

A Landscape Approach for Sustainability Science 1 2

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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. 4
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Keywords Landscape sustainability • Sustainability science • Human–nature interactions • Sustainability metrics 18
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Introduction 20

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 21
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24 prerequisite to survival. Nature, to put the matter as succinctly as possible, is part of us, and
25 we are part of nature

26 E. O. Wilson (2007)

27 Human activities have transformed ecosystems and landscapes profoundly around
28 the world, and the entire biosphere has been influenced in fundamental ways
29 (Kareiva et al. 2007; Wu 2008). In search of solutions to a myriad of environmental
30 and social problems, sustainability has become the defining theme of our time (Kidd
31 1992; Kates et al. 2005; Du Pisani 2006). Sustainability concerns our ability to maintain
32 coupled human–environmental systems in a desirable state for multiple generations
33 in the face of anthropogenic and environmental perturbations and uncertainties. To
34 meet the needs and challenges of sustainability, a new kind of science has emerged
35 in the past 2 decades—sustainability science—that focuses on the dynamic interactions
36 between society and nature (Kates et al. 2001; Clark and Dickson 2003; Clark
37 2007; Weinstein 2010). The ultimate goal of sustainability science is not just to
38 understand the human–environment relationship, but rather to improve it through
39 producing knowledge and solutions for management, planning, and policy that are
40 needed for a transition toward sustainability. Thus, sustainability science has to be
41 integrative and pluralistic. As Reitan (2005) put it, sustainability science is “the
42 cultivation, integration, and application of knowledge about Earth systems gained
43 especially from the holistic and historical sciences (such as geology, ecology, clima-
44 tology, oceanography) coordinated with knowledge about human interrelationships
45 gained from the social sciences and humanities.”

46 Three salient characteristics seem essential to sustainability science. First, sustain-
47 ability science is multidimensional and transdisciplinary. This means that it deals
48 with the nexus of environment, economy, and society, with integrative approaches
49 cutting across natural and social sciences (Kates et al. 2001; Wu 2006). Second, sus-
50 tainability is multiscaled and hierarchically linked in space and time. Sustainability
51 can be defined at any scale from a local site (e.g., a household or a biological com-
52 munity) to the entire globe, although only the local, regional, and global scales have
53 frequently appeared in the sustainability literature. Regardless of its specific definition,
54 the sustainability of a system varies with scale in space and time and, as in other
55 hierarchical systems, processes at different scales are linked in both bottom-up and
56 top-down directions (O’Neill et al. 1986; Wu and Loucks 1995; Wu 1999). So, we
57 not only need to ask the questions of what to sustain and what to develop, but also
58 over what area and for how long. Third, sustainability science emphasizes use-
59 inspired, place-based research. Real-world problems occur in “places” and we must
60 go “places” to understand and solve them. As Kates (2003) stated, “Sustainability
61 science is regional and place based. . . ., it is in specific regions, with distinctive social,
62 cultural, and ecological attributes, that the critical threats to sustainability emerge and
63 in which a successful transition needs to be based.” This does not simply mean that
64 sustainability science is an “applied” discipline; it is a transdisciplinary enterprise
65 that bridges the traditional divide between basic and applied research by focusing on
66 use-inspired and place-based problems (Clark 2007).

If the “place” in sustainability science is essential, then what is the “place?” 67
 Kates (2003) asked the same question: “What constitutes an appropriate classification 68
 of place? In part, the distinction is surely one of scale, and a grand query of sustain- 69
 ability will be these scale relationships.” So, defining “place” in sustainability 70
 research is critically important to effectively dealing with the issues of scale and 71
 hierarchical linkages as well as integrating the environmental, economic, and social 72
 dimensions. In this chapter, therefore, I argue that, although “place” can be defined 73
 at any scale, “landscape” represents the most pivotal scale for sustainability research. 74
 I will first discuss what landscape is and then present a landscape perspective on 75
 sustainability, including conceptual and practical considerations. 76

Landscape as a Place for Sustainability 77

The term, “landscape,” is a key concept in a number of fields, from social to geo- 78
 graphical and ecological sciences. Because of the plurality of its origins and inter- 79
 pretations, landscape has acquired various connotations. The same word may refer 80
 to a natural landscape, a cultural landscape, a political landscape, an economic land- 81
 scape, a mental landscape, an adaptive landscape, a landscape view, landscaping, or 82
 landscape painting (Fig. 1). “Landscape gives identity to place” and “landscape is 83
 where past and present meet” (Phillips 2007). Human geographers may think of 84
 landscape as “a work of human labor” or “an activity” of dynamic interactions 85
 between people and place (Mitchell 2000). As such, a landscape may also be 86

