Living in an increasingly connected world: a framework for continental-scale environmental science

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The global environment is changing rapidly, as the result of factors that act at multiple spatial and temporal scales. It is now clear that local processes can affect broad-scale ecological dynamics, and that broad-scale drivers can overwhelm local patterns and processes. Understanding these cross-scale interactions requires a conceptual framework based on connectivity in material and information flow across scales. In this introductory paper to *Frontiers'* Special Issue on *Continental-scale ecology in an increasingly connected world*, we (1) discuss a multi-scale framework, including the key drivers and consequences of connectivity acting across spatial and temporal scales, (2) provide a series of testable hypotheses, predictions, and an approach, and (3) propose the development of a "network of networks", which would take advantage of existing research facilities and cyberinfrastructure. This unique framework and associated technology will enable us to better forecast global environmental change at multiple spatial scales, from local sites to regions and continents.

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The interplay between fine-scale patterns and processes and broad-scale dynamics is increasingly being recognized as key to understanding ecosystem dynamics, particularly as the number and magnitude of global change drivers increases over time (Huston 1999; Rodó *et al.* 2002; King *et al.* 2004). Cross-scale interactions (CSI) are processes at one spatial or temporal scale that interact with processes at another scale, often resulting in non-linear dynamics with abrupt threshold responses (Holling 1992; Carpenter and Turner 2000; Peters *et al.* 2004a, 2007). These interactions may generate behavior that emerges at broader scales and cannot be predicted based on observations at single or even multiple independent scales (Michener *et al.* 2001). Redistribution of material, energy, and information flow within and among spatial units (ie connectivity) is one potentially powerful explanation for these cross-scale interactions. The degree of connectivity is determined both by the spatial structure of the environment and by the way in which this structure influences the change in redistribution rate – a definition similar to one used by landscape ecologists (With *et al.* 1997).

In a nutshell:

- The world is becoming increasingly connected through the flow of materials, organisms, and information, both within and among regions that may or may not be adjacent or even close to each other
- Connectivity pathways allow fine-scale processes to propagate and impact large areas; in some cases, broad-scale drivers can overwhelm fine-scale processes to alter ecosystem dynamics
- Changes in connectivity have the potential to produce rapid and dramatic changes in ecosystem dynamics unlike any observed in recorded history
- Understanding global connectivity and its consequences requires the creation of an international ecological "network of networks" for observation and experimentation, and the accompanying cyberinfrastructure for analysis and synthesis

All ecosystems around the world are connected through a globally mixed atmosphere and, historically, regional connections existed through a variety of both biotic and abiotic processes. This connectivity has been altered through human transport of propagules, toxins, and diseases, as well as anthropogenic disturbances and changes in land use (Reiners and Driese 2003; MA 2005; Herrick and Sarukhán 2007). Thus, changes in one location can have dramatic influences on both adjacent and distant areas, either at fine or broad scales. For example, the extreme drought of the 1930s in the central Great Plains of the US interacted with cultivation of marginal croplands to generate high rates of soil erosion from individual fields, which subsequently resulted in the Dust Bowl (Figure 1). This site- to regional-scale set of events spread across the continent, to affect broad-scale patterns in soil and air quality, migration patterns, human health, and the economy (Peters *et al.* 2004a).

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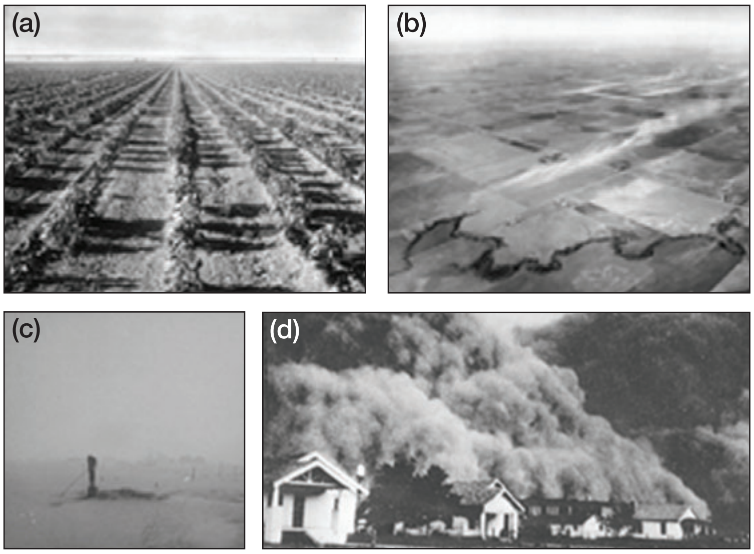

