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ARTICLE

Linking landscape, land system and design approaches to achieve sustainability

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ABSTRACT

Sustainability science is a use-inspired and place-based transdisciplinary enterprise that integrates natural and social sciences, engineering/design sciences, and humanities to produce actionable knowledge for improving human wellbeing while maintaining long-term environmental integrity. Regional landscapes represent a pivotal scale domain for studying and practicing sustainability because they integrate human-environment interactions, link local processes below and global patterns above, and provide a common platform for scientists, land designers/planners, policymakers, and stakeholders to collaborate on sustainability issues that resonate with all. An interdisciplinary confluence of ecological, geographical, and design/planning sciences is underway, but how this confluence can effectively contribute to the science and practice of sustainability is yet to be explored. Here I review landscape and land system-based approaches, including land change science, land system science, land system architecture, landscape ecology, landscape sustainability science, and geodesign, and discuss why and how they can be linked for achieving the common goal of sustainability.

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1. Introduction

The world is projected to need 35% more food, 40% more water, and 50% more energy by 2030 (CNA, 2014). These are daunting challenges because, while today's agriculture already uses a third of global arable land and consumes 71% of freshwater withdrawals (World Economic Forum, 2011; Zhang, 2013), about 2 billion people are still undernourished or malnourished, 2.8 billion people suffer from physical and economic water shortage, and 1.3 billion people live without access to electricity (Howells et al., 2013). Farming, livestock grazing, and plantations depend heavily on water, fossil fuel energy, and fertilizers, resulting in widespread problems of resource depletion, land degradation, and environmental contamination (Foley et al., 2005; Vitousek, Mooney, Lubchenco, & Melillo, 1997; Vitousek et al., 2009). Climate change will further worsen the situation, especially for developing countries where rising temperatures, declining precipitation, and increasing extreme weather conditions will seriously challenge human survival and sustainable development (Conway et al., 2015; IPCC, 2013; Obersteiner et al., 2016).

As a result, sustainability has become a prevalent theme that defines our era (Kates, 2012; MEA, 2005; World Commission on Environment and Development, 1987; Wu, 2013a). We do not have any other choice: 'There is only one alternative to sustainability: unsustainability' (Bossel, 1999, p. 1). To meet the sustainability challenge, the disciplinary silos of natural and social sciences must be broken down, and

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a place-based, use-inspired, transdisciplinary science is much needed (Kates, 2012). This new science is the science of sustainable development, or sustainability science, a term coined by the National Research Council (1999). During the past two decades, sustainability science has been developing rapidly, with increasingly cohesive and converging key themes and core research questions (Bettencourt & Kaur, 2011; Fang, Zhou, Tu, Ma, & Wu, 2018; Kates, 2011, 2012; Kates et al., 2001). Because sustainability is about improving human wellbeing while maintaining environmental integrity (World Commission on Environment and Development, 1987), it is hard to think of any research field that is not relevant to sustainability science. However, the role of ecological and geographical sciences is fundamentally important. As de Vries (2013) stated:

> "We live in physical space and the sciences of ecology and geography contribute in manifold ways to our understanding and organization of natural and economic, social and cultural space. They are the material linchpin between our quality-of-life aspirations on the one hand and the resources to fulfill them on the other . . .. . . It may be argued that ecology and geography are the core of sustainability science, but the natural and engineering sciences and the economic and social sciences may be of equal importance" (de Vries, 2013, p. 534).

During recent decades, ecologists and geographers have not only been making their sciences more relevant to sustainability, but also collaborating to develop new approaches to enrich, and instill rigor into, the evolving science of sustainability. In particular, a number of landscape (or land system) approaches have been developed by ecological and geographical scientists. The major objectives of this paper are to review several landscape approaches, and discuss how they can be linked to help advance the science and practice of sustainability on the landscape and regional scales. Specifically, I will first argue that developing a rigorous science of sustainability requires an emphasis on strong sustainability and landscape/regional scales. Then I will compare and contrast six land system-based approaches that are relevant to sustainability research and practice, including land change science, land system architecture, land system science, landscape ecology, landscape sustainability science, and geodesign. Then, I will discuss how these approaches can be linked for achieving landscape and regional sustainability. Finally, I will conclude the paper with key findings and suggestions.

2. Focusing on 'strong sustainability' and landscape/regional scales

'Sustainability means many things … At the core, though, it must mean the preservation of the services that we derive from ecosystems' (Levin, 2012, p. 432). Two contrasting sustainability views – 'strong sustainability' and 'weak sustainability' – are important to be distinguished because they have profound influences on how sustainability is defined, measured, and to be achieved (Daly, 1995; Dietz & Neumayer, 2007; Wu, 2013a). The key difference between the two sustainability views hinges on the degree to which natural capital can be substituted by manufactured capital (i.e., substitutability between the economy and the environment). According to the weak sustainability view, a system is sustainable as long as its total capital (including both natural and manufactured) increases or remains the same. In this case, a region with rapid economic growth but severe environmental degradation may still be considered sustainable. On the other hand, the strong sustainability view recognizes that many life-support functions of ecosystems are not substitutable and that long-term socioeconomic prosperity depends ultimately on environmental integrity (Figure 1). Thus, strong sustainability limits, not precludes, the economy-environment substitutability through, for example, identifying the critical natural capital for a particular region or nation (Ekins, Simon, Deutsch, Folke, & De Groot, 2003).

