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RESEARCH ARTICLE

Informing landscape planning and design for sustaining ecosystem services from existing spatial patterns and knowledge

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Abstract Over the last decade we have seen an increased emphasis in environmental management and policies aimed at maintaining and restoring multiple ecosystem services at landscape scales. This emphasis has resulted from the recognition that management of specific environmental targets and ecosystem services requires an understanding of landscape processes and the spatial scales that maintain those targets and services. Moreover, we have become increasingly aware of the influence of broad-scale drivers such as climate change on landscape processes and the ecosystem services they support. Studies and assessments on the relative success of environmental policies and landscape designs in maintaining landscape processes and ecosystem services is mostly lacking. This likely reflects the relatively high cost of maintaining a commitment to implement and maintain monitoring programs that document responses of landscape processes and ecosystem services to different landscape policies and designs. However, we argue that there is considerable variation in natural and human-caused landscape pattern at local to continental scales and that this variation may facilitate analyses of how environmental targets and ecosystem services have responded to such patterns. Moreover, wall-to-wall spatial data on land cover and land use at national scales may permit characterization and mapping of different landscape pattern gradients. We discuss four broad and interrelated focus areas that should enhance our understanding of how landscape pattern influences ecosystem services: (1) characterizing and mapping landscape pattern gradients; (2) quantifying relationships between landscape patterns and environmental targets and ecosystem services, (3) evaluating landscape patterns

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with regards to multiple ecosystem services, and (4) applying adaptive management concepts to improve the effectiveness of specific landscape designs in sustaining ecosystem services. We discuss opportunities as well as challenges in each of these four areas. We believe that this agenda could lead to spatially explicit solutions in managing a range of environmental targets and ecosystem services. Spatially explicit options are critical in managing and protecting landscapes, especially given that communities and organizations are often limited in their capacity to make changes at landscape scales. The issues and potential solutions discussed in this paper expand upon the call by Nassauer and Opdam (Landscape Ecol 23:633–644, 2008) to include design as a fundamental element in landscape ecology research by evaluating natural and human-caused (planned or designed) landscape patterns and their influence on ecosystem services. It also expands upon the idea of "learning by doing" to include "learning from what has already been done."

Keywords Landscape gradients · Landscape pattern · Ecosystem services · Adaptive management

Introduction

The twentieth century has witnessed an unprecedented influence of humankind on fundamental environmental and physical processes that sustain life on earth (Ojima et al. 1994; McCarthy et al. 2001; EEA 2004). Through modifications of the earth's surface and global biogeochemical cycles, humankind has increased the pace and amount of productive ecosystems lost to desertification, reduced availability and reliability of clean and abundant sources of water and food, increased risks to natural hazards such as floods and fires, and increased disease and exposure to harmful chemicals through environmental modifications and release of harmful chemicals into the environment (Houghton 1994; Ojima et al. 1994; Bellamy et al. 2005; Young and Harris 2005). We are also starting to observe broad-scale ecological impacts of global climate change, including changes in the frequency, size, and severity of disturbance events (Westerling et al. 2006) and decline of widely distributed species such as the polar bear (Stirling and Derocher 2007). The specific human influences and drivers of these observed changes are complex and multi-scaled in nature (Carpenter et al. 2005).

Over the last decade, we have seen an increased emphasis on landscape perspectives in environmental planning at multiple scales (Potschin and Haines-Young 2006; Musacchio 2009a, b; Termorshuizen and Opdam 2009; Wiens 2009; Pearson and McAlpine 2010; Wu 2010; Theobald et al. 2012). For example, in the US, Landscape Conservation Cooperatives, consisting of a number of agencies and stakeholders, have been established to promote and apply landscape perspectives and concepts into conservation (Austen 2011). In Europe, projects like Econnect have helped establish policies for broad-scale landscape designs, including corridors (Füreder et al. 2011). Similar studies in the US have helped establish priorities for conservation corridors across multi-state areas (Carr et al. 2002; Western Governors' Association 2008; Theobald et al. 2012). In the Netherlands, corridors of water, wetlands, and green space (also known as "blue-green veining") are being established within agricultural landscapes to provide wildlife migration corridors and sources of natural predation on agricultural pests (Grashof-Bokdam et al. 2009; Steingrover et al. 2010). Spatially explicit landscape designs that take into account the broader landscape context are seen as critical in mitigating and adapting to broad-scale drivers associated with global change (Opdam and Wascher 2004; Wiens 2009; Pearson and McAlpine 2010; Verboom et al. 2010; Fleishman et al. 2011; Wiens et al. 2011; Theobald et al. 2012). Moreover, maintaining and restoring key landscape elements at multiple spatial scales may be critical in sustaining a wide range of ecosystem functions and services (de Grott 2006; Holzkaemper et al. 2006; Opdam et al. 2006; Egoh et al. 2007; Kienast et al. 2009; Pearson and Gorman 2010; Ryan et al. 2010), even within developed landscapes (Grashof-Bokdam et al. 2009; Musacchio 2009b; Wu 2010).

Two important aspects of restoring and sustaining landscape functions and ecosystem services are the concepts of landscape design (Opdam et al. 2006; Nassauer and Opdam 2008; Musacchio 2009b) and adaptive management (Walters 1986; Lindenmayer et al. 2008) or "learning by doing" (Walters and Holling 1990; Opdam 2010). Nassauer and Opdam (2008) urged the field of landscape ecology to include research into a third aspect of pattern and process: design. They argued that this will facilitate greater use of landscape ecology principles in environmental management. It also provides a greater union between theoretical and applied aspects of landscape ecology that have often divided research in the US versus that in Europe (Wu and Hobbs 2007). Adaptive management or the "learn by doing" approaches are important aspects of improving landscape designs, improving management and/or conservation results as they help increase the effectiveness of management prescriptions, and reducing uncertainty in conservation planning (Walters 1986; Walters and Holling 1990; Butterfield and Malmstrom 2006; Bormann et al. 2007; Nichols et al. 2007; Vernier et al. 2009). A critical aspect of these approaches is implementation of monitoring systems to evaluate responses of important ecological characteristics and functions to conservation measures and policies (Nichols et al. 2007). Unfortunately, very few projects involve sustained monitoring that permit an analysis of responses to on-the-ground management and environmental policies, but especially at broader landscape scales where costs of such monitoring are often cost-prohibitive (Bernhardt et al. 2005; Bunnell 2006; Lindenmayer et al. 2008).

