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ARTICLE

Designing spatiotemporal multifunctional landscapes to support dynamic wildlife conservation

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ABSTRACT

With a growing human population, we are faced with the challenge of managing limited spaces for multiple social and environmental needs. Identifying opportunities to align social and environmental needs is thus a transdisciplinary design challenge. To meet this task, we present the concept of spatiotemporal multifunctionality (i.e. the provisioning of more than one human or environmental function in a given place at different times) and demonstrate how integrating principles of landscape ecology, social-ecological systems, and land system architecture enables a dynamic approach to landscape design and planning. Such an integration is capable of providing conservation tools for diverse social-ecological systems to maximize spatiotemporal multifunctionality. We use migratory birds as a working example to present a dynamic conservation opportunity and related challenges. By adding a temporal component to land-use classification in areas of high human use, we demonstrate the potential to enhance land-system sustainability and promote human-wildlife coexistence in a changing world.

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Introduction

A major characteristic of the Anthropocene is the rapid pace of human development driving global environmental change (Steffen, Crutzen, & McNeill, 2007). Assuming that human behavior and population growth continue as currently projected, we can expect sustained challenges to biodiversity conservation, including species extinctions, habitat loss and conversion, and the exploitation of wild resources (Jenkins, 2003). One of the greatest policy challenges of the Anthropocene will be to design and implement development strategies that enable human progress while simultaneously ensuring the sustainability of Earth's systems and biodiversity (Griggs et al., 2013; Steffen et al., 2007).

To allow for both human development and biodiversity conservation, some advocate for a 'land sparing' conservation model, dividing land into two monofunctional entities, one focused on commodity production and the other dedicated to the protection of biodiversity and natural resources (Egan & Mortensen, 2012; Fischer et al., 2008; Phalan, Onial, Balmford, & Green, 2011; Vandermeer & Perfecto, 2005). Conversely, the 'land sharing' model is proposed to integrate

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agricultural production and biodiversity conservation in a multifunctional landscape (Fischer et al., 2008; Green, Cornell, Scharlemann, & Balmford, 2005; Vandermeer & Perfecto, 2005). In lieu of removing working agricultural landscapes from production, proactive design of landscapes to meet both conservation goals and human needs is a development priority (Landis, 2017).

Landscape architecture and design have primarily focused on the spatial arrangement of land uses. However, a focus on the temporal nature of use is an additional design dimension that is seldom engineered (Ahern, 2005; Motloch, 2000), especially in rural landscapes. Designing working landscapes to temporarily provide important ecological functions for wildlife and other natural resources may make conservation practices more compatible with human use. For example, migratory species have temporary habitat needs, and protected areas often do not provide adequate spatial connections to assist movement across human-dominated landscapes (DeFries, Hansen, Turner, Reid, & Liu, 2007; Martin et al., 2007). Biological corridors can effectively achieve landscape connectivity by creating connections between existing protected areas (Convention on Biological Diversity, 2011). However, obtaining and permanently protecting large migratory corridors is a conservation challenge (O'Farrell & Anderson, 2010). In these cases, focusing on the temporal characteristics of migratory needs may uncover additional opportunities to design landscapes to become more dynamic and provide multiple functions within the same space.

Anticipating future habitat changes can also inform reserve design to have a longer lasting conservation impact (Araújo, Cabeza, Thuiller, Hannah, & Williams, 2004). To avoid complications that arise from acquiring land for permanent protection and to be responsive to range shifts caused by climate change, moveable reserves have been proposed in breeding and foraging zones of migratory ocean fish (Hyrenbach, Forney, & Dayton, 2000). Similarly, dynamic ocean management is a new tool to supplement static management approaches that uses real-time data on shifting social and environmental characteristics to generate responsive management plans to set harvest quotas and reduce bycatch (Hobday et al., 2014; Lewison et al., 2015; Maxwell, Hazen, Morgan, Bailey, & Lewison, 2012). In working landscapes, a dynamic conservation program paid farmers to flood their rice fields during certain times of the year to create temporary habitat for migratory and wintering shorebirds (Reynolds et al., 2017). This effort resulted in bird richness numbers three-times greater and abundance four-times greater than fields not enrolled in the program and costs approximately one-tenth the price of static conservation strategies. Nonetheless, while dynamic conservation strategies may be a viable option in many landscapes, their potential is largely unknown since they rely on the integration of principles from several disciplines and require managers to rapidly integrate current social and environmental data, which may not be readily available.

