distinguished by feedback loops leading to accumulation of cultural and ecological assets." Forman (1990) postulated 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." More detailed studies need to be carried out to further test these observations, propositions, and hypotheses. This represents a promising future direction for operationalizing the science and practice of sustainability science.

Measuring Landscape Sustainability

For a landscape-based approach to sustainability to succeed in research and practice, measures must be developed to gauge sustainability at the landscape scale. A great number of sustainability indicators (or sustainable development indicators—SDIs) have been developed in the past several decades since the 1992 Earth Summit in Rio de Janeiro which proposed the fundamental principles and the program of action for achieving sustainable development. Especially after the World Summit on Sustainable Development (Earth Summit 2002) in Johannesburg in 2002, a number of international organizations, governmental agencies, NGOs, local communities and corporations, and academic scholars have devoted significant effort to the design and implementation of indicators that gauge the state and trajectory of environmental conditions and socioeconomic development. Today, hundreds of indicators and indices of sustainable development have been developed and used at the global, national, and local scales.

SDIs are indicators that provide information on the state, dynamics, and underlying drivers of human–environmental systems and represent arguably the most popular approach to gauging sustainable development. Landscape sustainability indicators should be developed based on the commonly recognized criteria, including: (1) an indicator set should cover the various dimensions of sustainability and their complex interactions; (2) indicators should be indicative of the state and changes of the targeted aspects of sustainability; (3) indicators should be informative based on available data; (4) indicators should be readily understandable and policy-relevant; and (5) the methods for weighting and aggregating variables should be transparent and unbiased (Wu and Wu 2011). A number of existing SDIs may be incorporated into landscape indicator systems (see examples in Table 1).

Indicator frameworks can help identify gaps in available data, indicator sets, and our overall understanding of the human–environmental relationship in landscapes (Wu and Wu 2011). Three indicator frameworks in the sustainability literature should be useful for developing landscape sustainability indicators: the Pressure-State-Response (PSR) framework, the theme- or issue-based frameworks, and the capital frameworks. With the PSR framework (Fig. 3), indicators of pressures represent forces that drive landscape changes; state indicators focus on current landscape conditions; and response indicators pertain to societal reactions to changes in the state of the landscape and underlying drivers. A theme-based framework organizes indicators around key issues, as illustrated in the 2001 indicator set by the United Nations Commission on Sustainable Development (CSD) (Fig. 4). The CSD theme-based framework has a hierarchical structure, with four dimensions of sustainable development (social, environmental, economic, and institutional), 15 themes, and 58 core indicators. The capital-based framework attempts to calculate the wealth of a region as a function of different kinds of capital: manufactured or built capital (all produced assets that form the human economy in a traditional sense), natural capital (the natural environment and resources), human capital (capacities of people to work, including knowledge, skills, and health), and social capital (stocks of social networks, trust, and institutional arrangements). Sustainability in this case depends heavily on whether a strong or weak sustainability perspective is pursued.

Table 1 A select group of sustainability indices commonly used in the assessment of sustainable development (Wu and Wu 2011)