Figure 1. *Development of the US Dust Bowl, an event that propagated from the cultivation of many individual fields on marginal land in the 1920s to widespread abandonment in the 1930s during a severe drought, which led to continental-scale impacts of massive dust storms (www.weru.ksu.edu). (a) Many individual fields cultivated in the Great Plains in the 1920s (b) became highly connected following drought and strong winds in the 1930s, through wind erosion. (c) Extensive areas of soil were eroded, creating (d) massive dust storms, with effects on human health, the economy, and migration across the continent.*

Connectivity across scales can also link continents: hurricanes along the east coast of North America often originate as fine-scale thunderstorms in eastern Africa (Price *et al.* 2007). In 2003, it took only 8 months for severe acute respiratory syndrome (SARS) to spread from a single province in China to 29 countries, resulting in over 8400 confirmed cases around the globe (WHO 2003). Ozone, carbon monoxide, mercury, and other particles from degraded land in China cross the Pacific Ocean to affect air quality in North America (Jaffe *et al.* 2003). The ecological consequences of these broad-scale connections for phenomena at finer scales, from sites to regions and continents, are often unknown. Furthermore, the influence of fine-scale ecological patterns and processes at local sites on broader-scale patterns at regional to continental and global scales is poorly understood.

Here, we provide a conceptual framework to understand and predict broad-scale ecosystem dynamics based on connectivity in material and information flow, linking multiple scales of observation, from local sites to regions and continents. Although we focus on dynamics in the US, as a major part of North America, our framework applies to all continents and to inter-continental dynamics as well. We also suggest an approach to test hypotheses about interactions across scales, and to predict future dynamics. Finally, we describe how our cross-scale framework can be used to leverage existing and emerging research networks to integrate datasets and ecological knowledge.

■ Connectivity framework: a hierarchy of interacting scales

A theory of connectivity across scales is emerging, and it builds on concepts from diverse disciplines, including landscape ecology, Earth-system science, population ecology, macroecology, hydrology, and biogeochemistry. This theory provides one key to forecasting large-scale, multi-process phenomena, and is the basis for our conceptual framework. Our basic premise is that the climate system and human activities operate across multiple, and often disparate, spatial and temporal scales to influence, and be influenced by, ecological systems (Figure 2). Three major scales of climate drivers may lead to synchronicity in ecosystem responses as a result of connectivity via air masses. We use the term "driver" to refer to broad-scale processes and human activities that directly or indirectly influence ecological and socioeconomic systems. This definition allows for interactions among drivers as well as feedback mechanisms between drivers and responses. One example is seen in climatically induced shifts in vegetation that produce changes in surface-energy balance, which then feed back to alter weather patterns that affect both ecosystems and human society (eg Pielke *et al.* 2007). Observed precipitation and temperature patterns at site to regional and continental scales (Figure 3) result from a combination of three climate drivers:

(1) global circulation patterns and other broad-scale drivers, such as solar insolation, which influence long-term climatic averages, with resulting effects on ecosystem structure and function across large regions;
(2) sub-continental to continental-scale phenomena driven by patterns such as the Northern Annular Mode (NAM), the Pacific–North American pattern (PNA), and the El Niño–Southern Oscillation (ENSO); and
(3) mesoscale patterns from a few to several hundred kilometers , as weather interacts with local to regional topography and land surface properties.

However, along with these multi-scale patterns in climate, other gradients are often needed to explain regional- and continental-scale variability in ecosystem dynamics. For example, connectivity along major river systems leads to variable patterns in land use, human settlement, invasive species, and nutrient distribution in soil or sediment that overlay climate-based variations in connectivity (WebFigure 1). Human activities at local scales increasingly drive and connect ecosystem dynamics and land change at broader, regional scales (Luck *et al.* 2001; Dietz *et al.* 2007). In addition, interactions among climate, human populations, and disturbance agents, such as disease vectors, have both ecological and socioeconomic consequences (Yates *et al.* 2002).