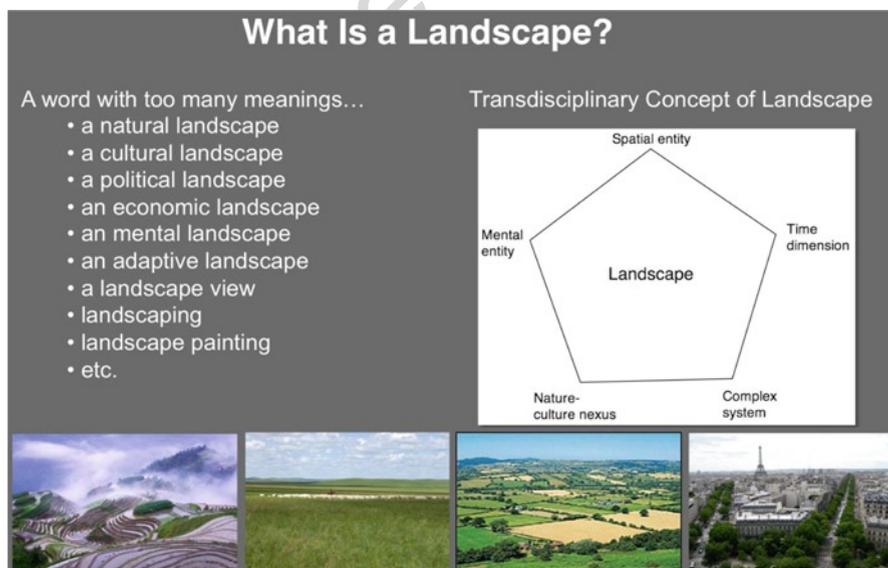


Fig. 1 A transdisciplinary concept of landscape based on discussion in Tress and Tress (2001)

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

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

105 In the field of landscape ecology, the word “landscape” has different meanings.
106 The main differences among various definitions reflect the different spatial scales at
107 which a landscape is perceived and the different aspects of a landscape are empha-
108 sized (Wu and Hobbs 2007). For example, Forman and Godron (1986) defined
109 landscapes as kilometers-wide geographic areas, which corresponds to the “human-
110 perceived” landscape. This is the scale at which the field of landscape ecology was
111 originally developed in Europe, and at which most landscape studies have been
112 conducted ever since. This human-perceived landscape scale, in general, seems to
113 coincide well with geographic units such as watersheds and urban regions (Forman
114 1995), as well as spatial domains of human perception (Gobster et al. 2007). Thus,
115 it resonates with the public, the decision-makers, and researchers who are conscious
116 about the environmental setting in which they live, work, and play.

117 However, most landscape ecologists consider landscape as a multiscale or hier-
118 archical concept, meaning that a landscape is a spatially heterogeneous area of vari-
119 ous sizes, depending on the subject of study and the research questions at hand
120 (Urban et al. 1987; Wu and Levin 1994; Pickett and Cadenasso 1995; Turner et al.
121 2001). In this case, landscape is an “ecological criterion” (Pickett and Cadenasso
122 1995), and its essence does not lie in its absolute scale but in its internal heterogene-
123 ity. Different plant and animal species perceive, experience, and respond to spatial
124 heterogeneity at different scales, and patterns and processes in landscapes tend to
125 have different characteristic scales (Wu and Loucks 1995). Apparently, one does not
126 need to consider a landscape of tens of square kilometers in order to study how the
127 spatial patterning of grasses affects the movement of beetles (Wiens and Milne
128 1989) or is affected by gophers (Wu and Levin 1994).

129 Tress and Tress (2001) proposed a “transdisciplinary landscape concept” of
130 landscape that encompasses five dimensions: (1) landscape as a spatial entity, (2)
131 landscape as a mental entity, (3) landscape as a temporal dimension, (4) landscape
132 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 trans-disciplinary 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

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

[AU1]

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

230 and random processes are essential to ecosystem structure and function, and (5)
231 ecological (meta)stability is often achieved through structural and functional redun-
232 dancy and spatial and temporal incorporation of dynamic patches.

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

246 Ecosystems and the biosphere are the prototypical examples of complex adaptive
247 systems (Levin 1999), and so are landscapes. Interactions between spatial patterns
248 and ecological and socioeconomic processes at differing scales are keys to the
249 behavior of such systems. Key to the sustainability of any complex adaptive sys-
250 tems, including landscapes, is resilience. Holling (1973) defined resilience as the
251 ability of a system to absorb change and disturbance without changing its basic
252 structure and function or shifting into a qualitatively different state. This “ecological
253 resilience” or “ecosystem resilience” stresses persistence, change, and unpredict-
254 ability, and differs fundamentally from the equilibrium-based “engineering resil-
255 ience” which focuses on efficiency, constancy, and predictability (Holling 1996).