Although weak sustainability is not sustainable in the long run, it is a useful concept in sustainability discourses as well as in geospatial planning for sustainability across scales. For instance, strong sustainability on a broad scale may actually require weak sustainability in certain locales – think of a sustainable region with well-planned natural areas and agricultural systems, as well as urban centers that are not self-sufficient (Forman, 2008, 2014; Wu, 2013a). In other words,

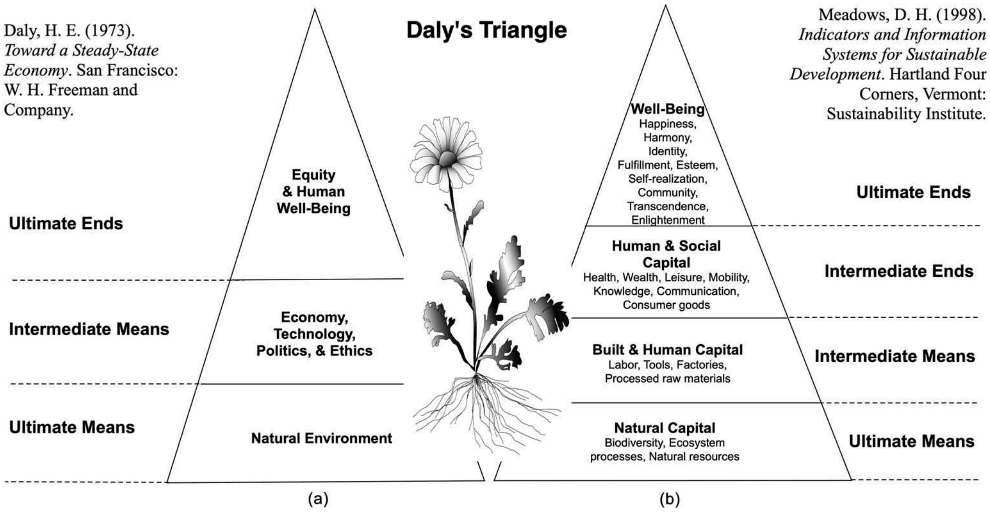

Figure 1. A strong sustainability framework known as Daly's Triangle, in which the natural environment is viewed as the 'ultimate means' to achieve the 'ultimate ends' of human well-being (including equity), whereas economy, technology, politics, and ethics are 'intermediate means' to bridge the ultimate means and ultimate ends (redrawn from Daly, 1973; Meadows, 1998).

the long-term sustainability of a region is determined fundamentally by the kinds, amounts, and spatial configurations of constituent human-environmental systems of the region. Thus, regional- and national-level planning is necessary in order to achieve the dual goal of meeting human needs and maintaining biodiversity and ecosystem function. Such top-down planning should explicitly consider the local-scale details and regional patterns of biodiversity, ecosystem function, ecosystem services (benefits that people derive from ecosystems), and socioeconomic processes through bottom-up approaches, so that broad-scale plans are operational on fine scales and 'small details' actually add up to the desired 'big picture'.

Sustainability needs to be achieved on local, regional, and global scales, and the science of sustainability must consider all these scales accordingly. However, landscapes/regions are arguably the most operational and effective scale domain for linking land(scape) architecture and ecology and for addressing most sustainability issues (Forman, 2008; Wu, 2006, 2012, 2013a). Global sustainability has to depend on regional sustainability that is influenced profoundly by landscape composition and configuration. Landscapes are places where people live, work, and interact with nature, where biodiversity and ecosystems reside and function, and where ecosystem services are generated, delivered, and consumed through human-environment interactions. Thus, landscapes are quintessential human-environment systems. On the one hand, landscapes 'integrate environmental processes' (Nassauer, 2012); on the other hand, landscapes influence people's physical and psychological wellbeing through four ways of human-environment interactions: knowing, perceiving, interacting, and living within (Russell et al., 2013). Landscapes/regions represent a pivotal scale domain for the science and practice of sustainability, as they link local actions below and global impacts above (Wu, 2006, 2012, 2013a; Forman, 2008). Landscape sciences (e.g., landscape ecology, landscape/regional geography, and landscape planning and design) focus on 'regional and place-based' problems and solutions, and thus need to play an instrumental role in sustainability research and practice.

Because weak sustainability is not sustainable in the long term, the core of sustainability science must be strong sustainability-oriented and multi-scaled. Strong sustainability needs to incorporate biophysical and socioeconomic details of landscapes on multiple scales. An actionable science of sustainability may focus on landscapes/regions as the fundamental scale domain, but meanwhile, explicitly consider the global context and local-scale processes. This view seems consistent with Kates (2012, p. 7) who explained eloquently why 'regional and place-based' studies of human-environment systems are key to sustainability science, technology, and transitions:

> "… much of the science and technology developed to support sustainability will be regional and place-based, and focused at intermediate scales where multiple stressors intersect to threaten or degrade human-environment systems. … It is at these intermediate scales that the complexity of coupled human-environmental systems is more readily comprehensible, where innovation and management happen, and where significant transitions toward sustainability may have already begun".

During the past few decades, a number of landscape and land system approaches have been developed to address sustainability issues on spatial scales ranging from the local to regional and global scales (e.g., Benson & Roe, 2007; Bürgi, Ali, et al., 2017; DeFries & Rosenzweig, 2010; Forman, 2008; Hanspach et al., 2014; Reed, Van Vianen, Deakin, Barlow, & Sunderland, 2016; Sayer et al., 2013; Wu, 2012, 2013b). Converging towards a common theme of sustainability, these approaches reflect the strengths (and limitations) of ecological, geographical, and design/planning sciences in which they are rooted. In the next section, I will discuss several landscape/land system approaches, including land change science, land system architecture, land system science, landscape ecology, landscape sustainability science, and geodesign. Spanning several disciplines, all these approaches are important for developing a rigorous science of strong sustainability connecting local, regional, and global scales.