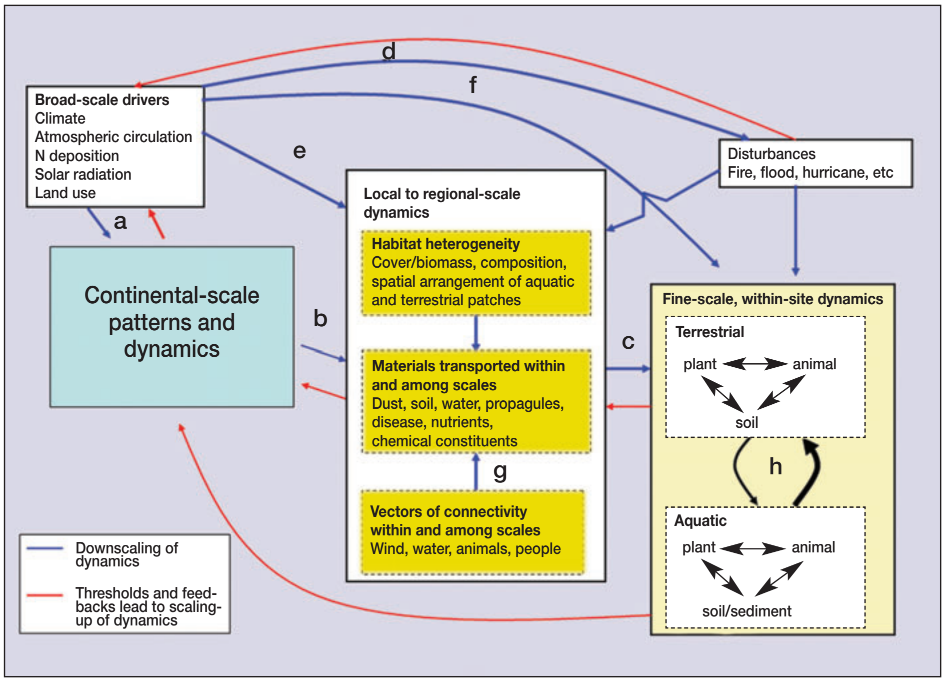

Figure 2. *Continental-scale patterns and dynamics result from climate and people as broad-scale drivers interacting with finer-scale vectors that redistribute materials within and among linked terrestrial and aquatic systems. Climate and land-use change interact with patterns and processes at multiple, finer scales (blue arrows). (a) These drivers can influence broad-scale patterns directly, and these constraints may act to overwhelm heterogeneity and processes at (b) meso-scales and at (c) the finer scale of local sites. Broad-scale drivers can also exert an indirect impact on broad-scale patterns through their interactions with disturbances, including (d) the spread of invasive species, (e) pattern–process relationships at meso-scales, or (f) at finer scales within a site. Connectivity imparted by the transfer of materials occurs both at (g) the meso-scale and at (h) finer scales within sites where terrestrial and aquatic systems are connected. These dynamics at fine scales can propagate to influence larger spatial extents (red arrows). Feedbacks occur throughout the system. The term "drivers" refers to both forcing functions that are part of the system and to external drivers.*

Thus, connectivity across scales results from climate and land use as broad-scale drivers interacting with finer-scale patterns and processes that redistribute materials within and among linked terrestrial and aquatic systems (Figure 2). Thresholds and feedbacks associated with these dynamics often result in non-linear system behavior, as the rates of change vary discontinuously through time and across space (Peters *et al.* 2004a). Connectivity occurs via transport vectors (eg wind, water, animals, people) that move materials and resources (eg dust, soil, water, energy, nutrients, propagules, diseases, and chemical constituents) within and among terrestrial and aquatic systems across a range of spatial and temporal scales (Reiners and Driese 2003; Peters *et al.* 2006). Changes in drivers and pattern–process relationships through time and across space can alter ecosystem dynamics within particular locations, and can change dynamics across locations and large regions (Allen 2007; Peters *et al.* 2007). Although our framework shares some similarities with hierarchical systems theory (Allen and Starr 1982), this approach is designed to understand and predict the conditions when broad-scale drivers will overwhelm fine-scale variability, and when fine-scale processes propagate to influence broad spatial extents. This approach also needs to account for uncertainties in predictions that exist for large-scale systems (Ludwig *et al.* 1993).

■ What can we expect in an increasingly connected world?

Globally, some materials and resources are becoming more concentrated over time (eg nitrogen), while others are becoming more broadly distributed (eg infectious diseases, invasive species). Some resources, such as those in freshwater, are becoming both more concentrated and more widely distributed, depending on the spatial and temporal scales of observation (Baron *et al.* 2002). In certain cases, connectivity in one vector can either increase or decrease connectivity in other vectors, with consequences for resource redistribution and ecosystem dynamics (Breshears *et al.* 2003). For example, human settlement patterns at fine scales can increase connectivity in non-vegetated areas through wind and water erosion (Nates and Moyer 2005), yet can decrease connectivity in wildlife movement and dispersal of infectious diseases by fragmenting landscapes (Haddad *et al.* 2003). Connectivity of a single resource can change in different ways at different scales. For example, at the continental scale, human activities are increasing connectivity between areas through increases in atmospheric nitrogen (N) deposition, yet N levels are increasing and becoming less connected among spatial units as population density and sprawl increase (Figure 4).