Thus, identifying opportunities to temporarily align social and environmental needs is a transdisciplinary design challenge. Using an example of working landscapes and migratory birds, we highlight these challenges and identify potential dynamic conservation opportunities. We first introduce the working example to provide context. Ultimately, we present the concept of spatiotemporal multifunctionality and demonstrate how its integration with principles of landscape ecology, social-ecological systems, and land system architecture enables a dynamic approach to landscape design and planning.

Working example: opportunities for dynamic conservation of grassland birds

Non-permanent conservation programs such as the Conservation Reserve Program (CRP) seek to incentivize environmental improvement through long-term contracts to increase their longevity. The CRP was established by the Food Security Act of 1985 with the intention of offsetting the costs of restoring, enhancing, and protecting certain grasses, shrubs, and trees that improve water quality, prevent soil erosion, and strengthen wildlife habitat in 10–15 year contracts (Herkert, 1997; Johnson & Igl, 1995). As of 2016, 23.8 million acres of cropland were enrolled in the CRP, with the majority of these lands planted to grassland habitat (U.S. Department of Agriculture, 2016). Additional CRP management options were added to the 2014 U.S. Farm Bill and give more flexibility to land owners. These include emergency foraging (e.g. in drought years), rotational grazing, and new management options for invasive species control (Stubbs, 2014). CRP is not recognized as a dynamic conservation approach; however, as a long-term contractual land management program, it provides a temporal framework embedded with additional management opportunities from which to examine the provisioning of dynamic wildlife habitat.

For example, grassland birds have undergone some of the most rapid and consistent population declines of any vertebrate group in North America (Drum et al., 2015; Herkert, 1995; Peterjohn & Sauer, 1993), largely due to loss of grassland habitat and grassland degradation (Askins et al., 2007; Brennan & Kuvlesky, 2005; Drum et al., 2015; Murphy, 2003). Between 2008 and 2011, nearly 23 million acres of grassland, wetland, and shrubland in the United States were converted to intensive row crop production (Faber, Rundquist, & Male, 2012). Agricultural intensification including dense monocultures, high inputs of fertilizers and pesticides, loss of native pasture, and intensive autumn sowings will likely contribute to the continued loss of native grasslands, and these anticipated outcomes accentuate the need for dynamic conservation opportunities to improve landscape multifunctionality (Campbell & Cooke, 1997; Donald, Green, & Heath, 2001; Fuller, 2000).

Although many North American grassland birds have displayed long-term population declines, some researchers have attributed positive population impacts to landscape changes supported by agricultural conservation programs, particularly the CRP (Drum et al., 2015; Herkert, 1997, 1998). A variety of grassland bird species utilize CRP fields, and some species are more abundant in landscapes with a higher proportion of CRP acreage (Best et al., 1997; Blank, 2013; Johnson & Schwartz, 1993; King & Savidge, 1995; Ribic, Guzy, & Sample, 2009; Riffell, Scognamillo, & Burger, 2008; Riley, 1995). However, because CRP lands vary in size, configuration, and type of seed mixture planted (Vickery & Herkert, 2001), not all grassland bird species have benefitted from the program as most grassland bird species remain in decline (Stanton, Morrissey, & Clark, 2018). However, habitat needs of species such as the grasshopper sparrow (*Ammodramus savannarum*) and bobolink (*Dolichonyx oryzivorus*) vary by season and have not been well met by single-scale management strategies. Specifically, these species prefer grasslands of intermediate height and clumped vegetation interspersed with patches of bare ground (Bent, 1968; Blankespoor, 1980; Dechant et al., 2002; Vickery, 1996) in early-spring or late-fall following the breeding season (Renken, 1983). During the breeding season though, in mid-April to late-August, these species prefer undisturbed areas (Frawley, 1989; Rodenhouse, Best, O'Connor, & Bollinger, 1993; Whitmore, 1981). The 2014 U.S. Farm Bill is responsive to these continued declines and restricted the most harmful practices (e.g. harvesting and grazing) during the ground nesting season, yet has not incentivized practices that generate seasonal habitat needs.