Experiments linking landscape composition and pattern to ecological processes and ecosystem services have been limited in geographic scale and scope because of costs and logistics (McGarigal and Cushman 2002). For example, most studies involving experimental manipulations of landscapes and responses of biota have been limited in scale to a few to tens of meters in size (Wiens et al. 1997; With and Pavuk 2011). Many studies in landscape ecology involving larger geographic areas often rely on simulated changes in landscape composition and pattern and modeled responses of species (see Holzkaemper et al. 2006 for an example).

Observational systems and broad-scale monitoring provide a potential alternative to cost prohibitive, broad-scale experimental manipulations (Parr et al. 2003; Sagarin 2009; Sagarin and Pauchard 2010). Wall-to-wall spatial data now exist that permit analysis of spatial composition, pattern, and position of key landscape features and attributes from local to continental scales, including land cover (Vogelmann et al. 2001; Feranec et al. 2007, Jaeger and Madrinan 2011), elevation (Gesch et al. 2002), surface water flow and river and stream networks (Jones et al. 2010a), and soils (Levick et al. 2004; Montanarella et al. 2006). For the US and Europe there are now three dates (early 1990s, 2000/2001, and 2006) of land cover data that permit an analysis of landscape change (Xian et al. 2009, Jaeger and Madrinan 2011, respectively). Moreover, these data offer the potential to characterize and map variation in landscape pattern resulting from natural and human-related processes, including those related to designed landscapes (e.g., green infrastructure in urban areas, Kong and Nakagoshi 2006).

We discuss the potential to expand upon the concept of design in landscape ecology research highlighted by Nassauer and Opdam (2008) and Opdam (2010) by taking advantage of variation in landscape patterns that already exist. The basic aim is to understand how landscape functions and ecosystem services have responded to the large variety and number of existing landscape patterns, including those resulting from intentional planning and design. As such, the results should be useful in understanding how to design, protect, and enhance landscapes relative to ecosystem services at multiple scales. We discuss four general but interrelated activities where landscape ecology can contribute to the sustainability of environmental targets and ecosystem services: (1) characterizing and mapping landscape pattern gradients, (2) relating landscape pattern to ecosystem services and environmental targets, (3) evaluating landscape pattern and multiple ecosystem services, and (4) applying an adaptive management framework with regards to landscape design. We also discuss opportunities and challenges within each of these general areas.

Characterizing and mapping landscape patterns important to ecosystem services

Studies of landscapes suggest that there is considerable variation in land cover and land cover pattern across the US (Theobald and Romme 2007; Jones et al. 2010a; Wickham et al. 2008, 2010, 2011), Europe (Kienast et al. 2009; Jaeger and Madrinan 2011), China (Liu and Tian 2010), and globally (Bartholome and Belward 2005). Some of these patterns may have resulted from major biophysical drivers that shape the landscape whereas other patterns may result from some form of human intervention or design (Nassauer and Opdam 2008; Jaeger and Madrinan 2011). The increasing availability of digital spatial data spanning entire continents at relatively fine scales (1–30 m) make it possible to characterize and map detailed landscape composition and pattern (see Jones et al. 2010a and Wickham et al. 2011 for examples). In the US and Europe, wall-to-wall Landsat-based land cover data are available for three different dates (early 1990s, early 2000s, 2006; Feranec et al. 2007; Xian et al. 2009). Moreover, Landsat data have been used to assess landscape change across China (Liu et al. 2005; Liu and Tian 2010), Southeast Asia (Giri et al. 2003), Canada (Fraser et al. 2011), as well as globally for mangrove forests (Giri et al. 2011). Land cover classification algorithms have improved since the early 1990s and new land cover products provide relatively detailed information on landscape composition and pattern. Moreover, high resolution remote sensing data (aerial photography and data from commercial satellites) provide fine-scale (1–2 m) data on important landscape features such as fence rows, hedge rows, riparian zones, and plant species distributions (Davies et al. 2010). For example, the National Agriculture Imagery Program (NAIP) provides 1-m resolution, digital aerial photography for the several areas across the conterminous US (http://datagateway.nrcs.usda.gov/). Data are collected on approximately 2-year cycles with the earliest data from 2003.

A key objective is to characterize and map landscape patterns across a wide range of geographic biophysical settings into landscape composition and pattern gradients. Gradient analysis has been used to characterize different types of landscape composition and pattern (Luck and Wu 2002; Cifaldi et al. 2004; Neel et al. 2004; Kong and Nakagoshi 2006). It also has been used to evaluate responses of ecological processes and attributes to different amounts of land cover and land use at different spatial scales (Blair and Launer 1997; McDonnell et al. 2001; Ator et al. 2003; Honnay et al. 2003; Cifaldi et al. 2004; Thuiller et al. 2004; Cushman et al. 2007; Grimm et al. 2008; Zhang et al. 2008; Cuffney et al. 2010). However, these studies don't explicitly consider landscape pattern gradients and their relationship to landscape processes and ecosystem services. As such, they provide little information on the importance of pattern and position (location) of key landscape features (e.g., wetlands, riparian buffers, migration corridors, etc.) in sustaining landscape processes and ecosystem services. Several studies have shown that the value of specific landscape elements to species (e.g., corridors) often depends on the composition and pattern of the surrounding landscape as well as individual species characteristics (Andren 1994; Gustafson and Gardner 1996; Ricketts 2001; Kie et al. 2002; Steffan-Dewenter 2003; Coulon et al. 2004; Murphy and Lovett-Doust 2004; Tubelis et al. 2004; Dixon et al. 2006; Holzkaemper et al. 2006; Horskins et al. 2006; Cushman et al. 2012; Lange et al. 2012).