Our framework is particularly useful for focusing a suite of ecological questions on the key drivers of contemporary change at multiple scales. These questions were identified by the ecological community as critically important to forecasting future ecosystems at broad scales (eg NRC 2001; AIBS 2004 a,b; MacMahon and Peters 2005). Specific hypotheses can be tested, based on our connectivity framework (see WebPanel 1). These hypotheses are organized around two major issues: ecological effects of connectivity at local versus global scales, and the effects of increasing versus decreasing connectivity, as influenced by different transport vectors.

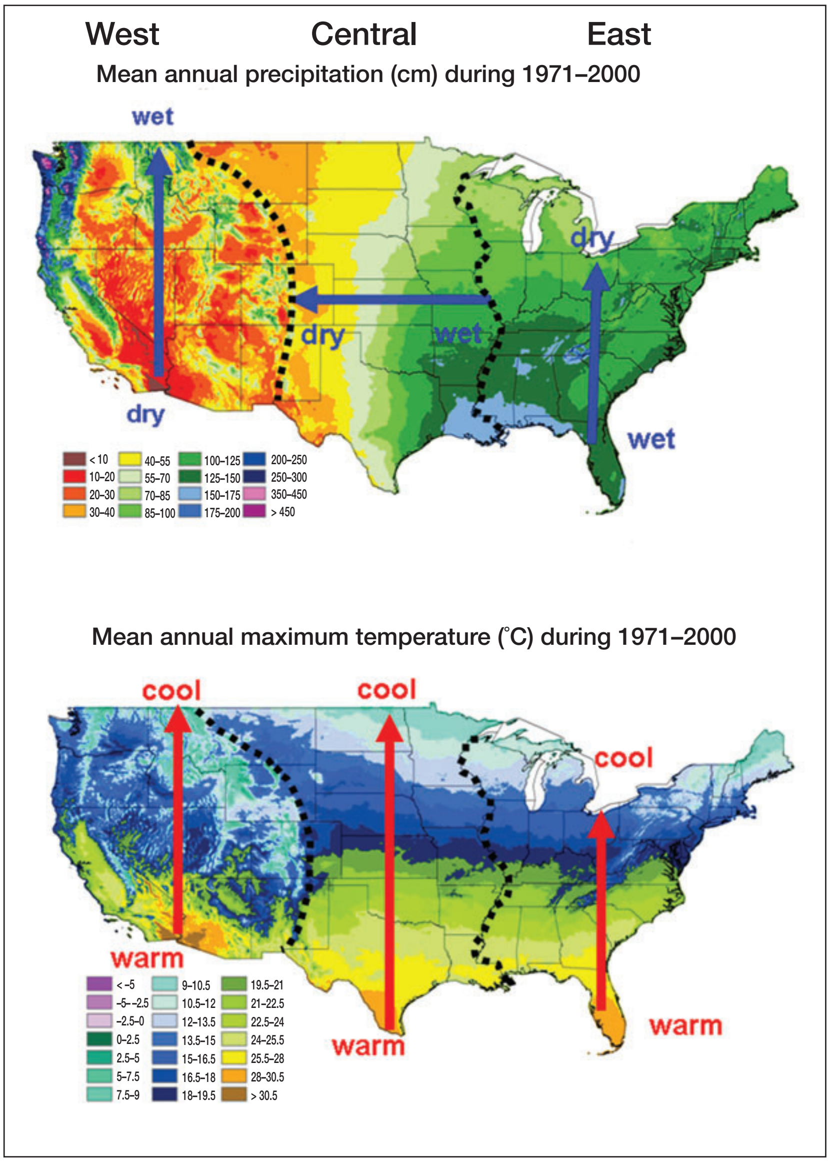

Figure 3. *The US can be divided into three general regions based on a combination of broad-scale patterns in (a) precipitation (annual total) and (b) annual maximum daily temperature. Shown are average annual values (1971–2000) from the PRISM model (http://prismclimate.org). Gradients for each climatic variable are shown in blue (precipitation) or red (temperature).*

■ Approach to conducting continental-scale research

Testing hypotheses and addressing questions from our framework (WebPanel 1) will require a new strategy for experimental design that includes a network of sites distributed across the US (as representative of North America) and the globe, and along the continental margins. Our design strategy consists of five steps, outlined below.

Step 1. Identify continental-scale patterns in broad-scale drivers

Spatial patterns in three broad-scale environmental drivers critical to our framework and relevant to ecosystems (precipitation, temperature, and N deposition) can be discerned using long-term data (> 30 years) collected from standard weather stations (www.nws.noaa.gov/) and sampling collectors of atmospheric chemistry (eg http://nadp.sws.uiuc.edu/) located throughout the US. Average seasonal and annual precipitation, and minimum, average, and maximum seasonal and annual temperatures are some of the most important climatic variables controlling ecosystem dynamics by influencing connectivity of resources across scales (Figure 3).