By identifying the landscape functions needed by the target species, managers can more readily identify management options that provide these functions. Specific options might include light to moderate grazing (Kantrud, 1981; Skinner, 1974; Whitmore, 1981), rotational, semi-annual burning (Forde, Sloan, & Shown, 1984; Madden, Hansen, & Murphy, 1999), or mowing and haying in early spring (Bollinger, 1988; Swengel, 1996). It is also recommended that treatments be applied on a rotational basis on small (20–30 ha) isolated areas within the larger landscape mosaic to provide a diversity of successional stages (Madden, 1996; Renken, 1983; Rohrbaugh, Reinking, Wolfe, Sherrod, & Jenkins, 1999). These practices could be implemented in grasslands where grasshopper sparrows and bobolink are likely to occupy and have management schedules that nearly coincide with their arrival.

To illustrate this point, we used working lands in Potter County, South Dakota to identify areas that had potential to provide additional foraging or breeding habitat for grasshopper sparrows in 2016 (Figure 1). During this time, Potter County was enrolled in over 12,000 acres of CRP, had high occupancy of grassland sparrows relative to other counties, and was comprised of high quantities of diverse working lands which required management practices at various times throughout the year (U.S. Department of Agriculture, 2017). For example in 2016, 58% of its total area was designated cropland and 34% pasture/grassland (USDA CDL, 2016). To identify conservation opportunities, we paired eBird Abundance Models (Fink et al., 2018; Sullivan et al., 2014), which estimate weekly relative abundance of grasshopper sparrows at an 8.4 km resolution, with the United States Department of Agriculture Cropland Data Layer (USDA National Agricultural Statistics Service Cropland Data Layer [USDA CDL], 2016) which classifies crop cover at a 30 m resolution. We used crop-specific planting and harvesting information for South Dakota (USDA NASS, 2010) to identify weeks that working lands were likely to provide foraging and breeding habitat. For this exercise, we assumed that these areas used conservation management practices (e.g. conservation tillage or rotational grazing) that would provide the preferred mixed and intermediate foliage heights. We considered crop classes of soybean, corn, hay, alfalfa, wheat, pasture, and fallow cropland as capable of providing foraging or breeding habitat for grasshopper sparrows (Dechant et al., 2002). Cover was included as foraging habitat if it was in early stages of growth or following harvest and additionally as breeding habitat if planting or harvesting disturbances did not coincide with breeding activities (Dechant et al., 2002). Demonstrated by the changes in total overlap of bird abundance and potential functional habitat shown in Figure 1, the impact of conservation opportunities initially appears to be a function of bird abundance, habitat requirements, and crop management schedules. In the outer-weeks of the study period, abundance is low as birds begin to migrate in and ultimately out of the county. However, potential habitat also fluctuates over time and creates new priority areas for each temporal window. Spatiotemporal