Indicator	Description
Green GDP	Although GDP is the most popular measure of economic performance, it does not accurately reflect actual human or environmental well-being. Empirical data show that GDP is often negatively correlated with environmental quality, and its positive correlation with social well-being measures disappears after GDP reaches a certain level. Green GDP is a variant developed in the early 1990s in an attempt to factor in the effects of natural resource consumption and pollution on human welfare
Human development index (HDI)	HDI was created in the 1990s by the United Nations Development Program to assess the levels of human and social development. The index is composed of three primary aspects: life expectancy, education, and standard of living. HDI has become a standard and widely reported indicator in many official reports and academic publications. A major criticism of HDI is its abstraction from the environmental dimension of human welfare
Inclusive wealth (IW)/genuine savings (GS)	Unlike the Green GDP, which is a "flow" measure, IW/GS are stock-based. The economic patterns of production and consumption are necessarily contingent upon the availability and configuration of the available resources, or "capital." Thus, inter-temporal transfers of economic opportunity are best represented by the value of capital stocks. The "inclusive" and "genuine" primarily refer to the inclusion of natural resources into economic accounting. According to this framework, a region or country is sustainable over a given period if its IW/GS per capita does not decline over that time
Genuine progress indicator (GPI) and index of sustainable economic welfare (ISEW)	GPI and ISEW are essentially equivalent metrics, although the former is more widely recognized than the latter. Like the Green GDP, they adjust the standard flow-based metric of economic performance to consider the role of environmental well-being. However, unlike Green GDP, GPI and ISEW divide economic transactions between those that make a positive contribution to human welfare and those that make a negative contribution (e.g., an oil spill). GPI and ISEW also include the imputed values of nonmarketed goods and services and adjust for income distribution effects
Material flows accounting (MFA)	MFA tracks the weight of a number of different material flows in the economy, including production inputs and outputs, matter moved in the environment to access resources, and residual material from the production process. By aggregating different material flows, MFA produces a single metric called the total material requirement (TMR), which gives a picture of the physical metabolism of the economic system. Although monetary accounting is still more widespread, the use of MFA is expanding
Ecological footprint (EF)	EF measures the land (and water) area that is required to support a defined human population indefinitely (Wackernagel and Rees 1996). The basic unit of measurement is the "global hectare," a normalized unit capturing the average biocapacity of all hectares of all biologically productive lands in the world. This comprehensive measure enables the comparison of human demands on the planet's ecosystems to the regenerative capacity of those ecosystems
Environmental sustainability index (ESI) and environmental performance index (EPI)	Published between 1999 and 2005, ESI was used as a measure of humanity's natural resource use. The computational methodology involved combining 76 variables into 21 metrics, which were then averaged to yield a single index. ESI was succeeded by EPI, which is developed by the same institutions and has been published in 2006, 2008, and 2010. EPI narrows its aims to two objectives: environmental health and ecosystem vitality. EPI is meant to provide a report of "more immediate value to policy-makers"

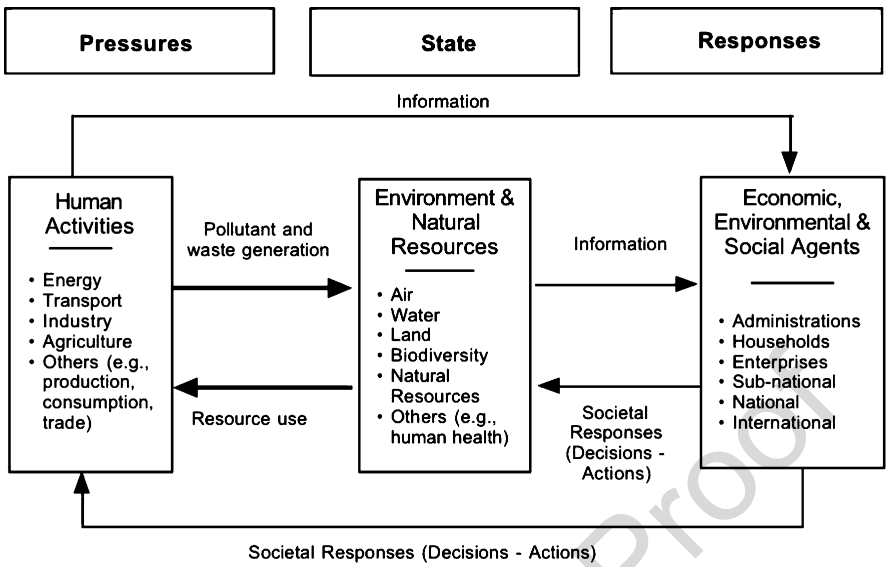

Fig. 3 Illustration of the pressure–state–response framework for the development of sustainability indicators

By modifying these frameworks to focus on the landscape scale, sustainability indicators can be developed for different kinds of landscapes. For example, the PSR framework may work better for natural and seminatural landscapes, whereas the theme- and capital-based frameworks seem more appropriate for human-dominated landscapes. Many existing landscape indices may find their places in these frameworks, but systematic efforts are needed to integrate SDIs and landscape pattern metrics. In addition, scalograms using landscape indicators may provide an effective approach to revealing hierarchical linkages and relating key elements of sustainability across multiple scales (Wu 2004).