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

264 From a resilience perspective, landscape sustainability is not about maintaining
265 the landscape at a steady state by reducing the variability in landscape dynamics or
266 optimizing its performance, but rather focusing on the landscape’s adaptive capa-
267 bilities to cope with uncertainties. In the face of changing climatic conditions and
268 intensifying land uses, the ability to self-organize and preserve system integrity is
269 crucial to realizing landscape sustainability. Recent studies have suggested that high
270 diversity of heterogeneous components, modular structures, and tight feedback
271 loops often characterize resilient complex adaptive systems (Levin 1999; Levin and
272 Lubchenco 2008). The hierarchical patch dynamics perspective corroborates this
273 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.

318 **Measuring Landscape Sustainability**

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

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

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

Indicator	Description	
		t1.1
		t1.2
		t1.3
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	t1.4 t1.5 t1.6 t1.7 t1.8 t1.9 t1.10
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	t1.11 t1.12 t1.13 t1.14 t1.15 t1.16
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	t1.17 t1.18 t1.19 t1.20 t1.21 t1.22 t1.23 t1.24 t1.25
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	t1.26 t1.27 t1.28 t1.29 t1.30 t1.31 t1.32 t1.33
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	t1.34 t1.35 t1.36 t1.37 t1.38 t1.39 t1.40 t1.41
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	t1.42 t1.43 t1.44 t1.45 t1.46 t1.47 t1.48
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”	t1.49 t1.50 t1.51 t1.52 t1.53 t1.54 t1.55 t1.56

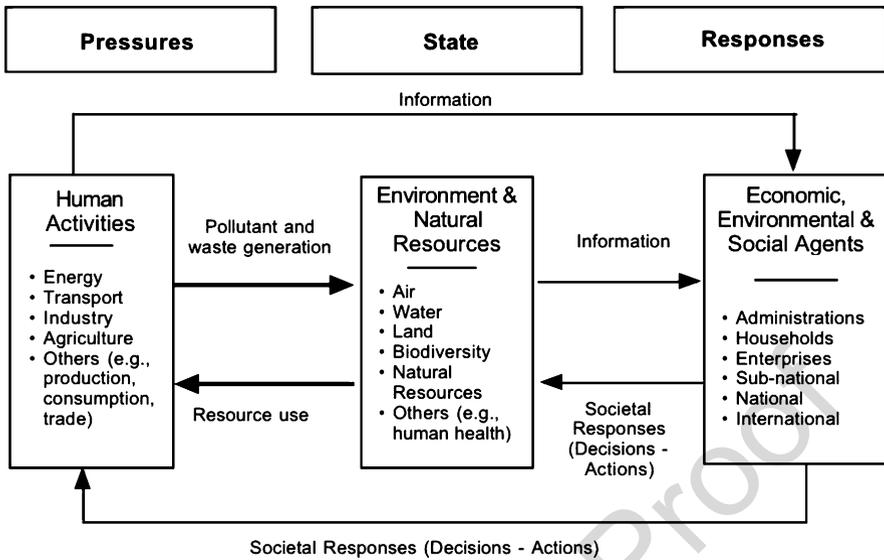


Fig. 3 Illustration of the pressure–state–response framework for the development of sustainability indicators