3. Landscape and land system approaches for sustainability

It is necessary to clarify how the two terms, 'landscape' and 'land system' are used in this paper. It is widely accepted in landscape ecology that 'a landscape is an area that is spatially heterogeneous in at least one factor of interest' (Turner & Gardner, 2015, p. 7). This general definition is scientifically appropriate and beneficial as it encourages observational, experimental, and theoretical investigations on a wide range of spatial scales (Allen & Hoekstra, 1992; Wu & Loucks, 1995). However, in order to make it directly relevant to sustainability research, here I use the term 'landscape (system)' to refer to the totality of a regional landscape with all its environmental, economic, and social dimensions included. This is in line with Naveh and Lieberman (1994, p. 21) who promoted the holistic definition of landscapes as 'the total spatial and visual entity of human living space, integrating the geosphere with the biosphere and the noonspheric man-made artifacts'. Tress and Tress proposed a comprehensive 'transdisciplinary landscape concept' which has five facets: (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.

Defined as such, landscapes are geospatially heterogeneous, socioeconomically driven, regional human-environment systems (Wu, 2012, 2013a), which are similar to 'land systems' as defined by Verburg, Erb, Mertz, and Espindola (2013, p. 433): 'Land systems represent the terrestrial component of the Earth system and encompass all processes and activities related to the human use of land, including socioeconomic, technological and organizational investments and arrangements, as well as the benefits gained from land and the unintended social and ecological outcomes of societal activities'. Thus, 'landscape approaches' and 'land system-based approaches' in this paper both refer to geospatially explicit land(scape)-based approaches that deal with coupled human-environmental systems.

3.1. Land change science

There are three closely related but distinct land system-based approaches developed primarily by geographers and remote sensing scientists during the past few decades: land change science, land (system) architecture, and land system science. The three approaches are similar to each other conceptually and ontologically. An important source of inspiration and impetus of these approaches has been the landmark book, entitled 'The Earth as Transformed by Human Action' (Turner et al., 1990). The land system approaches have been actively promoted by scientists working on the Global Land Project (GLP), which was initiated in 2005 by the International Geosphere-Biosphere Programme (IGBP) and the International Human Dimensions Programme on Global Environmental Change (IHDP) as an outgrowth of IGBP's Global Change and Terrestrial Ecosystems (GCTE) project and IHDP's Land Use and Land Cover Change (LUCC) project during the 1990s (GLP, 2005).

Land change science was proposed in the early 2000s, originally as 'integrated land-change science' (Turner, 2002; Turner, Moran, & Rindfuss, 2004). It 'seeks to understand the dynamics of land cover and land use as a coupled human–environment system to address theory, concepts, models, and applications relevant to environmental and societal problems, including the intersection of the two', and 'has emerged as a fundamental component of global environmental change and sustainability research' (Turner, Lambin, & Reenberg, 2007; pp. 20, 666). Land change science has focused on observing and monitoring land use and land cover change (LUCC), understanding the biophysical and socioeconomic mechanisms of LUCC, and assessing the impacts of LUCC on ecosystem processes and services (Rindfuss, Walsh, Turner II, Fox, & Mishra, 2004; Turner et al., 2007). These issues on LUCC are also a key research topic in modern landscape ecology (Forman, 1995; Turner & Gardner, 2015; Wu, 2013b, 2017), and thus the overlap between land change science and landscape ecology is extensive.

3.2. Land system architecture

Land system architecture (Turner, 2016; Turner, Janetos, Verburg, & Murray, 2013; Vadjunec, Frazier, Kedron, Fagin, & Zhao, 2018) or land architecture (Li et al., 2016; Turner, 2010) refers to 'the structure of land systems, where structure refers to the kind, magnitude, and spatial pattern of land uses and covers in a bounded area' (Turner, 2010, p. 171). This resembles the definition of 'landscape pattern' in landscape ecology which consists of landscape composition and configuration (Forman, 1995; Turner & Gardner, 2015). The land system architecture approach is 'an outgrowth of land change science, with obvious connections to landscape ecology and landscape architecture' (Turner et al., 2013, p. 395). These connections are inevitable as landscape ecology, landscape architecture, and land system architecture all focus on landscape elements and their spatial configurations within a geographical area.

How does land system architecture differ from landscape architecture – a well-established profession and discipline? Broadly defined, landscape architecture combines art and science to spatially arrange landscape elements for human use and enjoyment, involving designing, planning, and managing local landscapes and their constituent elements for different purposes (see Huang, Xiang, Wu, Traxler, & Huang, 2019 for a summary of major historical developments in landscape architecture). The American Society of Landscape Architects (ASLA) defines landscape architecture as follows: 'Landscape architects analyze, plan, design, manage, and nurture the built and natural environments. They design parks, campuses, streetscapes, trails, plazas, and other projects that help define a community' (https://www.asla.org/aboutland scapearchitecture.aspx). According to Turner et al. (2013, p. 395), 'land system architecture expands the reach of landscape architecture beyond the urban/peri-urban "built" environments and local environmental concerns of the planning communities, linking to the spatial dimensions of landscape ecology but with attention to human outcomes beyond the impacts of changes in ecosystem services per se'. Besides spatial scales, land system architecture and landscape architecture (as well as landscape ecology) also differ in their origins, methodologies, and research emphases.