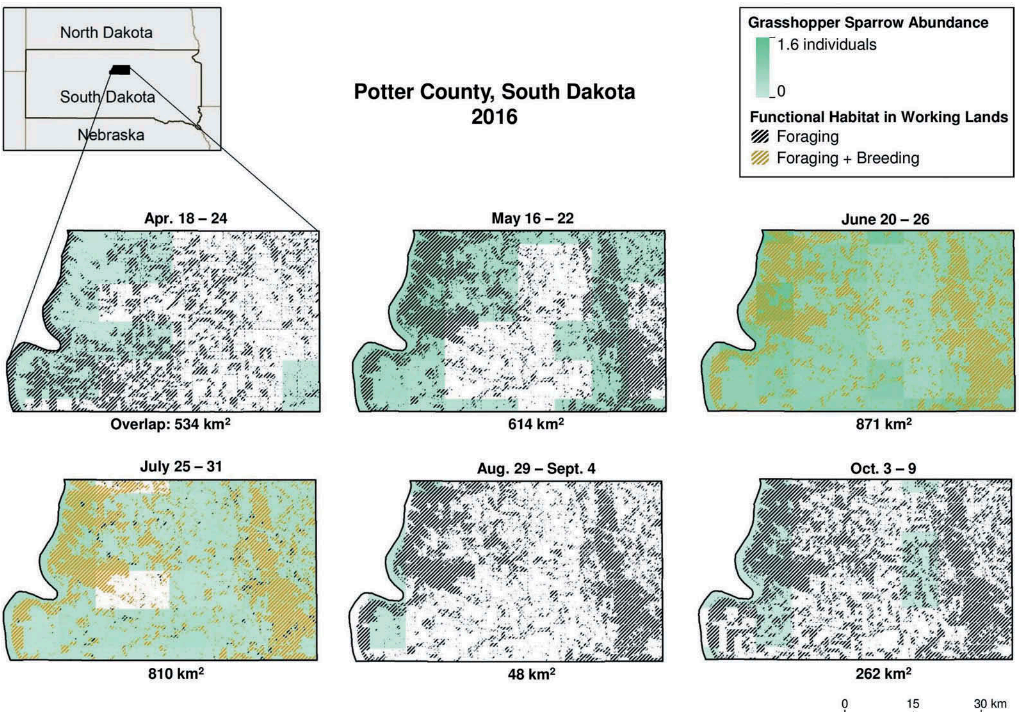

Figure 1. Spatiotemporal opportunities for conservation management in working lands for the grasshopper sparrow (*Ammodramus savannarum*) in Potter County, South Dakota in 2016. Grasshopper sparrow relative abundance was derived from eBird Abundance Models and is the expected count for a one-hour bird walk at 07:00 covering one kilometer of distance. Hatched lines represent the presence of working lands (e.g. pasture – 2,631 ha, corn – 1,188 ha, soybean – 1,054 ha, wheat – 954 ha, hay – 157 ha, fallow cropland – 77 ha, and alfalfa – 54 ha; total areas in Potter County) which have the potential to provide grasshopper sparrow habitat during that time given the use of conservation tillage or rotational grazing. Each county reproduction represents a 1-week period, every 4 weeks, during peak grasshopper sparrow migration. The values below describe the total area of potential working land habitat which overlaps with relative grasshopper sparrow abundance that is estimated to be greater than zero.

mapping exercises such as this can serve as a preliminary guide to identify areas where management practices could provide supplemental habitat (Figure 1). Additionally, further exploration of alternative timings of the usual management activities could be used to identify when and where a slight adjustment in schedule could generate new spaces suitable for grasshopper sparrow.

By clearly defining conservation objectives, managers can identify the optimal landscape configuration and management timing that will benefit target species but also identify potential negative consequences on non-target species and operators. For example, regular grassland management may be detrimental to Henslow's sparrows (*Ammodramus henslowii)* and northern harriers (*Circus hudsonius*), which require relatively undisturbed, tall dense grasslands (Hecht, 1951; Herkert, 1994; Herkert, Simpson, Westimerer, Esker, & Walk, 1999). In sites with a diverse mixture of species, a balance of both managed and unmanaged CRP lands may be most beneficial to a wide variety of grassland birds. However, the likelihood for a management alteration to occur and align with species' occupancy will depend on local social and environmental characteristics, each generating various tradeoffs for field operators and conservation managers.

Grassland birds are embedded within complex social-ecological systems, and habitat management does not solely rely on biophysical features (Drum et al., 2015). Nearly 85% of U.S. grasslands are privately owned, totaling about 300 million acres, with approximately 82% of current grassland bird populations distributed directly on private lands (North American Bird Conservation Initiative, 2014). Social value systems associated with different landowner types are important drivers of grassland bird population outcomes and can be influenced by national, regional, and local policies (Drum et al., 2015). Revising conservation programs for private lands thus requires an understanding of how socioeconomic factors affect the decision-making processes of landowners (Drum et al., 2015; Means, 1998). Ultimately, these social factors will influence the likelihood that dynamic conservation can be operationalized in CRP lands.

This example emphasizes the difficulty of integrating diverse types of spatiotemporal data needed for a dynamic conservation program. To address this issue, we present how spatiotemporal multifunctionality and existing theoretical frameworks can be used to more easily design and implement dynamic conservation.