Although it is possible to characterize and map areas that have some form of protective status (e.g., via the Protected Areas Databases, PAD-US 2009), other types of landscape patterns resulting from biophysical constraints, conservation plans, and designs, especially those in urbanizing and agricultural areas, are harder to find. Spatial data on urban designs are highly fragmented and local in nature (Wu 2010). Moreover, most landscape metrics dealing with land cover composition and connectivity/fragmentation fail to capture linear features and hub-and-corridor spatial patterns (Fig. 1). And yet linear features, such as forested riparian zones and corridors are known to enhance wildlife populations and other ecosystem services (Naiman et al. 1993; Spackman and Hughes 1995; Baudry et al. 2003; Coulon et al. 2004; Fabos and Ryan 2004; Burgman et al. 2005; Damschen et al. 2006; Dixon et al. 2006; Lees and Peres 2008; Baron et al. 2009; Jones et al. 2010a). Such features often provide a disproportionate value to conservation of ecosystems services within human-dominated landscapes (Jones et al. 2006; Oneal and Rotenberry 2009; Cuffney et al. 2010; Knight et al. 2010; Mayer et al. 2010).

A potential approach to characterize and map landscape pattern gradients is to develop a set of observed to expected (O/E) values for different types of patterns in landscapes. O/E approaches have been used extensively in comparative assessments of aquatic organisms (Van Sickle et al. 2005; Hawkins 2006) and birds (O'Connell et al. 2000), and they provide a way to compare ecological conditions across broad geographical areas. Expected values for specific landscape patterns could be generated from neutral models (Neel et al. 2004; Gardner and Urban 2007; Riitters et al. 2009). In developed and protected landscapes, we might expect significant departures of certain landscape pattern characteristics from those patterns generated from neutral model landscapes. Two examples are given to illustrate the potential of this approach: one related to natural land cover connectivity and one related to agricultural land use. Each of these is related to one or more ecosystem

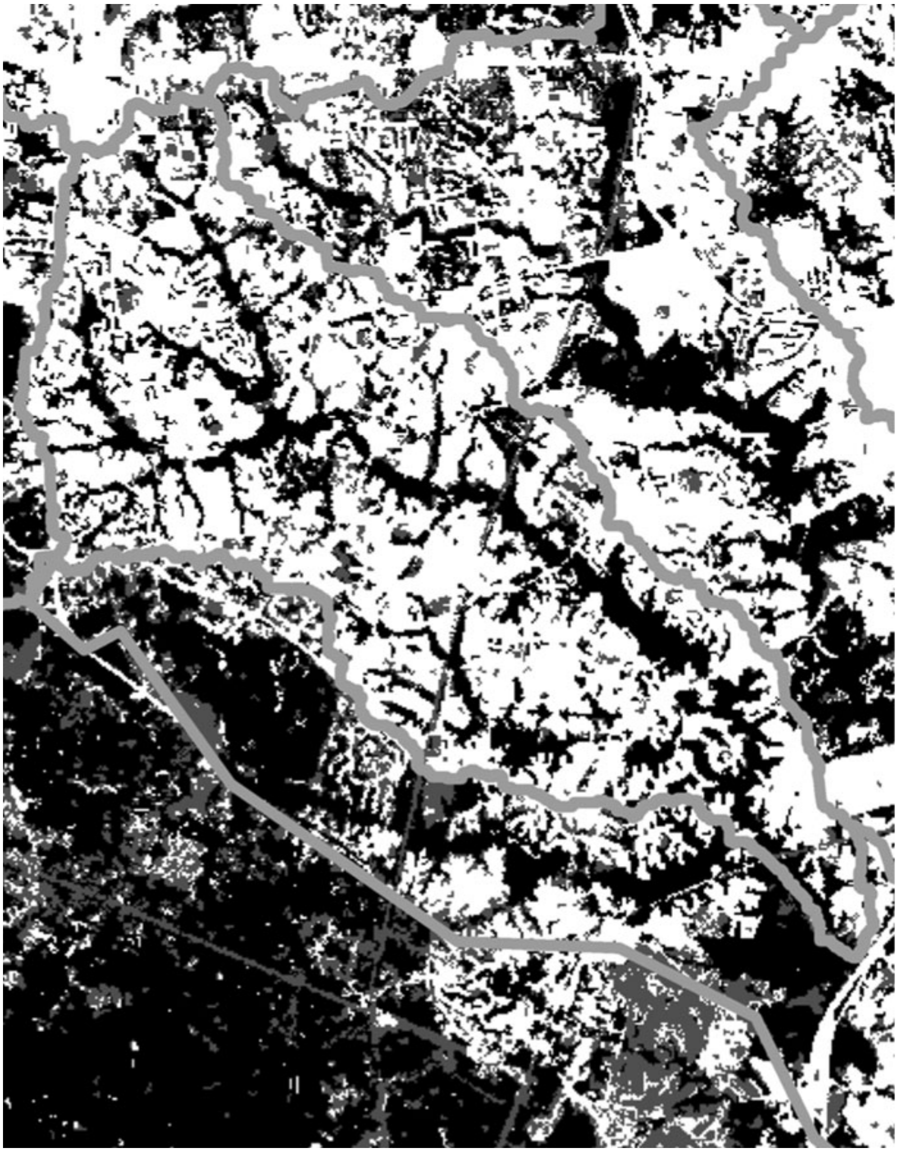

Fig. 1 Example of linear features (streams) connecting forests in a northern Virginia USA landscape. *Gray* or *black* indicates natural land cover (mostly forests) and *white* indicates developed lands (agricultural and built environment). The linear network of forests is also connected to a large block of continuous forest (hub)

service and they are often important considerations in environmental planning and conservation.