Recently, Turner (2016) discussed 'land architecture-mosaic approaches' and their application in urban sustainability research, explicitly integrating the land system architecture approach with the land mosaic concept in landscape ecology (Forman, 1995). Vadjunec et al. (2018) called for further bridging land system architecture and landscape ecology. Indeed, such an integration is much needed for making our landscapes and regions more sustainable, although landscape ecology and landscape architecture (including landscape planning and landscape design) have been interacting with each other increasingly during the past three decades (to be discussed further below).

3.3. *Land system science*

Land system science also builds on, and goes beyond, land change science, with increased emphasis on land management, governance, and sustainability solution-oriented issues (Rounsevell et al., 2012; Verburg et al., 2013). It is now considered as 'a crucial component of earth system science' (Verburg et al., 2015, p. 34). Land system science and land change science are closely related in terms of their main research topics and methodological approaches. Rounsevell et al. (2012) simply adopted the definition of land change science (Turner et al., 2007) for land system science, but the term of land system science now seems more preferred by land system researchers, with a more comprehensive connotation.

It seems that land change science has evolved into land system science that combines geography, ecology, and social sciences, while land system architecture complements land system science by providing a planning and design component. As such, both land system science and land system architecture are fundamentally important to developing the core of sustainability science, especially from a strong sustainability perspective. A quick literature search suggests an upward trend for all the three approaches in terms of the number of publications and citations to them (Figure 2). Land change science now greatly exceeds the other two approaches since its first seminal paper in 2004, but the number of publications and citations in land system architecture and land system science have been increasing rapidly since 2010 and 2012, respectively (Figure 2).

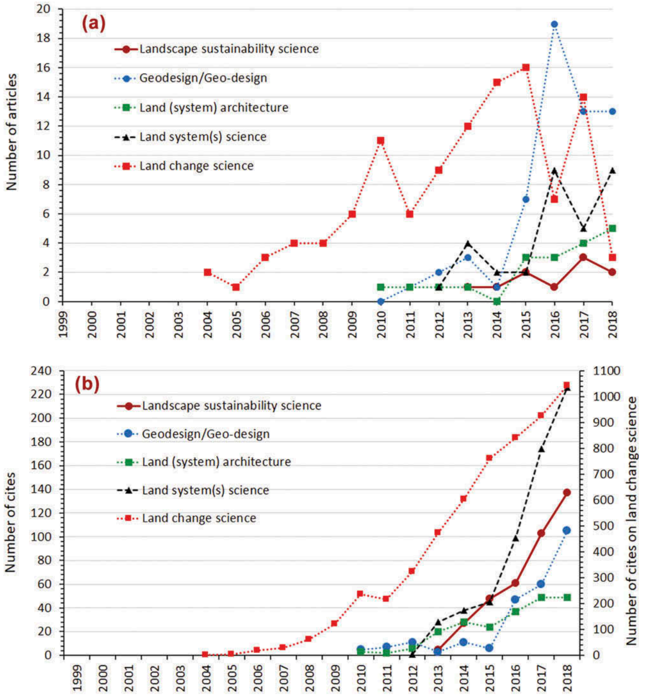

Figure 2. The number of articles on land change science, land system science, land (system) architecture, geodesign, and landscape sustainability science (A), and the total number of citations to each of the above categories (B), based on the Web of Science Core Collection (accessed on 31 January 2019). Search phrases were 'land change science', 'land system(s) science', 'land (system) architecture', 'geodesign' or 'geo-design', and 'landscape sustainability science. The search domain included the titles, abstracts, and keywords of journal articles in the database.

The accuracy of the numbers in Figure 2 aside, the rapid developing trend of land change science and land system science is unmistakable.

3.4. Landscape ecology

Carl Troll (1939) coined the term, landscape ecology, inspired particularly by the vivid patterns revealed in aerial photographs and the ecosystem concept by Arthur Tansley (1935) which links soil, vegetation, and atmosphere and unites plants, animals, and microbes. So, landscape ecology was born to be geospatial and interdisciplinary – a product of integrating geography and ecology. As such, not until remote sensing, computers, and GIS became available in the 1980s, did landscape ecology begin to develop rapidly in theory, methodology, and applications and become a globally recognized science. Although the field has famously focused on the effects of spatial pattern on ecological processes, its emphasis on human-environment interactions and landscape architecture has also been prominent throughout its history (Dramstad, Olson, & Forman, 1996; Forman & Godron, 1986; Nassauer, 1997; Naveh & Lieberman, 1994). Now, landscape ecology has evolved into a highly interdisciplinary and transdisciplinary field that focuses on studying and improving the relationship between spatial pattern and ecological processes within local and regional landscapes (Wu, 2006, 2013b).