Landscape ecology has developed a large number of pattern metrics (or indices) to quantify the composition and configuration of landscapes (Li and Wu 2007). Many of these metrics have been successfully used to quantify how landscapes change over time and how different landscape compare and contrast. Landscape metrics can provide rich information on the diversity and relative abundance of different kinds of landscape components, as well as the shape complexity and spatial configuration of patch mosaics. Among the most commonly used ones are the number of patch types and their proportions, patch density, edge density, patch size, patch or landscape shape indices, connectivity indices, and fragmentation indices. Some of these landscape metrics are conceivably useful in landscape sustainability assessment, although more research is needed to relate landscape metrics to sustainability variables and to develop sustainability-oriented landscape metrics (Wu and Hobbs 2002; Li and Wu 2004).

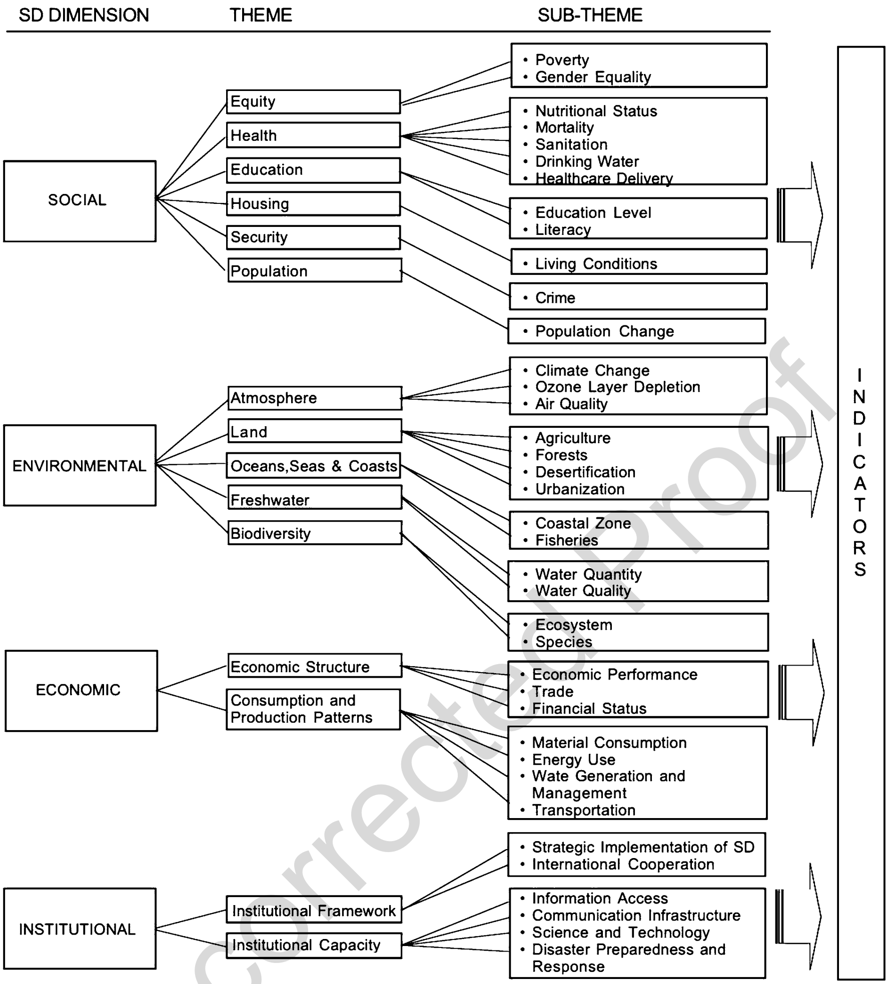

Fig. 4 The theme-based indicator framework developed by United Nations Commission on Sustainable Development (UNCSD 2001)

Landscape Ecology as a Cornerstone of Sustainability Science

If landscapes represent a pivotal scale of sustainability, then the ecology of landscapes ought to have something to offer to the science and practice of sustainability. Landscape ecologists have long considered the relevance of their science to sustainability (Naveh 1982; Forman 1990; Naveh 2007) and, more recently, to sustainability science (Potschin and Haines-Young 2006; Wu 2006; Musacchio 2009, 2011; Turner 2010). In this section, I briefly discuss some of the key ideas in landscape ecology and how this field can contribute to the development of sustainability science.