Figure 2 represents a set of neutral landscapes where the focal land cover area is related to connectivity (degree of spatial autocorrelation among adjacent cells; Neel et al. 2004). Of particular interest are those landscapes that occupy the lower right hand corner of Fig. 2. These landscapes have higher levels of connectivity given the amount of the focal land cover type; their patterns may reflect natural biophysical constraints or human-caused designs (e.g., conservation reserves). However, none of the neutral model outcomes for landscapes in the lower right hand corner of the figure reflect highly connected focal land cover types along linear pathways (e.g., forests connected along stream networks through an urban or agricultural area). This may result from the way connectivity is measured; highly linear focal land cover distribution will have higher amounts of non-focal edge and hence lower connectivity values. Moreover, there are no circumstances where linear pathways are connected to larger core areas (another potential pattern resulting from conservation design). An important research question is whether or not this

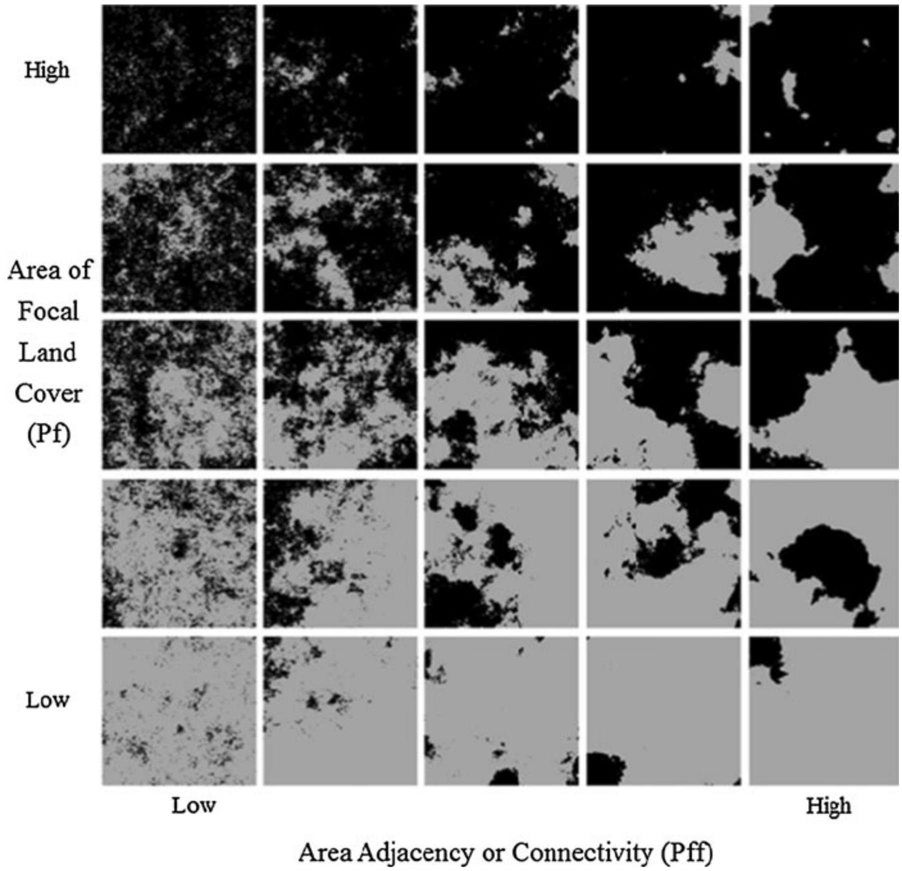

Fig. 2 Neutral model landscapes comparing the amount of a focal land cover type (Pf = natural land cover indicated by the *darker color*) versus the relative connectivity of the focal land cover (Pff). Modified from Neel et al. (2004)

type of neutral model approach can be used to identify and map linear and hub-and-spoke landscape patterns within agriculture and urban landscapes.

Riitters et al. (2009) used morphological spatial pattern analysis to identify spatial characteristics of land cover pattern. This approach results in a set of landscape pattern types that differ from more traditional landscape analysis and mapping, including mapping of core areas, islets, and connectors (Riitters et al. 2009). Moreover, Riitters et al. (2009) generated neutral percolation models and were able to demonstrate abrupt phase transitions for different landscape pattern types. This approach may be one way to identify and map designed landscapes across broad geographic areas. Moreover, Riitters et al. (2009) used sliding windows of varying sizes to evaluate how the patterns change among different spatial scales. Being able to evaluate landscape patterns at different spatial scales will be important as different types of landscape functions and associated ecosystem services often correspond to different scales (Turner 1989, 2005). However, the sliding window approach may limit the capacity to capture and map narrow linear features (e.g. natural land cover riparian buffers) in developed landscapes, but especially at larger scales (larger windows) since larger windows would capture more surrounding anthropogenic cover.

Another approach to characterize and map areas with linear landscape features might involve generating neutral land cover pattern and then comparing those patterns to the distribution of stream and hydrological networks, or perhaps to indicators of topographic relief. High amounts of natural land cover along linear features such as stream networks, but especially within developed landscapes, are likely to reflect either natural biophysical constraints (e.g., too wet or steep to develop) or human-related design and environmental management, or some combination of both. These types of linear pathways may represent intentional landscape designs to protect stream networks and to create corridors for animal migration, among other things.

Other existing landscape metrics may offer potential to characterize and map different types of landscape patterns. The clumpy index measures class aggregation independently of class area (Neel et al. 2004). As such it is a useful metric to quantify the relative importance of habitat area and fragmentation (Cushman et al. 2012). The correlation length index (Short Bull et al. 2011) may provide a way to characterize and map linear landscape pattern. This index quantifies the extensiveness of patches in spanning the landscape in terms of the average distance an organism could travel in a random direction and remain in habitat when dropped randomly in a habitat patch. The patch cohesion and aggregation index are metrics that quantify class aggregation (Opdam et al. 2003). The aggregation index is commonly used in fragmentation studies, and patch cohesion was shown by Schumaker (1996) to be a strong indicator of habitat fragmentation effects on population connectivity. However, we are uncertain as to how well these approaches will work over extensive areas (e.g., regional and national scales).

The second example of expected to observed landscape pattern involves the distribution of agriculture within a landscape. Agriculture and cropland on steep slopes have been correlated to increased nutrients and sediment in streams which can affect water quality and stream biota (Jones et al. 2001). A neutral model of cropland distribution as it relates to steep slopes compared to the actual distribution of cropland on steep slopes could be used to identify those areas where environmental policies have been put into place, or areas where there is a disproportionate amount of cropland on steep slopes (areas vulnerable to soil loss, erosion, and sedimentation of surface waters). Moreover, this analysis could be expanded to include the distribution of cropland on hydric and erosive soils. Natural vegetation on steep slopes and hydric and erosive soils helps reduce loss of vegetation productivity, soil nutrients and water, and prevents nutrient and sediment loading to aquatic ecosystems.