As a well-established field, landscape ecology offers a number of theories and methods for the science of sustainability on what Kates (2012) referred to as 'intermediate scales' (i.e., landscapes and regions). Its relevance to sustainability is evident from the top 10 research topics: (1) pattern-process-scale relationships in landscapes and regions, (2) landscape connectivity and fragmentation, (3) scale and scaling, (4) spatial analysis and landscape modeling, (5) land use and land cover change, (6) landscape history and legacy effects, (7) landscape and climate change interactions, (8) ecosystem services in changing landscapes, (9) landscape sustainability, and (10) accuracy assessment and uncertainty analysis (Wu, 2013b; Wu & Hobbs, 2002). Thus, although landscape ecology is focused emphatically on the relationship between spatial pattern and ecological processes, it overlaps widely with physical and cultural geography, landscape architecture, land system architecture, geodesign, and land system science, in terms of both research topics and methodologies. Opdam, Luque, Nassauer, Verburg, and Wu (2018) articulated that landscape ecology can offer four fundamental contributions to sustainability science: a spatially explicit approach; a multiple scale approach; a systems concept that invites stakeholders and disciplines to share their knowledge, values, and concerns; and a systems approach that connects social and ecological science for sustainable solutions. Frazier et al. (2019) further discussed the importance of landscape ecology to sustainability and ecological civilization, highlighting three lines of research: linking landscape patterns with biodiversity, ecosystem processes/function, and ecosystem services across scales; measuring and understanding connectivity and flows across spatially heterogeneous landscapes; and developing a systems understanding of the disturbance dynamics and landscape resilience. More in-depth discussions on the relationship between landscape ecology and sustainability science are found in Wu (2006, 2012, 2013a).

3.5. Landscape sustainability science

'Landscape sustainability science' integrates landscape ecology with sustainability science based on the MEA (2005) ecosystems-human wellbeing framework (Wu, 2013a). If land system science is a sustainability science approach rooted in geography, then landscape sustainability science is an outgrowth of landscape ecology to address sustainability challenges. Yet, the two approaches seem to share a lot more than just their abbreviations – LSS – although land system science seems to place more emphasis on the global scale than landscape sustainability science.

Landscape sustainability here refers to the dynamic capacity of a regional landscape to consistently provide long-term ecosystem services essential for maintaining human well-being in the region under environmental and sociocultural changes; and landscape sustainability science is defined as a place-based, use-inspired, and solution-driven science of understanding and improving the relationship between ecosystem services and human well-being in changing landscapes (Wu, 2013a, 2014). Landscape sustainability science includes several key elements that interact with each other, together characterizing how changes in landscape pattern affect biodiversity, ecosystem processes, ecosystem services, and human wellbeing, and how landscapes can be better designed/planned to maintain and improve landscape sustainability (Opdam et al., 2018, Huang et al. 2019).

The core components of landscape sustainability science are landscape pattern (including composition and configuration), ecosystem services, and human well-being, with its research focus on the dynamic relationship among those three core components. Changes in landscape pattern are driven directly by land use/land cover change and climate change, as well as indirectly by human demography, economic development, and institutions such as laws, policies, and regulations (Bürgi, Bieling, et al., 2017; Bürgi, Hersperger, & Schneeberger, 2004; Turner et al., 1990). Landscape changes affect biodiversity, ecosystem functions, and their relationships, which will in turn influence ecosystem services that they provide to human society (MEA, 2005; Turner & Gardner, 2015). Landscape pattern can also directly affect ecosystem services, such as landscape effects on human physical and psychological wellbeing (Wu, 2013a and references therein). Changes in ecosystem services further affect human wellbeing, which is also influenced by a suite of other socioeconomic factors (MEA, 2005). A key assumption here is that these changes are context-dependent and often associated with not only the kind and amount of landscape elements, but also their configurations (shape, connectivity, and spatial arrangement). Recent studies have shown that spatial tradeoffs and synergies are common among different kinds of ecosystem services and between ecosystem services and human well-being (Bennett, Peterson, & Gordon, 2009; Castro et al., 2014; Qiu et al., 2018; Spake et al., 2017).

Abundant evidence exists in landscape ecology that the composition and spatial arrangement of the ‘land mosaic’, consisting of both biophysical and socioeconomic patches and networks, affect and are affected by flows of organisms, material, energy, and information. Both landscape structure and functions, in turn, determine ecosystem services. Also, numerous studies from environmental and social psychology, public health science, and health geography have shown that landscape-based ecosystem services are important to physical and psychological wellbeing across cultures and socioeconomic classes (Dummer, 2008; Russell et al., 2013; Sheather, 2009; Sullivan & Chang, 2017; Thompson, 2011). Thus, landscape sustainability can be enhanced by improving landscape patterns through landscape design and planning that require collaborations among natural, social, engineering, design/planning, and health sciences.

Is it possible to have a sustainable world in which nations depend heavily on each other for basic resources for a good life? Is it possible to have a sustainable nation in which cities have footprints overlapping broadly with each other or even going beyond the nation? Is it possible to have a sustainable city whose life depends on excessively sucking resources from afar? Probably not. To deal with myriad unsustainable problems, sustainability science must be downscaled to the local landscapes and regions. Landscape sustainability science emphasizes reducing ecological footprints, minimizing externalities, enhancing self-regenerative capacity, and improving ecosystem services of the regional landscape. This does seem to call for localization of resource utilization, but such a localization is not social or political ‘isolation’. As Reitan (2005) and Selman (2009) argued, landscape sustainability is enhanced by, or requires, localization of human demands for ecosystem services attuned to the particular landscape setting. Landscape sustainability science aims to provide ‘actionable’ knowledge for making our landscapes more sustainable in the face of urbanization, globalization, and climate change.