Step 2. Stratify a continent into regions, based on broad-scale patterns in drivers

The US can be roughly divided into Eastern, Central, and Western regions, based on a combination of broad-scale patterns in key climatic drivers. The Rocky Mountains and the Mississippi River provide general demarcations between regions to illustrate broad-scale patterns. Fine-scale variation exists within these general regions that may not follow the regional-scale pattern. Each region has contrasting patterns and correlations between precipitation and temperature (Figure 3), variable human population settlement and growth dynamics, and contrasting forecasts for climate change (IPCC 2007).

In the Eastern region of the US, the dominant climatic pattern is a positive correlation between temperature and precipitation, with both variables, in general, decreasing from south to north (Figure 3). Spatial variation in N inputs results mainly from nitrogen oxide (NO_x) emissions from agricultural regions, NO_x emissions from industrialized regions, and transport via wind and deposition as rain and snow (Figure 4). This region contains about 60% of the total US population, mostly living in coastal counties, which comprise only 17% of the land area. Most people are concentrated in the Northeast, which includes four large metropolitan areas (New York, Washington/Baltimore, Philadelphia, and Boston), and represents the most densely populated coastal region in the nation (Crossett *et al.* 2004). Most invasions of exotic plants and animals originate here, especially along the coastal flyway and major river systems (eg the Mississippi–Ohio and the St Lawrence), which serve as invasion corridors to the mid-continent. The Eastern region has a long history of intensive land use followed by abandonment (Foster and Aber 2004). Most of the forests are still regrowing and absorbing substantial

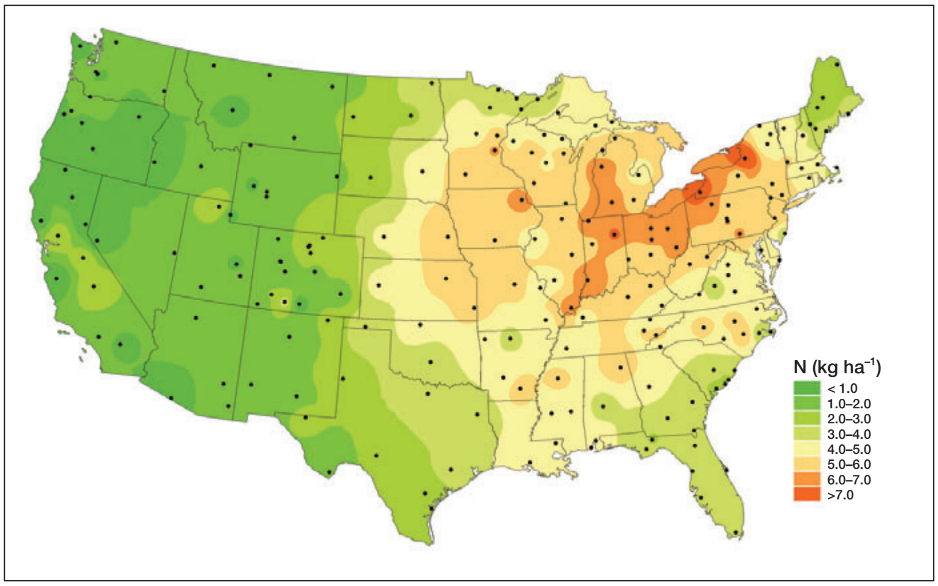

Figure 4. *Continental variation in N deposition (NADP 2007). The map depicts 5-year (2002–2006) annual weighted-average concentrations of ammonium and nitrate at National Trends Network (NTN) sites. To include sites with high proportions of snow, NADP data completeness criteria (http://nadp.sws.uiuc.edu/documentation/completeness.asp) were relaxed from 75% to 60%, except for the criterion requiring precipitation depth measurements at least 90% of the time.*

amounts of carbon, and much of the land is privately owned. Older urban areas along the eastern seaboard are losing population as extensive residential developments continue to spread in suburban and exurban lands.

In the Central region, precipitation and temperature occur as orthogonal, linear gradients that result in natural experimental opportunities with almost completely independent driving variables (Figure 3). This region includes a climate threshold of historical relevance. The 100th meridian, the north–south precipitation isoline of approximately 63.5 cm average rainfall per year, marks the boundary between rain-fed cultivation and grazing-based agriculture. This threshold has shifted back and forth with climatic cycles, with disastrous consequences to humans and the economy. The relatively flat topography eliminates orographic effects (effects related to or caused by physical geography) and allows unimpeded north–south and west–east movement of weather fronts, including some of the most violent storms on the planet. This corridor includes the central migratory flyway for birds, and provides a clear path for invasion by southern plants, animals, and pathogens into the center of the country.