Linear features can be evaluated along a gradient of the amount of anthropogenic land cover (agriculture and urban) in the landscape (landscape context). Additionally, hub (core) and spoke (linear features such as corridors) patterns can also be evaluated along gradients of landscape context (e.g., the amount of natural vs. anthropogenic land cover). Digital data on soils, geology, and elevation can also be used to establish and evaluate landscape gradients (Cushman et al. 2007). For example, the effectiveness of linear conservation features such as forested riparian zones may vary by with stream network density, stream gradient, and ground water-surface water interactions (Jones et al. 2010a). Landscape pattern gradients also can be established based on the different sizes and shapes of landscape features. For example, riparian zones can be characterized by the types of vegetation and length and width. These attributes influence the quality and types of ecosystem services associated with riparian zones (Jones et al. 2010a).

Quantifying relationships between landscape pattern and ecosystem services

Once landscape pattern gradients have been characterized and mapped, the next task is to evaluate responses of specific landscape functions and ecosystem services along these gradients. This presents a major challenge given the nature of existing studies and monitoring networks linking landscape pattern to ecological processes and ecosystem services. Conceptually, the relationships between landscape composition, landscape processes, and ecosystem services are fairly straight forward (Turner 1989; de Grott 2006; Willemen et al. 2008; Musacchio 2009a, b; Nelson et al. 2009; Termorshuizen and Opdam 2009; Pearson and McAlpine 2010; Jaeger and Madrinan 2011). However, empirical documentation of these relationships has been difficult, but especially the separate influence of pattern from composition and amount (Turner 2005; With and Pavuk 2011). There have been a number of studies linking in situ measures of environmental attributes (e.g., bird species abundance and distribution) and ecosystem services to landscape composition and pattern (for example, see Cushman and McGarigal 2004). Corridors, especially through developed landscapes, have been shown to positively affect species abundance and distribution (Spackman and Hughes 1995; Damschen et al. 2006; Dixon et al. 2006; Lees and Peres 2008; Oneal and Rotenberry 2009), but these responses can vary by species (Mech and Hallett 2001; Horskins et al. 2006). Natural land cover in riparian buffers and along surface water flow pathways within watersheds has been show to mitigate the impacts of developed land on surface waters (Lowrance et al. 1984; Storey and Cowley 1997; Jones et al. 2001; Sweeney et al. 2004; Baker et al. 2006, Barker et al. 2006; Jones et al. 2006; Knight et al. 2010; Mayer et al. 2010). A few studies have evaluated multiple ecosystem services and their relationships to important landscape features such as riparian zones (Bolund and Hunhammar 1999; Sweeney et al. 2004; Kienast et al. 2009; Johnson et al. 2010). Despite these findings, there has been limited success separating out the influences of pattern from composition in field studies (Fahrig 2003; With and Pavuk 2011), perhaps as a function of the types of landscape metrics used in the analyses. Most studies documenting separation of pattern (connectivity and fragmentation indices) from composition have involved landscape and population simulations (for example, see Cushman et al. 2012). As discussed earlier, existing landscape metrics (e.g., size, shapes, and adjacency indices) may not capture fundamental patterns in landscapes important to landscapes processes and ecosystem services. The following is a summary of some potential approaches to link landscape pattern to ecosystem services.

Responses to gradients based on in situ monitoring networks

Most existing monitoring programs lack sampling designs that are based on landscape composition and pattern gradients (Cuffney et al. 2010; Jones et al. 2010b). Additionally, there has been little commitment to implementing and sustaining monitoring to evaluate response of landscape processes and ecosystems services to different landscape designs (e.g., corridors through developed areas, riparian restoration, etc.). Moreover, inconsistencies in monitoring protocols and sampling designs used in local-scale projects preclude comparisons across broader geographic areas. Lack of broader-scale studies on landscape pattern are rare due to costs, historical management focuses, and lack of monitoring data documenting response (Haddad et al. 2003, Bernhardt et al. 2005; Lindenmayer et al. 2008). Moreover, there has been a lack of studies that specifically address broad-scale landscape pattern gradients that evaluate the effectiveness of different types of designs (Nassauer and Opdam 2008).

Despite these shortcomings, there is a need to evaluate existing in situ monitoring programs and their potential to quantify relationships between ecosystem services and landscape composition and pattern gradients. As mentioned earlier, observation systems offer a potentially powerful way to evaluate environmental change and likely drivers and causes of change (Parr et al. 2003; Sagarin 2009; Sagarin and Pauchard 2010). Observation systems can be used to create statistical functions or models, and to validate a variety of process models (Jones et al. 2010b). In our case, we want to know if existing monitoring networks will allow us to evaluate landscape patterns and the responses of ecosystem services to those patterns.

Many existing monitoring programs have been designed to measure certain attributes and processes of specific species and ecosystems (Jones et al. 2010b). For example, aquatic and terrestrial species measures are collected on different monitoring networks (Jones et al. 2010b). Some monitoring networks may be of sufficient spatial distribution and density to assess different landscape processes and ecosystem services on the same landscape pattern gradients (e.g., the Forest Inventory and Analysis, Cushman et al. 2007; Cushman and McKelvey 2010). In some cases, national monitoring networks have added additional sites to evaluate landscape composition gradients. For example, the US National Water Quality Assessment Program (NAWQA) added several in situ sites along urban to exurban gradients to determine how streams responded to different intensities of urbanization (Cuffney et al. 2010). Moreover, monitoring programs with systematic designs and protocols permit analyses of landscape pattern and ecosystem services at multiple scales over broad areas. Herrick et al. (2010) and Carlisle et al. (2010) were able to conduct national-scale assessments of ecosystem productivity and aquatic biota, respectively, because the monitoring networks they used had standard designs and indicators. Wickham et al. (2008, 2010, 2011) were able to conduct US-wide assessments of forest fragmentation, green infrastructure, and drinking water quality, respectively, because of nationally consistent land cover data. Jones et al. (2006) established the importance of forested riparian buffers in filtering nitrogen in streams in different biophysical settings across the mid-Atlantic Region of the US by using standardized in situ monitoring data and regionally consistent land cover data. O'Connor et al. (1996) related patterns of breeding bird diversity to environmental correlates at national to regional scales using data from the Breeding Bird Survey (Sauer et al. 2003). They were able to show regional differences in how bird diversity responded to multiple biophysical drivers.