Spatiotemporal multifunctionality

Redesigning anthropogenic landscapes can expand the total potential habitat for wildlife (Nassauer & Opdam, 2008; Rosenzweig, 2003). Efforts to design and increase spatial multifunctionality can achieve biodiversity targets at nearly half the cost of other conservation planning strategies (Reyers, O'Farrell, Nel, & Wilson, 2012) and can be integrated into intensively managed areas (Lovell & Johnston, 2009; Scherr & McNeely, 2008). Additional to the spatial arrangement of multifunctionality, the temporal nature of heterogeneity, specifically in cropping systems (i.e. crop phenology, management, and sequence), has been recognized as fundamental to landscape processes (Vasseur et al., 2013).

However, time is often overlooked when designing functionally heterogeneous landscapes. Yet, wildlife needs are not static and depending on their life stage, certain species will seek different habitat types. Conversely, one habitat type can provide different functions to multiple species simultaneously, making the spatiotemporal matrix of functional availability and species occupancy become rather large. For example, Fahrig et al. (2011) called for a classification of landscape heterogeneity by the habitat function it provides to a species or group of species. In addition to spatially classifying land cover type by function, we propose land cover be classified temporally (i.e. what cover exists at a particular time, which species use it, and how they use it; Figure 2). Thus, spatiotemporal multifunctionality is the provisioning of more than one human or environmental function in a given place at different times. To operationalize this procedure, land cover can first be classified as either providing or not providing habitat (Figure 1). Next, it can be further classified by land use according to the ability of each unit (e.g. pixel) for providing specific functions. In the

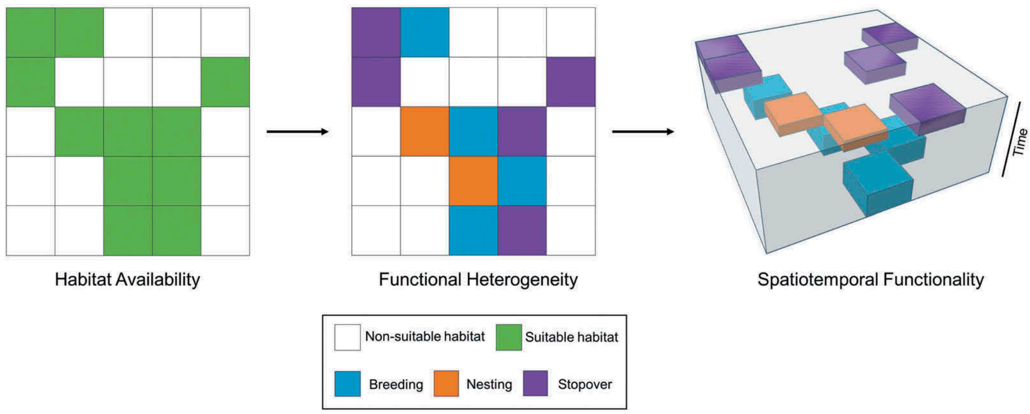

Figure 2. A progression for mapping a hypothetical, spatiotemporal habitat classification matrix for a single species of interest. Land use is first classified as providing or not providing habitat. It can further be classified as the ability of each unit to provide specific functions and is used to enhance functional heterogeneity within a landscape. Lastly, we build on the functional classification of each unit in space by also defining when that function is provided in time. In doing so, managers can identify management interventions that change the spatiotemporal functional heterogeneity to better meet species habitat needs.

working example of grassland birds, those functions include foraging and breeding habitat, but the functions will change according to different species and conservation goals. This step can be used to map and ultimately enhance the functional heterogeneity within the landscape. Lastly, the functional land use/land cover classification of each unit is further categorized according to the function it provides across time. By classifying landscape spatiotemporal functionality in this manner, we can design landscapes to not only be multifunctional in space (Lovell & Johnston, 2009), but also multifunctional in time.

Efforts to include and interpret a measure of time in spatially explicit processes, such as the process outlined in Figure 2, has elicited the development of new methodological tools to interpret spatiotemporal patterns. Within the sub-field of time geography, space-time paths represent one of the first attempts to record and understand how the spatiotemporal sequence of locations affects how an individual interacts with the world (Hägerstrand, 1970). These space-time paths were later developed into a Geographic Information System (GIS) tool (Shaw, Yu, & Bombom, 2008) to foster adoption. Indeed, spatiotemporal models are often represented in GIS (Peuquet, 1994), for example, using the snapshot data model (i.e. multiple spatial layers representing one instance of time; Armstrong, 1988) or three-dimensionally via a space-time cube (Kraak & Koussoulakou, 2005) or through space-time density surfaces (Delmelle, Dony, Casas, Jia, & Tang, 2014). Yet, despite the availability of several tools and models, more work is needed to better implement time in geovisualizations in a GIS environment (An et al., 2015; Goodchild, 2013), which could improve the efficiency of classifying the spatiotemporal functions provided by landscapes and highlight opportunities to increase spatiotemporal multifunctionality.