The Central region encompasses much of the Mississippi River watershed, which eventually drains into the Gulf of Mexico. Large-scale N-deposition gradients are related to human population density (Figure 4). This region also includes a gradient of human population density because the eastern portion has much higher densities than the western portion. The high proportion of private ownership of agricultural land has limited the impact of federal land management agencies, in contrast with the West. In warmer parts of the Central region, urban and suburban areas are experiencing large influxes of population, resulting in an emerging north–south gradient in population.

The Western region differs from both the Eastern and Central regions because of high topographic variability (Figure 3). A relatively uniform heterogeneity of elevation-driven temperature and precipitation gradients is associated with mountain ranges across the western US. Precipitation and temperature have a strong negative correlation at both the local scale (eg elevation gradients) and the sub-continental scale (from the warm, dry south to the cool, wet north). Strong seasonality in rainfall and snowmelt drives runoff characteristics in the region. Runoff can also be altered by water management; in California, reservoirs store spring snowmelt for use in the summer, when water demand for agriculture and power is highest, effectively truncating the normal spring peak in the hydrograph (Kimmerer and Schubel 1994). Dry deposition accounts for most spatial variation in N, and high N inputs are concentrated in, and upslope of, basins with either high human population densities or intensive agriculture (Fenn *et al.* 2003). Overall, portions of the Western region have the lowest precipitation rates and human population density, and greatest public ownership of land compared to the other two regions. Not surprisingly, human population density is strongly correlated with water availability along the continental precipitation gradient, and in areas where water is concentrated by either topography or engineering. Nevertheless, the West is experiencing rapid urbanization, and harbors some of the fastest-growing metropolitan regions in the country (eg Phoenix, El Paso, Las Vegas). California had the fastest growth in coastal population in the US between 1980 and 2003, increasing by 9.9 million people (Crossett *et al.* 2004).

Step 3. Define gradients and identify sites within and among regions

Fine-scale gradients nested within broad-scale drivers can be selected to answer the same questions in different parts of the continent with different environmental conditions. These gradients are often hierarchical and related to meso- and sub-continental-scale patterns in climate, atmospheric chemistry, resource quality and quantity (eg water, nutrients), and land use. River basins, in particular, provide a sub-continental gradient in water availability that connects adjacent and non-adjacent areas via the transfer of materials, organisms, and information (WebFigure 1). Other gradients nested within river basins can be connected by other transport vectors. Understanding the interactions among these vectors and ecological patterns across spatial and temporal scales can provide new insights to continental-scale dynamics.

In the Southwest, for example, a snowmelt gradient associated with the Rio Grande starts in southern Colorado and extends to southern Texas, where the river reaches the Gulf of Mexico (WebFigure 1). Associated with this snowmelt gradient and regional-scale transport by water are gradients in temperature and precipitation that are not necessarily linear along the river, which generally flows north to south. Mosaics of land use, invasive species, infectious diseases, and nitrogen deposition occur within these regional-scale gradients. Fine-scale patterns in land use (eg rural, exurban, suburban, urban) exist, and are similar to those in many parts of the country. Ecological systems now considered wildlands, as well as managed lands, are being encroached upon by growing urban areas (see Grimm *et al.* [2008] in this issue). These urban fringes may consist of suburban and exurban sprawl areas that are expanding and creating either barriers or corridors to connectivity in adjacent or embedded wildlands. Barriers disrupt migratory pathways of animals, while corridors increase rates of spread of exotic species from cities to natural areas. Land-use gradients of wildland–urban fringe–urban areas occur throughout the country, although the characteristics of each land-use type (eg housing density, wildland type), distances between types, and connectivity in terms of the rates of transfer among types differ regionally (Grimm *et al.* [2008] in this issue).

River basins in other regions, such as the Columbia, Colorado, San Joaquin, and Missouri, have similar hydrologic, climatic, and land-use gradients that can be used to evaluate the regional- to continental-scale consequences for ecosystem dynamics of connectivity in multiple transport vectors. In addition, repeated patterns of interacting gradients can be used to investigate continental-scale terrestrial and aquatic responses to drought and other extreme climatic events (Marshall *et al.* [2008] in this issue; Williamson *et al.* [2008] in this issue), spread of invasive species and infectious diseases (Crowl *et al.* [2008] in this issue), transfer of pollutants (Grimm *et al.* [2008] in this issue), coastal instability (Hopkinson *et al.* [2008] in this issue), and disturbances, such as fire and hurricanes (Hopkinson *et al.* [2008] in this issue; Marshall *et al.* [2008] in this issue). The nested gradients selected will depend on the specific questions and responses being addressed.

Site selection should capture key characteristics of the gradients being studied. Sites that are expected to exhibit state changes in the near future (decades) and those that are expected to be comparatively stable (centuries) should be included in the design.