An important task is to evaluate the degree to which existing monitoring networks capture landscape pattern gradients. Results from this type of evaluation might influence changes to sampling designs of existing monitoring networks, similar to those changes implemented by NAWQA (Cuffney et al. 2010).

Landscape models

There are a number of existing landscape models that evaluate the potential influence of landscape composition and pattern on environmental targets and ecosystem services. Most of these models use look-up tables to relate landscape attributes and functions to environmental targets and ecosystem services. For example, many of the existing projects on ecosystem services use look-up tables to attribute particular ecosystem services to land cover or other biophysical data (Naidoo and Ricketts 2006; Troy and Wilson 2006; Kienast et al. 2009; Nelson et al. 2009). Expert opinion is another approach used to attribute landscape functions and ecosystem services to land cover and other biophysical data (Failing et al. 2004; Willemen et al. 2008; Vernier et al. 2009). Resampling of existing data provides a way to estimate uncertainty in the model results (Wickham et al. 2002; Wickham and Wade 2002). One issue with these types of models is that they are vertical in nature with little or no horizontal relationships or functions (Jones et al. 2010b). For example, the RUSLE soil loss and SWAT watershed models attribute grid cells from a combination of digital biophysical data and look-up tables to evaluate soil loss and sediment loads, respectively (Nyakatawa et al. 2001; Betriel et al. 2011). Unfortunately, none of these models evaluates different landscape pattern gradients where interactions across the landscape are important (e.g., corridors). However, hydrologic models often include grid cell to grid cell interactions and can be used to evaluate the importance of vegetation and flow processes in landscape (Voinov et al. 2004; Ludwig et al. 2005). Graph theory, circuit theory, and landscape genetics are three relatively new approaches that evaluate the importance of landscape position and pattern to movement and evolution of biota. Graph theory evaluates potential movement patterns by species given the distribution of patches of suitable habitat (Urban and Keitt 2001; Decout et al. 2012). Circuit theory evaluates landscape flows and connectivity for ecological processes using resistance, current, and voltage factors from electric circuit theory (McRae et al. 2008). When applied to raster maps it can find patches and specific areas in landscapes that are critical to specific ecological flows and movement across landscapes. Landscape genetics uses molecular markers to evaluate spatial relationships between observed patterns in landscape composition and pattern (e.g. preferred habitat distribution and quality, corridors, landscape context, barriers to migration) and genetic distances among populations in a landscape (Mech and Hallett 2001; Manel et al. 2003; Coulon et al. 2004; Dixon et al. 2006; Horskins et al. 2006; Landguth and Cushman 2010; Short Bull et al. 2011; Cushman et al. 2012). As such, it is possible to evaluate the functional effectiveness of habitat corridors (Dixon et al. 2006; Horskins et al. 2006) and the role of landscape context as it influences migration and population connectivity (Cushman et al. 2012). Moreover, graph and/or circuit theory combined with landscape genetics provides a framework to identify critical pathways of movement by species in landscapes and the relationships of those pathways to landscape features and their distributions (Garroway et al. 2008; Luque et al. 2012). The primary limitation of this approach is the lack of data on multiple species over broad areas.

Meta-analysis of existing studies is another approach that can be used to model relationships between landscape composition and pattern and environmental targets and ecosystems services. This approach uses key words to find data on specific research questions. For example, Allen et al. (2010) used a meta-analysis to evaluate global-scale tree dieback associated with warming. Egoh et al. (2007) used a meta-analysis to evaluate the use of ecosystem service concepts in conservation assessments. Benayas et al. (2009) used a meta-analysis to characterize enhancement of biodiversity and ecosystem services in ecological restoration. Feld et al. (2009) used a meta-analysis to characterize the type and scale of ecosystem service studies. A key need is to conduct a meta-analysis of landscape pattern as it relates to various landscape and ecosystem processes.

The importance of landscape composition and pattern to particular landscape functions and ecosystem services may vary depending on the biophysical setting and spatial variation in drivers and stressors. For example, Jones et al. (2006) found that a higher percentage of forest at the catchment scale was needed to mitigate the impacts of atmospheric nitrogen; areas with higher nitrogen deposition needed more forest than in areas with lower nitrogen deposition to maintain stream nitrogen concentrations at acceptable levels. Wylie et al. (2009) showed that vegetation productivity (measured as the Normalized Difference Vegetation Index or NDVI) was a function of several biophysical attributes as well as disturbance. Additionally, they developed an "expected to observed" methodology to identify areas that were over-performing or under-performing with regards to long-term NDVI histories. Such an approach might help identify how different landscape patterns influence certain ecosystem services.

Landscape patterns that optimize multiple ecosystem services

An important aspect of evaluating landscape pattern is whether or not there are certain landscape patterns at multiple scales that result in synergies among different types of ecosystem services (Wu and Hobbs 2002; Naidoo et al. 2008). Thus far most studies have found limited spatial overlap between ecosystem services (Naidoo and Ricketts 2006; Naidoo et al. 2008; O'Farrell et al. 2010), although some geographic areas possess multiple ecosystem service synergisms. The functional unit and associated scale of those units as they relate to specific ecosystem services may also account for lack of spatial concordance among different ecosystem services (Costanza 2008; Benayas et al. 2009; Johnson et al. 2012). For example, certain water-related ecosystem services (e.g., filtration of nutrients and sediment) may result from landscape and biophysical patterns at catchment scales whereas bird species diversity might result from a combination of specific habitats at local and regional scales. Therefore, it is important to evaluate the type and scales of functional landscapes for each environmental target or ecosystem service. Different types of landscape characterizations and modeling approaches may be needed to assess landscape patterns for any given area with regard to multiple ecosystem services (Costanza 2008; Johnson et al. 2012).