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

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

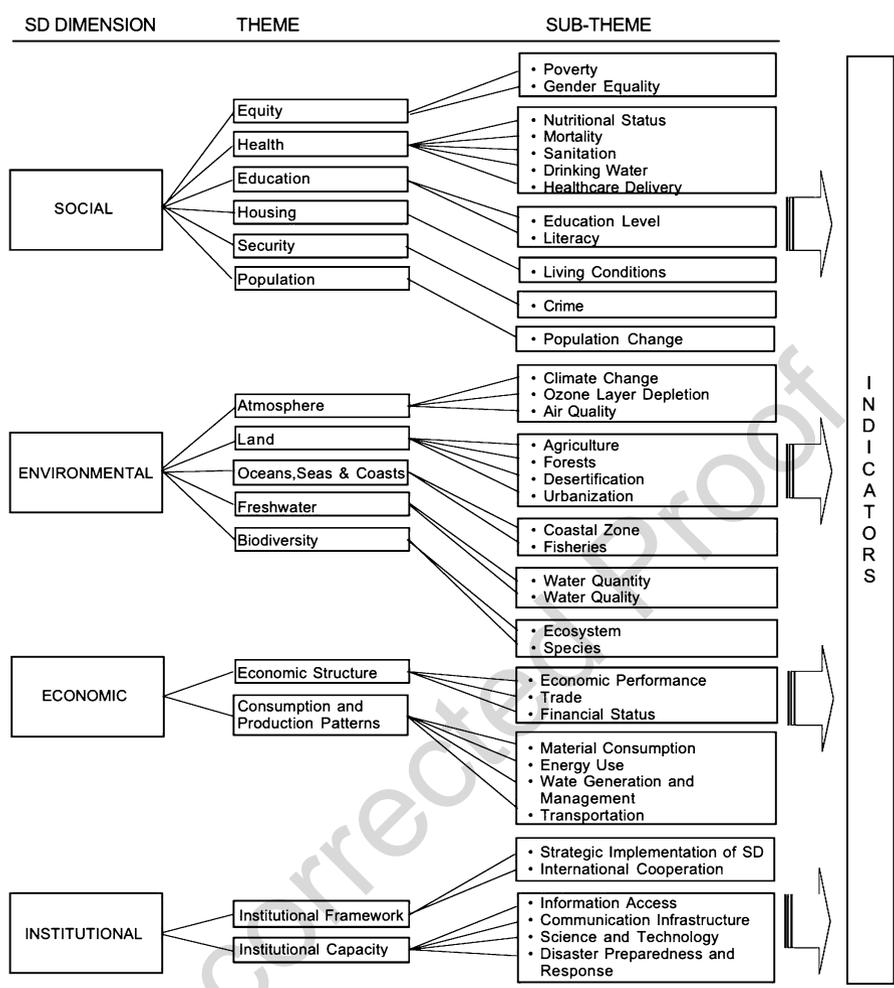


Fig. 4 The theme-based indicator framework developed by United Nations Commission on Sustainable Development (UNCSD 2001)

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.

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

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

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

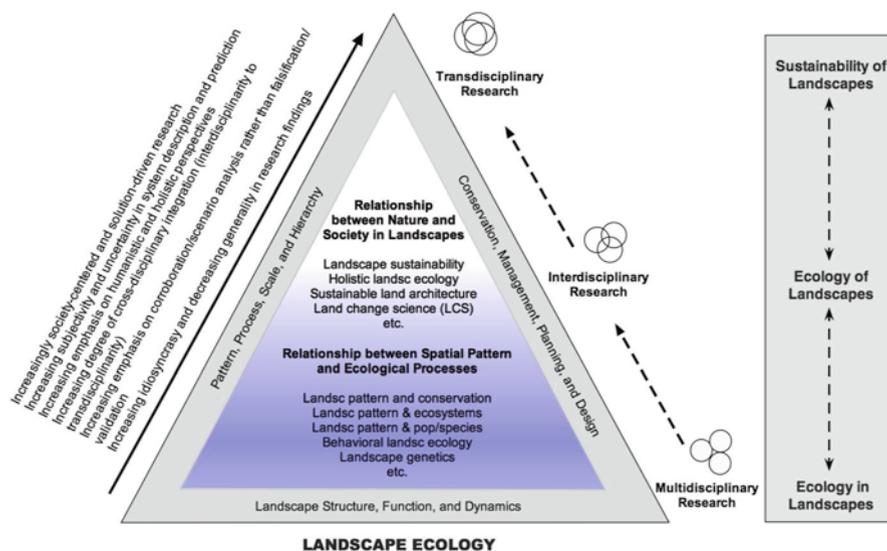


Fig. 5 The pyramid of landscape ecology as an interdisciplinary and transdisciplinary science

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

460 implausible to pick a scale that is not relevant to sustainability, some scales may be
461 more effective than others for studying and achieving sustainability. The importance
462 of the global scale is given because global sustainability is the ultimate goal of the
463 science and practice of sustainability. However, global-level studies usually have to
464 be coarse-grained and lack details that are directly relevant to local actions. At the
465 other end, studies at the scale of local communities, while extremely important, usu-
466 ally lack regional contexts and are difficult to scale up to the global scale.

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

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

486 **Acknowledgments** I to thank Dr. Michael P. Weinstein for inviting me to give a presentation at
487 the International Symposium on Sustainability Science at Montclair State University in October
488 2010, from which this paper has evolved. Also, I thank Tong Wu for a number of helpful discus-
489 sions on sustainability, resilience, and environmental economics. My research in landscape ecol-
490 ogy and sustainability has been supported by grants from National Science Foundation (DEB
491 9714833, DEB-0423704, BCS-0508002), US Environmental Protection Agency (R827676-01-0),
492 and collaborative grants from National Natural Science Foundation of China and Chinese Academy
493 of Sciences.

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