Step 4. Sampling scheme for measuring importance of connectivity across scales

Measuring the importance of connectivity to ecosystem dynamics in adjacent and non-contiguous areas requires coordinated and integrated efforts to sample transport processes and spatial context as well as drivers and local processes at each site. Changing pattern–process relationships across scales need to be studied explicitly (Peters *et al.* 2007). Representative samples with adequate replication are required at each scale, along with standardized indicators of change and sampling techniques (eg Herrick *et al.* 2005). Coordinated sampling among sites is insufficient without integration and an understanding of the key connectors across space and through time. For example, the same set of investigators collected similar measurements at sites located throughout the Dust Bowl region, yet they were unable to predict the continental-scale consequences of locally high plant mortality and movement of dust (Weaver and Albertson 1940).

In general, there are three parts to the sampling scheme. First, patterns and processes need to be characterized at each spatial scale. Key transport vectors (water, wind, animals, people) that move materials among spatial units and processes that occur within spatial units (eg sedimentation, fertilization, denitrification, land-use conversions) should be identified. The sources and sinks of materials need to be determined for each transport vector at each scale. The initial patterns in biota, soils, and climate should be documented along gradients of sites with different broad-scale drivers and transport vectors.

Second, short- and long-term dynamics must be documented using observations, experiments, and simulation models. Changes in pattern need to be monitored through time as the broad-scale drivers vary naturally. Drivers or patterns can also be manipulated experimentally to observe ecosystem responses under altered, yet controlled, conditions (eg Cook *et al.* 2004). Realistic mechanistic models are needed to predict ecosystem dynamics as drivers and transport of materials change along gradients and across the continent. These dynamics must be compared statistically with historical trends, if possible, to determine if changes constitute natural fluctuations, directional dynamics, or heightened variability.

Third, information should be integrated and synthesized, both within and across scales. The relative importance of local and transport processes to ecosystem dynamics needs to be compared statistically as drivers change through time. The results must be synthesized among sites, both within and across gradients and within and across regions, to compare responses and seek generalities.

Finally, this information can be used to determine when and where fine-scale processes propagate to influence large areas (adjacent or not), and the conditions under which broad-scale drivers overwhelm fine-scale processes.

Forecasting future dynamics

Addressing continental-scale questions will require development of ecological, hydrological, climatological, and sociological models that are integrated and linked with one another. Some models will address questions at local to regional scales, whereas others will incorporate fine-scale patterns and processes to simulate regional- to continental-scale dynamics. Still other models will forecast a future with conditions that are unprecedented in Earth's history; an empirical extrapolation of responses based on current or past conditions is therefore impossible and a mechanistic modeling approach will be required. In addition, these forecasting models will need to be both spatially explicit and spatially interactive to project experimental results from plots to local, regional, and continental scales (Peters *et al.* 2004b).