More complex models have been developed to assess multi-ecosystem service responses to landscape composition and pattern (Boumans et al. 2002; Feng et al. 2011) but these models require a great deal of data and process knowledge input. For example the Natural Capital Project (Nelson et al. 2009) has developed a three-tier modeling system to assess multiple ecosystem services; tier 1 involves a relatively course level assessment of ecosystem services (e.g., look-up tables by land cover type) whereas tiers 2 and 3 involve higher spatial resolution and more detailed processes models. Because of the limited amount of data (at finer scales) and process models, the project has been largely limited to tier 1 assessments (Naidoo et al. 2008). However, new biophysical database are driving down the scale of resolution over extensive areas and make detailed assessments more feasible (Jones et al. 2010a, b).

Scenario analysis has been used to evaluate the potential response of multiple ecosystem services to alternative landscape design solutions (Baker et al. 2004). Moreover, it has been used to assess the vulnerability of multiple ecosystem services to models of future environmental change (Busch 2006; Metzger et al. 2008). Scenario analysis requires development of spatial explicit landscape models for different ecosystem services and different approaches to model future landscape change. Baker et al. (2004) used public workshops to generate different scenarios for future landscape change (e.g. current trend, maximize development and resource extraction, maximize conservation); spatial explicit models of ecosystem services were then applied to the alternative landscape futures to help the public visualize how ecosystem services would change with a different set of options.

A key question with regards to landscape design is *can we make developed landscapes function more like natural landscapes with regard to multiple ecosystem services?* Wickham et al. (2002b) found that the amount of nitrogen and phosphorus in surface waters varied for specific amounts of natural versus anthropogenic land cover (Fig. 3), but especially in landscapes with lower amounts of forests. The variation for specific amounts of land cover may reflect different types of management and landscape designs among the different sample sites, or variation in amount and timing of sampling. A key issue is the degree to which multiple ecosystem services show similar patterns of variance with regards to land cover composition and pattern and whether common landscape patterns influence variance across those ecosystem services.

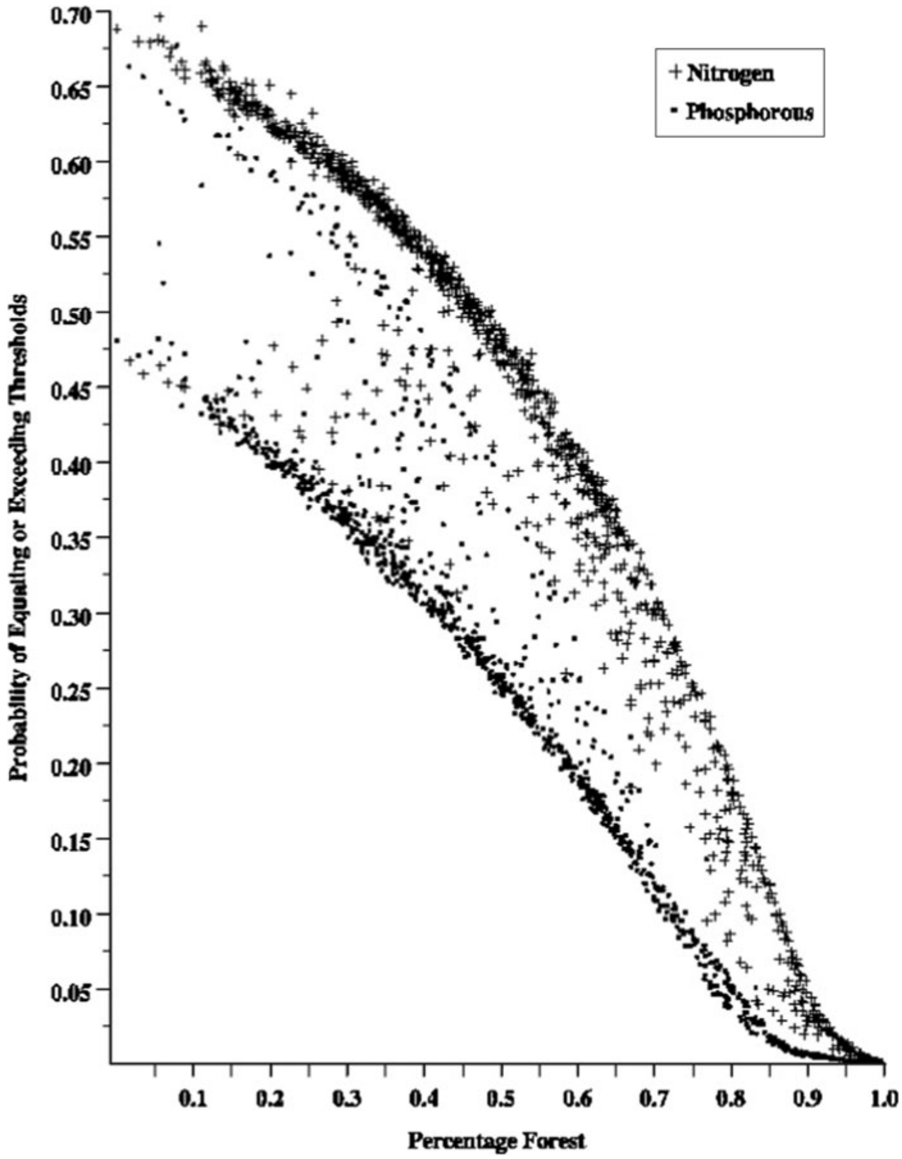

Fig. 3 Measured variance in the probability of phosphorus (P) and nitrogen (N) in surface waters exceeding the Clean Water Act standards based on the proportion of forested land cover (derived from Wickham and Wade 2002)

An important activity is to determine whether or not there are landscape pattern solutions for multiple ecosystem services, or whether trade-offs among ecosystem services will be more of the rule than the exception.