Although the term was coined in Europe in 1939, landscape ecology was not an established scientific field until the 1980s when remote sensing data and computers became widely accessible to scientists. The 1980s was also a time when ecological ideas of spatial heterogeneity and nonequilibrium dynamics flourished, and when landscape ecology took root in North America. Spatial heterogeneity is ubiquitous in all ecological systems, underlining the significance of pattern–process relations and scale. The main theme of contemporary landscape ecology, with an unmistakable focus on spatial heterogeneity, was articulated in Risser et al. (1984): "Landscape ecology focuses explicitly upon spatial pattern. Specifically, landscape ecology considers the development and dynamics of spatial heterogeneity, spatial and temporal interactions and exchanges across heterogeneous landscapes, influences of spatial heterogeneity on biotic and abiotic processes, and management of spatial heterogeneity." In addition, landscape ecology also fully recognizes the importance of the multidimensionality of landscapes and their cross-disciplinarity. Again, as Risser et al. (1984) put it: "A major forcing function of landscapes is the activity of mankind, especially associated cultural, economic, and political phenomena … Landscape ecology is not a distinct discipline or simply a branch of ecology, but rather is the synthetic intersection of many related disciplines that focus on the spatial-temporal pattern of the landscape."

Today, a general consensus seems to have emerged that landscape ecology is not simply an academic discipline, but rather a highly interdisciplinary field of study (Wu and Hobbs 2002, 2007). In an attempt to integrate the various connotations, Wu and Hobbs (2007) defined landscape ecology as the integration of the science and art of studying and influencing the relationship between spatial pattern and ecological processes on multiple scales. The "science" of landscape ecology focuses on the theoretical basis for understanding the formation, dynamics, and effects of spatial heterogeneity, whereas the "art" of landscape ecology reflects the humanistic and holistic perspectives necessary for integrating ecology, design and planning, socioeconomics, and management practices. Wu (2006) put forward a pluralistic and hierarchical framework that facilitates synergistic interactions between biophysical/pattern–process and holistic/humanistic perspectives in landscape ecology (Fig. 5). The "hierarchical" view here recognizes the varying scope and degree of cross-disciplinarity in landscape ecological studies, whereas the "pluralistic" view stresses the importance of different disciplines and perspectives. This pluralistic and hierarchical framework implies that all the five dimensions of landscape, as discussed in Tress and Tress (2001), are important in landscape studies.

Several key research areas in landscape ecology have been identified (Wu and Hobbs 2002, 2007). These include: quantifying landscape pattern and its ecological effects; the mechanisms of flows of organisms, energy, and materials in landscape mosaics; behavioral landscape ecology that focuses on how the behavior of organisms interacts with landscape structure; landscape genetics that aims to understand how landscape heterogeneity affects population genetics; causes and consequences of land use and land cover change; spatial scaling that deals with translation of information across heterogeneous landscapes; and optimization of landscape pattern for conservation or sustainability. Towards the transdisciplinary end of the spectrum landscape ecology is increasingly related to sustainability science in theory

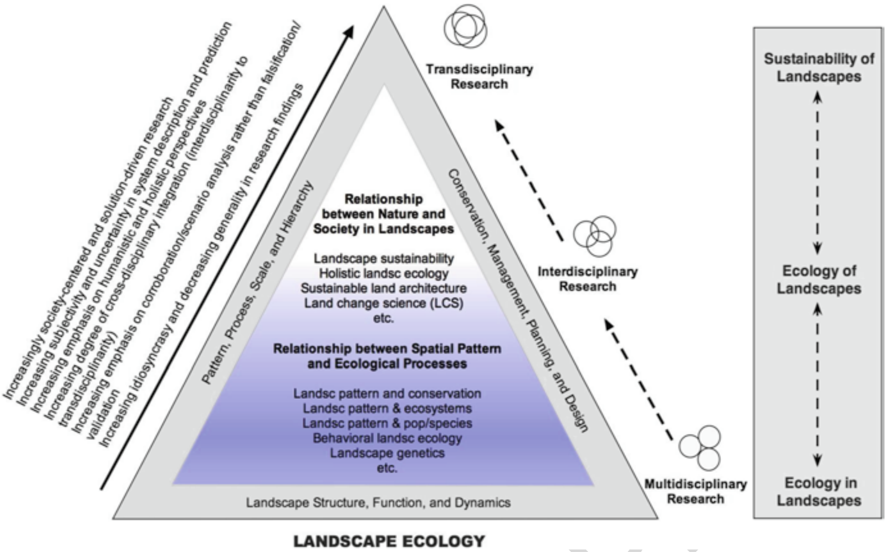

Fig. 5 The pyramid of landscape ecology as an interdisciplinary and transdisciplinary science