Conceptually, landscape sustainability seems in support of Tobler’s first law of geography: ‘everything is related to everything else, but near things are more related than distant things’ (Tobler, 1970, p. 236). Interestingly, this quote is remarkably similar to Simon’s (1973) explanation of why more sustainable complex systems tend to have a modular or hierarchical architecture: 'Everything is connected, but some things are more connected than others. The world is a large matrix of interactions . . . in which, by ordering those entries according to their orders of magnitude, a distinct hierarchic structure can be discerned' (Simon, 1973, p. 23). Both the first law of geography and the 'architecture of complexity' (sensu Simon, 1962) imply that the sustainability of complex systems requires 'bounded' connectivity; that is, connectivity among system components is balanced by the autonomy of system components. So, globalization sounds politically correct and economically rousing, but often leads to unexpected and undesirable outcomes (Figge, Oebels, & Offermans, 2017; Rees, 2002). Land system science and landscape sustainability science need to address these issues by looking into the geospatial patterns and processes and by linking the local, regional, and global scales.

3.6. Geodesign

Geodesign currently remains a loosely defined system of ideas, methodologies, and digital technologies agglomerated to foster an interactive process of design and planning in geospatial context (Miller, 2012; Steiner & Shearer, 2016). Geodesign relies on ever-advancing digital technologies, but its conceptual and methodological history is often traced back to Ian McHarg's (1969) 'Design with Nature' and Simon's (1996, p. 111) ecumenical view of design – 'Everyone designs who devises courses of action aimed at changing existing situations into preferred ones'. Although geodesign has taken decades to evolve into what it is now (Li & Milburn, 2016), it began to attract much attention from the academic world only during the recent decade, as indicated by the number of scientific publications and their citations (Figure 2).

Geodesign has been defined differently in the literature. Goodchild (2010, p. 18) believes that 'geodesign is not new, but instead represents a re-examination and perhaps a repurposing of a number of established fields'. Steinitz (2012) described geodesign broadly as 'an ongoing process of changing geography by design'. More specifically, Flaxman (2010, p. 29) defined geodesign as 'a design and planning method which tightly couples the creation of a design proposal with impact simulations informed by geographic context'. Ervin modified Flaxman's definition of geodesign by replacing the last two words 'geographic context' with 'systems thinking and digital technologies'. While systems thinking and digital technologies are essential to geodesign, 'geographic context' is certainly one key feature that defines geodesign and distinguishes it from design.

To emphasize the importance of both the supporting sciences and technologies, Goodchild (2010, p. 9) defined geodesign as 'planning informed by scientific knowledge of how the world works, expressed in GIS-based simulations'. He also emphasized that geodesign should be science-based design, and that the supporting sciences should include planning and landscape architecture, geography, ecology, hydrology, earth science, sociology, economics, political science, and geographic information science (Goodchild, 2010). However, how to integrate all these natural and social sciences with design through digital technologies remains a grand challenge for geodesign. But the potential is enormous. Geodesign, if properly integrated with the landscape-based ecology and sustainability perspectives and approaches, can play an instrumental role in promoting the science and practice of landscape sustainability (see Huang et al. 2019 for a recent review on geodesign definitions and applications).

4. Linking ecology, geography, and design for landscape sustainability

In the previous sections, I have discussed the importance of focusing on strong sustainability and landscape/regional scales, and reviewed several landscape and land system-based approaches that are directly relevant to studying and practicing strong sustainability. In this section, I will discuss how these geographical, ecological, and design approaches can be linked or integrated for achieving landscape and regional sustainability.

4.1. Necessity and feasibility of linking landscape/land system approaches

The necessity of linking landscape and land system approaches seems clear. Sustainability science and practice need to be grounded in real landscapes, and global sustainability cannot be possibly achieved without sustainable landscapes and regions. Sustaining our landscapes and regions requires the integration of different landscape/land system approaches that cut across ecology, geography, design/planning, engineering, and other natural and social sciences. A strong sustainability perspective must be emphasized because weak sustainability is not sustainable in the long run. As discussed in the previous sections, strong sustainability ensures the environmental integrity and the critical natural capital 'which is responsible for important environmental functions and which cannot be substituted in the provision of these functions by manufactured capital' (Ekins et al., 2003, p. 169). This requires that conservation and development be balanced, and that the kinds, amounts, and spatial arrangements of landscape elements be optimized following sustainability principles. While the global context and drivers must be considered, strong sustainability is not likely to be achieved without an explicit focus on the landscape/regional scales on which key human-environment interactions and major institutional changes take place.

There are at least two main reasons why it is feasible (and desirable) to link landscape/land system approaches. First, sustainability provides a necessary and undeniable unifying theme for all of the approaches (Figure 3). Achieving the sustainability of landscapes and regions is the explicit goal of landscape sustainability science, and should also be the ultimate goal of other land system-based research and design/planning endeavors. Indeed, providing principles and solutions for sustainable land development has become an increasingly prominent goal of land system science although land change science, earlier on, had a major focus on the drivers and impacts of land use and land cover change (Turner et al., 2007; Verburg et al., 2015, 2013). Concepts of resilience, sustainability, and ecosystem services also have been widely adopted in landscape design/planning (Ahern, 2005, 2013; Bohnet, 2010; Chen & Wu, 2009; Termorshuizen, Opdam, & van Den Brink, 2007; Turner et al., 2013).