Adaptive management of landscapes

Adaptive management provides a framework for the implementation and modification of environmental management and polices over time as more information is collected (Walters 1986; Walters and Holling 1990; Nichols et al. 2007; Vernier et al. 2009; Cushman and McKelvey 2010). Adaptive management recognizes that the science to support initial decisions on landscape designs is incomplete, often with high levels of uncertainty about potential outcomes (Burgman et al. 2005; Lindenmayer et al. 2008; Williams 2012; Williams and Brown 2012). Therefore, a key aspect of adaptive management is to implement monitoring to evaluate how environmental targets and ecosystem services respond to specific landscape pattern designs. For example, landscape planners might restore forested riparian zones along areas with adjacent cropland or pasture to improve stream water quality and to restore fish populations; the riparian buffers would provide services such as sediment and nutrient filtration and uptake, moderation of stream temperature, and reduction in extreme flooding. The buffers, if positioned correctly, might also serve as carbon sinks and migration corridors for wildlife. The adaptive management approach would use monitoring data to evaluate the effectiveness of the implemented landscape changes for one or more of the environmental targets or ecosystem services. The results of the monitoring would then be used to either maintain the current landscape design or to alter it. Additionally, adaptive management involves a periodic revisit of the overall goals and objectives of the project (Williams and Brown 2012). In some cases the monitoring data suggest that the original goals and objectives cannot be achieved and that new goals and objectives are needed. In other cases, new threats or pressures may dictate a new set of priorities for management of the landscape. The adaptive management approach is being used in several projects involving large landscapes or ecosystems including the Great Barrier Reef (McCook et al. 2010), the Pacific Northwest (Bormann et al. 2007), old growth forests (Moore and Conroy 2006), rangelands (Butterfield and Malmstrom 2006), and riverine habitats (O'Donnell and Galat 2008). It also is being used to evaluate the effectiveness of insect and weed control (Shea et al. 2002), as well as North American waterfowl conservation (Nichols et al. 2007).

The adaptive management approach is similar to the framework highlighted by Nassauer and Opdam (2008). They describe an iterative process where landscape design helps inform the science of landscape ecology (pattern and process) and vice versa. This type of iterative process also permits evaluation of novel landscape patterns (through different designs) and the effects of such patterns on landscape processes and ecosystem services; Nassauer and Opdam (2008) considered the new insights coming from such an approach as "knowledge innovation." Both approaches enhance the linkages between science and management and offer the potential to bring the fields of landscape ecology, conservation biology, and environmental management closer together.

The two case studies highlighted by Nassauer and Opdam (2008) use simulations and modeling to validate the effects of designed landscapes on environmental targets. Many of the adaptive management projects also have involved simulations and models to evaluate management effectiveness, but only a few have involved extensive in situ monitoring and remote sensing resulting in adjustments to management (Butterfield and Malmstrom 2006; Nichols et al. 2007, respectively). And of those involving in situ measurements, even fewer have involved adjustments of landscape pattern based on monitoring results (Bunnell 2006; Williams and Brown 2012). As discussed earlier, costs and logistics have limited monitoring to evaluate responses of environmental targets and ecosystem services to broad-scale habitat and landscape designs. However, as described in this paper, it may be feasible to relate and/or enhance existing monitoring programs to evaluate the responses of environmental targets and ecosystem services to different types of landscape patterns and designs over broad scales using landscape pattern gradients (Peters et al. 2008; Cushman and McKelvey 2010). Similar to the process described by Nassauer and Opdam (2008), the results would provide "knowledge innovation" to existing and planned landscape designs. Moreover, it might help fill the "response monitoring" gap in adaptive management projects.

Scale is a very important consideration in implementing an adaptive management approach for landscapes and ecosystem services. Most landscape planning occurs at the local or small catchment scale (Nassauer and Opdam 2008), yet changes in broad-scale drivers such as climate and land-use can dramatically influence the effectiveness of local-scale conservation and landscape planning (Wiens 2009). Therefore, adaptive management of landscapes needs to include planning and design at multiple scales (for example, local to regional-scale corridors), as well as assessments of responses of landscape functions and ecosystem services to design and management interventions across those scales (Turner et al. 2002). To do so will require increased levels of cooperation and data sharing across multiple jurisdictional boundaries. The establishment of Landscape Conservation Cooperatives in the US (Austen 2011) is an example of a response to this need.

Summary

Because of its emphasis on pattern and process, landscape ecology offers great potential to inform environmental decision makers on landscape designs that will sustain important landscape functions and ecosystem services. However, as Nassauer and Opdam (2008) point out, landscape ecology needs to incorporate landscape design into its fundamental research. We propose a set of related activities that takes advantage of existing variability in landscape patterns, as well as existing monitoring data and landscape models, to inform decisions about landscape planning and design. This includes characterizing and mapping landscape pattern gradients, quantifying responses of multiple ecosystem services to those gradients, and applying an adaptive management framework. An adaptive management approach for landscape design is necessary because of the uncertainty associated with responses of multiple environmental targets and ecosystem services to specific designs. Due to costs and other logistical constraints, monitoring of the responses of ecosystem services to specific landscape designs will likely continue to be limited. However, as highlighted in this paper, it may be possible to evaluate potential designs for ecosystem services based on the variation in landscape pattern that already exists.

The ultimate goal is to determine if there are a set of landscape design options that will help sustain multiple ecosystem services, but especially in areas under rapid development or that are being affected by broad-scale drivers such as climate change. Can a landscape with relatively large amounts of developed land be designed to function more like a landscape dominated by natural land cover? If so, what landscape features and elements provide the greatest benefit to ecosystem services? Where in the landscape are the greatest benefits derived from different design options? How do those opportunities change with biophysical setting and scale? These are important question because many landscapes are managed to deliver multiple ecosystem services and environmental benefits, even within and adjacent to urban areas. They are also important because the sustainability of ecosystem services on protected areas will depend on the design of the broader, more heterogeneous landscapes inhabited by people (Wiens 2009). By addressing these questions, landscape ecology can provide solutions to sustain a wide range of environmental targets and ecosystem services.

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