and practice (Fig. 5). The emerging "land-change science" focuses on observing and monitoring land use and land cover change, assessing its impacts on ecosystem processes and services, and understanding its causes and mechanisms (Rindfuss et al. 2005; Turner et al. 2007). Much of this has been part of key research topics and priorities (Wu and Hobbs 2002), and it is encouraging to see that ecologists and geographers converge on their views toward sustainability.

Overall, landscape ecology can contribute to sustainability science in several ways (Wu 2006). First, landscape ecology provides a hierarchical and integrative ecological basis for dealing with issues of biodiversity and ecosystem functioning from fine to broad scales. Second, landscape ecology has already developed a number of holistic and humanistic approaches to studying nature–society interactions. Third, landscape ecology offers theory and methods for studying the effects of spatial configuration of biophysical and socioeconomic component on the sustainability of a place. Fourth, landscape ecology has developed a suite of pattern metrics and indicators which can be used for quantifying sustainability in a geospatially explicit manner. Finally, landscape ecology provides both theoretical and methodological tools for dealing with scaling and uncertainty issues that are fundamental to most nature–society interactions (Wu et al. 2006).

Concluding Remarks

Sustainability science focuses on the dynamic relationship between society and nature, integrating environmental, economic, and social processes across scales of local communities, regions, and the entire global system. While it is difficult or implausible to pick a scale that is not relevant to sustainability, some scales may be more effective than others for studying and achieving sustainability. The importance of the global scale is given because global sustainability is the ultimate goal of the science and practice of sustainability. However, global-level studies usually have to be coarse-grained and lack details that are directly relevant to local actions. At the other end, studies at the scale of local communities, while extremely important, usually lack regional contexts and are difficult to scale up to the global scale.

To bridge this gap, landscapes represent an intermediate scale that is operational in research and actions and commensurate with human perception of the environment. Landscapes are not only the stage where environmental, economic, and social processes play out, but also the integrator of these processes. Landscapes are the products of interactions between human society and natural environment, representing a pivotal scale for linking local and global sustainability. Landscapes are arguably the most meaningful places in the place-based research in sustainability science. Also, landscapes provide a common ground for ecologists, geographers, planners and designers, and policy-makers to work together to shape and improve the society–nature relationship.

Sustainability science at the landscape scale will not only need to integrate the multiple dimensions of environment, economy, and society, but also should focus on elucidating the role of spatial heterogeneity in determining the sustainability of landscapes. Heterogeneity always makes scale matter. Thus, key research questions ought to address the issues on scale multiplicity, scaling relations, and hierarchical linkages. Consequently, landscape sustainability research will produce pattern–process–scale relations of places that are fundamental to sustainability science. To move forward with the landscape approach to sustainability, landscape ecology, as well as other related interdisciplinary fields, will continue to play an important role.

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References

Adger WN (2000) Social and ecological resilience: are they related? Prog Hum Geogr 24:347–364

Chen X, Wu J (2009) Sustainable landscape architecture: implications of the Chinese philosophy of "unity of man with nature" and beyond. Landsc Ecol 24:1015–1026

Clark WC (2007) Sustainability science: a room of its own. PNAS 104:1737–1738

Clark WC, Dickson NM (2003) Sustainability science: the emerging research program. PNAS 100:8059–8061