Second, all landscape/land system approaches, by definition, are inherently interrelated as they share the common biogeophysical platform – the landscape or land system – whose structure, function, and dynamics are influenced by myriad environmental and socioeconomic processes (Figure 3). In a Venn diagram with sustainability as the common theme and the ultimate goal, the regional landscape as the primary scale domain of action, and the biodiversity/ecosystems-human wellbeing spectrum and the land system structure-function spectrum indicating relative research emphases, the relationships and differences among the several landscape/land system approaches become more apparent (Figure 3). While landscape ecology and landscape sustainability science are linked through ecosystem services on which human wellbeing depends, land change/land system science makes critical contributions to the quantification, valuation, and management of ecosystem services (Crossman, Bryan, de Groot, Lin, & Minang, 2013). Landscape ecology and landscape sustainability science focus on biodiversity-ecosystem function-ecosystem services-human wellbeing interactions in spatially heterogeneous and temporally changing landscapes, whereas land change science and land system science have a greater emphasis on land use and land cover, land management and governance, and global land system dynamics. All of these landscape/land system-based sciences can contribute to, and gain from, landscape architecture, land system architecture, and geodesign – three fields that share a prominent emphasis on land system structure (or landscape pattern). Such cross-disciplinary fertilization is promising, but lacking at the moment. In the next section, I will discuss some ways to move forward.

4.2. Linking landscape/land system approaches through geodesign

We have entered a new geological epoch – the Anthropocene – in which human activity exerts dominant influences on the environment of the earth system (Crutzen, 2002; Lewis & Maslin, 2015). Most of the world's ecosystems have been influenced or even 'domesticated' (Kareiva, Watts, McDonald, & Boucher, 2007). The Anthropocene offers both grand unsustainability challenges

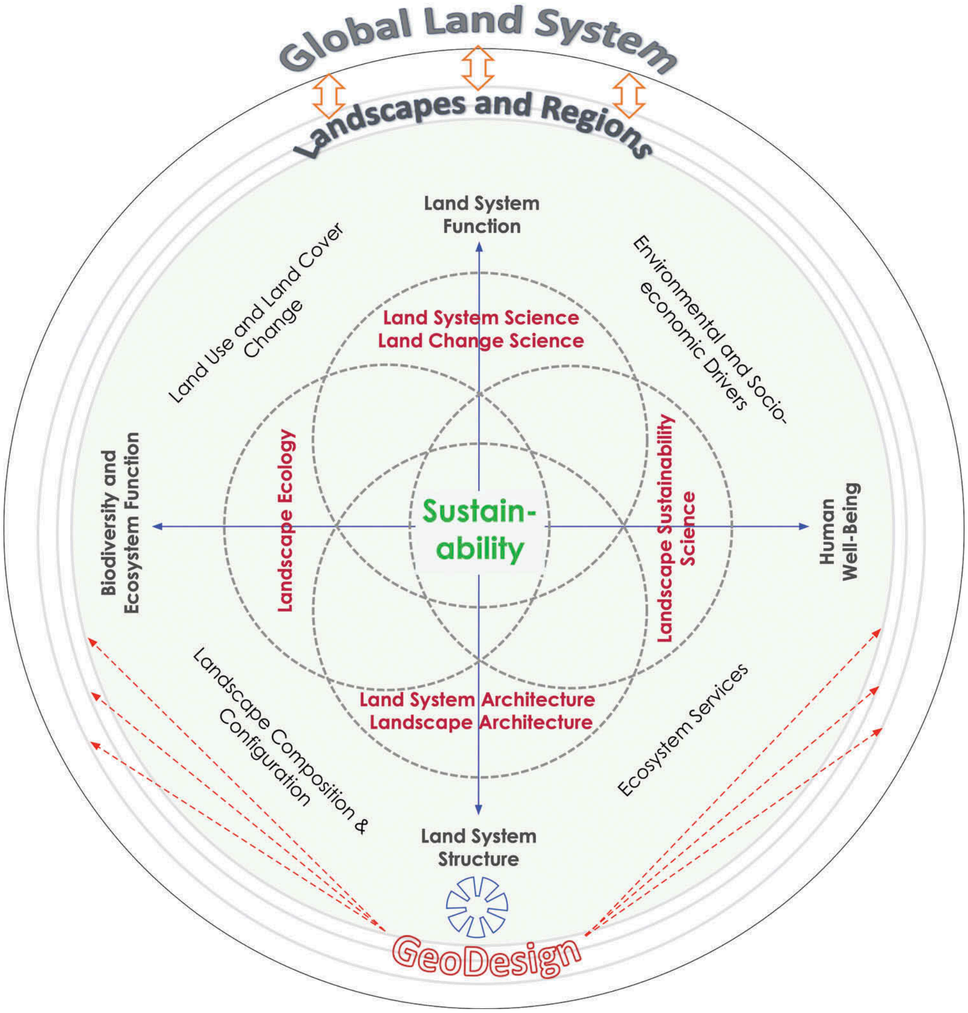

Figure 3. A schematic representation of the relationships among landscape and land system-based science and design approaches. The Venn diagram shows the connections among the different approaches (distinct but broadly overlapping). Sustainability is the primary common theme and the ultimate goal (thus centered in the diagram). Regional landscapes provide the primary platform for actionable sustainability research and practice, which interact with each other hierarchically to comprise the global land system. GeoDesign enhances other landscape sciences and their integration by offering advanced tools, and at the same time needs other landscape sciences for developing a sustainability-oriented, actionable science foundation. The biodiversity/ecosystems – human wellbeing spectrum and the land system structure – land system function spectrum provide two axes to help highlight the research emphases of these approaches.

and unprecedented innovation opportunities. For example, Olson et al. (2017) argued that the Anthropocene concept can be used as a ‘game-changer’ to promote social and technological innovations and transformations to sustainability. Instead of focusing solely on the ‘dark side’ of increasing human domination of the Earth’s ecosystems, Bennett et al. (2016) discussed 100 ‘seeds of a good Anthropocene’ as ‘social-ecological bright spots’. These are sustainability initiatives that engage bottom-up and participatory approaches which, according to the authors, represent transformative pathways to improve human wellbeing although scaling these ‘spots’ up to regional and global scales may be challenging (Bennett et al. 2016).