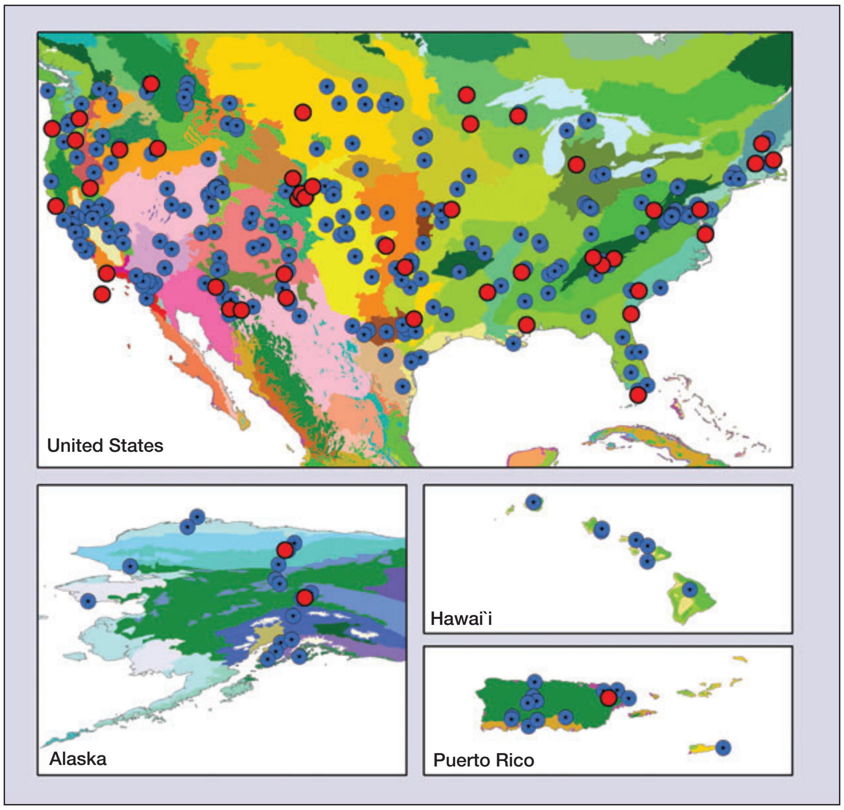

Figure 5. *Location of > 250 existing ecological research sites in the continental US, Alaska, Hawai'i, and Puerto Rico on a map of ecoregions. Red dots indicate sites in the EcoTrends project of long-term data (www.ecotrends.info); blue and red dots indicate sites in the Pole-to-Pole Ecological Lattice of Sites project. See www.worldwildlife.org for ecoregion legend. Underlying ecoregions map downloaded from www.worldwildlife.org/science/data/terreco.cfm.*

Most models thus far have been developed for specific sites with defined spatial and temporal resolutions, are based on existing input parameters, and have been validated under current environmental conditions (eg Schimel *et al.* 1997). A new generation of models is needed to address cross-scale interactions such as those posed here. These new models can build on existing models, but will require advances in programming and cyberinfrastructure to simulate responses that change through time or across space, and to identify and forecast potential thresholds. Simulating coupled socioecological systems will require linking models after resolving differences in spatial and temporal scales (eg Costanza and Voinov 2003). For example, ecohydrologic models couple biogeochemical processes with hydrologic transport to describe connectivity by water for hillslopes and watersheds (eg Tenhunen and Kabat 1999). Coupling advanced fluid-dynamic models, population dispersion models, or human demographic models with ecosystem models would dramatically improve our understanding of connectivity via multiple interacting vectors.

Relationship with existing and emerging networks of continental-scale research

Understanding connectivity in the flow of materials, organisms, and information at the continental scale requires a network of ecological research sites that provides spatial breadth (eg comprehensive representation of the full range of climatic, ecological, and socioeconomic conditions) and temporal depth (eg sites with long-term records). The concept of creating an ecological "network of networks" to study global climate change and other broad-scale phenomena dates back to a 1991 workshop (Bledsoe and Barber 1993). The report called for the creation of a network that included the National Science Foundation's Long Term Ecological Research (LTER) Network and Land-Margin Ecosystem Research sites (now folded into the LTER Program), National Oceanographic and Atmospheric Administration Marine Sanctuaries, the Department of Energy Research Park Network, the US National Park Service, and the Man and the Biosphere Reserves. Today, such an ecological network of networks in the US would also include US Geological Service (USGS) and USDA Forest Service and Agricultural Research Service sites, biological field stations and marine laboratories (eg Organization of Biological Field Stations, National Association of Marine Laboratories), the AmeriFlux network, and emerging environmental observatories (eg National Ecological Observatory Network, WATERS, Oceans Observatories Initiative). This network would encompass sites in every major ecoregion (Figure 5) to include the full range of climatic and environmental conditions. The network would also encompass valuable, long-term observations from an array of research sites that are presently being compiled in EcoTrends (www.ecotrends.info), a collaborative effort, designed to make long-term ecological data accessible for science and education.

Achieving a continental-scale understanding of the multiscale connectivity interactions raised here necessitates international collaboration to include Canada's Environmental Monitoring and Assessment Network, Mexico's National Commission for the Knowledge and Use of Biodiversity (CONABIO), and other relevant research sites and networks throughout North America. The availability of data from a North American "network of networks" would substantially augment the knowledge base that is emerging from international research networks like FLUXNET, the International Long Term Ecological Research Network, the OCEAN Sustained Interdisciplinary Timeseries Environment Observation System, the Global Lake Ecological Observatory Network, and the International Geosphere–Biosphere Program. Cyberinfrastructure would provide the data and resources for understanding ecological connectivity at the global scale and would entail closer integration of US (eg USGS NBII, NASA DAACs, Knowledge Network for Biocomplexity) and global (eg Committee on Earth Observation Satellites International Directory Network, the Global Observing Systems Information Center, the International Oceanographic Data and Information Exchange) networks. An initial step toward networking ecological sites globally is being made with the development of a common web interface that allows information about sites to be made easily accessible to users.

Conclusions

Given the availability of existing global networks, this is an exciting time for ecological research. Together, these networks provide a platform for continental-scale research with their legacy data, site-based knowledge and expertise, and, in many cases, shared concerns about the consequences of an ever-changing, increasingly connected world. A framework focused on connectivity provides a way to integrate the information being collected in a way that both facilitates and shows the necessity for collaborative research across multiple scales. The integrated understanding of an increasingly connected world derived from a global network of networks is essential for the continental-scale science needed to understand and forecast the causes and consequences of anthropogenic global environmental change.

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