Du Pisani JA (2006) Sustainable development—historical roots of the concept. Environ Sci 3:83–96
Forman RTT (1990) Ecologically sustainable landscapes: the role of spatial configuration. In: Zonneveld IS, Forman RTT (eds) Changing landscapes: an ecological perspective. Springer, New York
Forman RTT (1995) Land mosaics: the ecology of landscapes and regions. Cambridge University Press, Cambridge, UK
Forman RTT, Godron M (1986) Landscape ecology. Wiley, New York, NY
Gobster PH, Nassauer JI, Daniel TC et al (2007) The shared landscape: what does aesthetics have to do with ecology? Landsc Ecol 22:959–972
Holling CS (1973) Resilience and stability of ecosystems. Annu Rev Ecol Syst 4:1–23
Holling CS (1996) Engineering resilience versus ecological resilience. In: Schulze P (ed) Engineering within ecological constraints. National Academy Press, Washington DC
Holling CS (2001) Understanding the complexity of economic, ecological, and social systems. Ecosystems 4:390–405
Ji X (2007) Ji Xianlin on Chinese culture. China Books, Beijing, PRC
Kareiva P, Watts S, McDonald R et al (2007) Domesticated nature: shaping landscapes and ecosystems for human welfare. Science 316:1866–1869
Kates RW (2003) Sustainability science. In: IAP (Interacademy Panel on International Issues) (ed) Transition to sustainability in the 21st century: the contribution of science and technology. National Academies Press, Washington, DC
Kates RW, Clark WC, Corell R et al (2001) Sustainability science. Science 292:641–642
Kidd CV (1992) The evolution of sustainability. J Agric Environ Ethics 5:1–26
Leopold A (1949) A Sand County almanac. Oxford University Press, New York, NY
Levin SA (1999) Fragile dominions: complexity and the commons. Perseus Books, Reading
Levin SA, Lubchenco L (2008) Resilience, robustness, and marine ecosystem-based management. Bioscience 58:27–32
Levin SA, Barrett S, Aniyar S et al (1998) Resilience in natural and socioeconomic systems. Environ Dev Econ 3:222–236
Li H, Wu JG (2004) Use and misuse of landscape indices. Landsc Ecol 19:389–399
Li H, Wu J (2007) Landscape pattern analysis: key issues and challenges. In: Wu J, Hobbs R (eds) Key topics in landscape ecology. Cambridge University Press, Cambridge, UK
McHarg IL (1969) Design with Nature. Natural History Press, Garden City, New York
Mitchell D (2000) Cultural geography: a critical introduction. Blackwell, Oxford, UK
Musacchio LR (2009) The scientific basis for the design of landscape sustainability: a conceptual framework for translational landscape research and practice of designed landscapes and the six Es of landscape sustainability. Landsc Ecol 24:993–1013
Musacchio LR (2011) The grand challenge to operationalize landscape sustainability and the design-in-science paradigm. Landsc Ecol 26:1–5
Nassauer JI (1995) Culture and changing landscape structure. Landsc Ecol 10:229–237
Nassauer JI (ed) (1997) Placing nature: culture and landscape ecology. Island Press, Washington, DC
Naveh Z (1982) Landscape ecology as an emerging branch of human ecosystem science. Adv Ecol Res 12:189–237
Naveh Z (1998) Ecological and cultural landscape restoration and the cultural evolution towards a post-industrial symbiosis between human society and nature. Restor Ecol 6:135–143
Naveh Z (2007) Landscape ecology and sustainability. Landsc Ecol 22:1437–1440
O'Neill RV, DeAngelis DL, Waide JB et al (1986) A hierarchical concept of ecosystems. Princeton University Press, Princeton, NJ
Phillips A (1998) The nature of cultural landscapes—a nature conservation perspective. Landsc Res 23:21–38
Phillips A (2007) International policies and landscape protection. In: Benson JF, Roe M (eds) Landscape and sustainability. Routledge, New York, NY
Pickett STA, Cadenasso ML (1995) Landscape ecology: spatial heterogeneity in ecological systems. Science 269:331–334

Potschin M, Haines-Young R (2006) "Rio+10", sustainability science and landscape ecology. Landsc Urban Plann 75:162–174

Reitan PH (2005) Sustainability science—and what's needed beyond science. Sustain Sci Pract Policy 1:77–80

Rindfuss RR, Walsh DJ, Turner BL II et al (2005) Developing a science of land change: challenges and methodological issues. PNAS 101:13976–13981

Risser PG, Karr JR, Forman RTT (1984) Landscape ecology: directions and approaches. Illini Natl Hist Surv Spec Publ. 2, Champaign, IL