Herbert A. Simon said 50 years ago that ‘The world we live in today is much more a man-made, or artificial, world than it is a natural world’, and thus he urged that sciences need to be concerned with both ‘how things are’ (traditional natural sciences) and ‘how things ought to be’ (engineering and design sciences) (Simon, 1996, p. 2–5). In other words, pursuing science just for understanding how ‘nature’ works is not adequate; today’s sciences must also provide solutions for maintaining and improving the sustainability of coupled human-environment systems on scales ranging from the household to the entire globe. This is the ultimate goal of sustainability science which is the most comprehensive and transdisciplinary science in human history. To achieve this goal, landscape/land system-based approaches, guided by strong sustainability principles, can and must play a critically important role in integrating natural and social sciences through design and planning.

Since the 1990s, landscape ecology has increasingly interacted with landscape architecture. Golley and Bellot (1991, p. 4) described the close relationship between the two fields: ‘We can move back and forth from one to the other, with landscape ecology providing information to the planner-designer, and the planned and designed landscapes serving as field experiments to test hypotheses for the landscape ecologist.’ To elevate the relationship between the two fields to the next level, Ahern (2005) advocated to integrate landscape ecology and landscape architecture through ‘an evolutionary and reciprocal process’ which goes beyond simply moving back and forth from one to the other. The co-evolutionary and reciprocal integration between the two fields requires that ‘theory, principles, knowledge, and applications flow in both directions: science informs design, and design informs science’ (Ahern, 2005, p. 315). In a similar vein, Nassauer and Opdam (2008) aptly articulated a framework to integrate design into landscape ecology as a central component, which may be termed the ‘pattern-process-design paradigm’. Such vision for transdisciplinary integration is increasingly shared by landscape ecologists and landscape architects.

Geodesign seems to be able to provide a new and powerful platform for linking the various landscape/land system approaches to advance sustainability science in theory and practice (Huang et al. 2019). As discussed earlier, geodesign aims to change and improve the composition and configuration of land systems through design/planning for different purposes. Whatever these purposes are, they all should be aligned with regional and global sustainability goals. To achieve this goal, geodesign must be guided not only by ‘scientific knowledge of how the world works’ (Goodchild, 2010) but also by actionable science of how landscapes and regions ‘ought to work’ (*sensu* Simon, 1996) to achieve sustainability. The several landscape/land system approaches constitute the core of this actionable science needed for geodesign. In addition, the emerging field of Earth System Engineering and Management (ESEM; Allenby, 1999) may offer a number of useful engineering perspectives and technological approaches for enhancing geodesign, although I do not think that engineering the entire globe or even regional earth systems is ecologically and ethically justifiable. According to Allenby (2007, p. 7961), ESEM is ‘to rationally design, engineer and construct, maintain and manage, and reconstruct … the information-dense, highly integrated human, natural, and built systems’, which ‘can draw on experience from existing areas including industrial ecology methodologies such as life-cycle assessment (LCA), design for environment, materials flow analysis, and systems engineering’.

How to integrate all these fields to maximize our capacities for sustainability is yet to be explored by the science community as a whole. But it seems necessary and desirable for geodesign to be fully integrated with landscape sustainability approaches. Such ‘sustainable geodesign’ would provide the most scientifically comprehensive and most technologically advanced platform for studying, designing, and managing landscapes and regions for sustainability. Toward this goal, Huang et al. (2019) discussed how geodesign and the science of landscape sustainability can be integrated so that both fields benefit from each other. In particular, the authors proposed a landscape sustainability science-based geodesign framework for operationalizing the integration, supported by digital/geospatial technologies and guided by six perspectives: strong/weak sustainability, multiple scales, ecosystem services, sustainability indicators, big data application, and the sense of place. The sustainable geodesign framework consists of seven major elements: (1) problem identification and goal setting, (2) pattern and process analysis, (3) geodesign platform construction, (4) comprehensive simulation of ecosystem services and spatial pattern, (5) visualization, (6) human–computer interactions, and (7) design alternatives assessment. This is but one example of sustainable geodesign, and more will surely emerge in years to come.

5. Conclusion

Global sustainability is our ultimate goal, but it can only be achieved if our nations, regions, and landscapes are sustainable. Thus, focusing on landscape/regional scales is crucial for operationalizing sustainability science on all scales ranging from the local city/village to the entire world. In this paper, I have discussed several landscape/land system approaches which share a fundamental assumption: the composition and configuration of landscapes and regions or land system architecture can substantially influence biodiversity, ecosystem function, ecosystem services, and human wellbeing. Although these approaches are entrenched in ecological, geographical, and design sciences, respectively, the common goal for sustainability has broken down disciplinary silos and an interdisciplinary confluence is underway. When properly integrated, these landscape/land system sciences together can provide the theoretical basis and technical approaches needed to translate strong sustainability into actionable knowledge and guidelines for better planning, designing, and managing our landscapes and regions. Sustainable geodesign, or sustainability science-based geodesign, can hopefully serve as a scientifically comprehensive and technologically advanced platform to facilitate this cross-disciplinary integration. Linking ecology, geography, and design is more urgent than ever. It is a grand challenge, but with abundant opportunities and excitement.

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