Theoretical integration to implement dynamic wildlife conservation

The fields of landscape ecology, social-ecological systems (SES), and land system architecture (LSA) have established theories and methodologies that are useful for identifying spatiotemporal multifunctionality and implementing dynamic conservation. Therefore, instead of developing new theories for achieving dynamic conservation, integrating features from these established fields can build on existing work and create new theoretical linkages across disciplines.

Landscape ecology broadly focuses on understanding the reciprocal exchanges between spatial patterns and social and ecological processes in heterogeneous landscapes at different scales, while also focusing on how these processes and interactions change over time and how humans create change (Field, Voss, Kuczenski, Hammer, & Radeloff, 2003; Turner, 2005; Wu, 2013). Landscape ecology principles have shown that features of landscape mosaics such as size, shape, and configuration of patches can influence abundance differently depending on whether the species are specialists or generalists (Bender, Contreras, & Fahrig, 1998). These theories have also shown that species may also respond differently to habitat characteristics at multiple scales (Wiens, 1989). Thus, the same landscape configuration may not be suitable for similar species, requiring a species-specific approach. This dilemma highlights the difficulty and importance of identifying the patterns and processes that provide specific habitat functions to individual species (Turner, 2005).

Social-ecological systems research works to study and untangle the interactions and feedbacks that occur across human and environmental dimensions (Ostrom, 2009). To understand and balance social and environmental tradeoffs, several SES frameworks have been developed to organize different categories of complicated and complex systems and uncover latent processes driving social-ecological system outcomes (Binder, Hinkel, Bots, & Pahl-Wostl, 2013). Some frameworks, such as Ostrom's Social-Ecological Systems framework (Ostrom, 2009) and the Human-Environment System framework (Scholz & Binder, 2003) are suited for subsystems that are hierarchical and emphasize governance systems and decision making. SES frameworks provide managers a starting place to map who and what influences and is influenced by the system, and can be useful in delineating study system boundaries (Martín-López et al., 2017). Although most SES frameworks are designed to assess a system at a single point in time (Binder et al., 2013), using multiple copies of a framework of the same spatial extent to represent different time states can broaden a framework's temporal scope. For example, just as grassland bird habitat requirements and availability change throughout the year, so does the farmer's availability of time and resources. Since these social factors ultimately influence the ability to implement management practices, they too should be assessed over time.

Similar to landscape ecology which focuses on landscape patterns and processes, land system science (growing out of land change science) actively evaluates the dynamics of change within agricultural and urban landscapes (Verburg et al., 2015; Verburg, Erb, Mertz, & Espindola, 2013). By taking land system science into the design realm, land system architecture seeks to catalyze novel land systems by optimizing spatial and temporal interactions within the compositional structure of the landscape, including new designs for governance of land resources (Turner, Janetos, Verburg, & Murray, 2013; Verburg et al., 2013). Key concepts of LSA are adaptation to climate change, enhancing ecosystem services, and balancing environmental tradeoffs with societal goals (Turner et al., 2013). LSA addresses issues with local interventions while considering interactions across multiple spatial scales and can explicitly identify and set goals to design landscapes that create particular ecosystem functions that mitigate risks or optimize social and environmental tradeoffs (Crossman, Connor, Bryan, Summers, & Ginnivan, 2010). Since LSA is used as a design approach, it can be revisited to improve the ability of the system to adapt to changes throughout time and assess services provided by alternative designs (Pires, 2004; Turner et al., 2013).