Sauer CO (1925) The morphology of landscape. Publ Geog 2:19–53

Selman P (2007) Landscape and sustainability at the national and regional scales. In: Benson JF, Roe M (eds) Landscape and sustainability. Routledge, New York, NY

Simon HA (1962) The architecture of complexity. Proc Am Philos Soc 106:467–482

Tress B, Tress G (2001) Capitalising on multiplicity: a transdisciplinary systems approach to landscape research. Landsc Urban Plann 57:143–157

Turner BL II (1997) Spirals, bridges and tunnels: engaging human-environment perspectives in geography. Ecumene 4:196–217

Turner MG (2010) A landscape perspective on sustainability science. In: Levin SA, Clark WC (eds) Toward a science of sustainability. Toward a Science of Sustainability Conference, Warrenton, Virginia

Turner MG, Gardner RH, O'Neill RV (2001) Landscape ecology in theory and practice: pattern and process. Springer, New York, NY

Turner BL II, Lambin EF, Reenberg A (2007) The emergence of land change science for global environmental change and sustainability. PNAS 104:20666–20671

UNCSD (2001) Indicators of sustainable development: guidelines and methodologies. UN Commission on Sustainable Development [AU2]

Urban DL, O'Neill RV, Shugart HH (1987) Landscape ecology: a hierarchical perspective can help scientists understand spatial patterns. Bioscience 37:119–127

Walker B, Salt D (2006) Resilience thinking: sustaining ecosystems and people in a changing world. Island Press, Washington, DC

Webb M (1987) Cultural landscapes in the National Park Service. Publ Histor 9:77–89

Weinstein MP (2010) Sustainability science: the emerging paradigm and the ecology of cities. Sustain Sci Pract Policy 6:1–5

Wiens JA, Milne BT (1989) Scaling of 'landscape' in landscape ecology, or, landscape ecology from a beetle's perspective. Landsc Ecol 3:87–96

Wilson EO (2007) Foreward. In: Penn D, Mysterud I (eds) Evolutionary perspectives on environmental problems. Aldine Transaction, Piscataway, NJ

Wu J (1999) Hierarchy and scaling: extrapolating information along a scaling ladder. Can J Remot Sens 25:367–380

Wu J (2004) Effects of changing scale on landscape pattern analysis: scaling relations. Landsc Ecol 19:125–138

Wu J (2006) Landscape ecology, cross-disciplinarity, and sustainability science. Landsc Ecol 21:1–4

Wu J (2008) Making the case for landscape ecology: an effective approach to urban sustainability. Landsc J 27:41–50

Wu J, David JL (2002) A spatially explicit hierarchical approach to modeling complex ecological systems: theory and applications. Ecol Modell 153:7–26

Wu J, Hobbs R (2002) Key issues and research priorities in landscape ecology: an idiosyncratic synthesis. Landsc Ecol 17:355–365

Wu J, Hobbs R (2007) Landscape ecology: the-state-of-the-science. In: Wu J, Hobbs R (eds) Key topics in landscape ecology. Cambridge University Press, Cambridge, UK

Wu J, Levin SA (1994) A spatial patch dynamic modeling approach to pattern and process in an annual grassland. Ecol Monogr 64:447–464

Wu J, Loucks OL (1995) From balance-of-nature to hierarchical patch dynamics: a paradigm shift in ecology. Quart Rev Biol 70:439–466 608 609
Wu J, Wu T (2011) Sustainability indicators and indices. In: Madu CN, Kuei C (eds) Handbook of sustainable management. Imperial College Press, London, UK 610 611
Wu J, Jones KB, Li H et al (eds) (2006) Scaling and uncertainty analysis in ecology: methods and applications. Springer, Dordrecht, The Netherlands 612 613

Kates RW, Parris TM, Leiserowitz A (2005) What is sustainable development? Goals, indicators, values, and practice. Environment: Science and Policy for Sustainable Development 47(3):8-21
.
Tress B, Tress G, De'camps H, d'Hauteserre A-M (2001) Bridging human and natural sciences in landscape research. Landscape and Urban Planning 57:137-141
.
Wackernagel M, Rees WE (1996) Our Ecological Footprint: Reducing Human Impact on the Earth. New Society Publishers, British Columbia, Canada