Wildlife perception and response to resources is based on a continuum of resources rather than discrete habitat and non-habitat (Fahrig et al., 2011; Manning, Lindenmayer, & Nix, 2004) making the challenge of what and where to conserve all the more challenging (Bissonette & Storch, 2007). Approaches to addressing this dilemma include using both continuous and discrete measures in habitat model development (Duro et al., 2014), and maintaining focus on species-specific functional habitat management (Fahrig et al., 2011). However, continuous data on habitat quality aren't always available. Yet, even a discrete classification based on spatiotemporal functionality includes temporal measures to better describe the availability of resources. Although landscape ecology is largely focused on spatial heterogeneity, many researchers have considered how temporal patterns of disturbance affect landscape heterogeneity or how spatiotemporal patterns of pulsed resources affect wildlife abundance (Bissonette & Storch, 2007; Landres, Morgan, & Swanson, 1999; Pickett & White, 1984; Wu & Loucks, 1995). Yet, additional work is still needed to identify the current spatiotemporal functions of landscapes and understand how altering the space-time mosaic will change the provisioning of services to other species.

For example, in North America, 215 migratory bird species use agricultural landscapes as stopover locations for foraging, resting, breeding, or nesting (Dänhardt, Green, Lindström, Rundlöf, & Smith, 2010; Rodenhouse et al., 1993). The migration pathways for these species are relatively well documented and stay nearly the same each year, enabling the identification of a recurring pattern of species occurrence over time alongside an understanding of the processes that give rise to those patterns. The golden plover (*Pluvalis dominica*) has one of the longest known migrations, traveling from its wintering ground in southern South America to its breeding grounds in the tundra of northern North America (Johnson & Connors, 2010). Golden plovers utilize soybean and corn fields with standing water in Indiana and Illinois, USA for an average of 45 days from the end of March to mid-May (Stodola et al., 2014). This stopover period is crucial to gain body mass and begin molting in preparation for breeding. However, this stopover period coincides with the planting season in this region, which for corn is early May and for soybeans is late May (USDA National Agricultural Statistics Service [USDA NASS], 2010). Achieving optimal soil moisture is critical for agricultural managers during planting, and many use drainage tiles to achieve desired soil moisture levels, which reduces forage quality for the bird species (Sugg, 2007). Thus, Stodola et al. (2014) recommend focusing on management interventions that temporarily block drainage tiles when soil moisture has little effect on crop production to increase forage quality at stopover sites for the golden plover. As is the case for the golden plover, identifying landscape patterns and processes that give rise to different spatiotemporal functionalities can improve our ability to identify conservation opportunities and improve multifunctionality.

Social-ecological systems are also characterized by temporal patterns because social and environmental processes operate at different speeds. For example, migratory species often arrive and depart a location in a relatively short time frame, and conservation managers are often tasked with socially preparing the area to effectively alter landscapes (e.g. generate conservation funds, communicate with land managers, provide incentive structures), which may take months or potentially years. Yet, if the proper social structures are not established prior to the environmental need, the land managers may not be notified in time to alter management practices, resulting in a missed opportunity. Thus, effecting positive changes ultimately requires institutions who wish to implement dynamic conservation to quickly respond to environmental changes. For instance, institutions that manage the seasonal movements of cattle have increased their ability to adapt to environmental variability by spreading the intensity of resource use out over space and time (i.e. seasonal movements and permits to sufficiently find high forage quality yet reduce over grazing; Janssen, Anderies, & Ostrom, 2007).

Not all working lands can provide temporary wildlife habitat though. Agricultural systems are dependent on production schedules to meet societal demands, and the timing, extent, intensity, and type of management strategies employed contribute to their ability to support migratory wildlife (Brady, 2007; Burger, 2006). The variety of crop produced and the size, location, and landscape configuration also determine the suitability of an area to provide conservation opportunities (Figure 3). However, management alternatives (e.g. staggering burn years or grazing intensities, delaying mowing after ground nesting species have brooded, or delaying tillage until after fall migration) are available to land managers, and the timing and type of these strategies affects the suitability of these landscapes as wildlife habitat. Additionally, due to cost of implementation or costs associated with loss of productivity, the timing and type of these strategies may not be economically viable. For example, harvesting three-weeks rather than one-week early could have significant impacts on yield, thus requiring an understanding of the social, environmental, and economical tradeoffs associated with any alteration. Similarly, the availability of governmental or non-governmental incentives can also influence the viability of an alternative for each land manager. Thereby, SES frameworks can be used to identify and sort these social characteristics in places where dynamic conservation may be ecologically feasible.

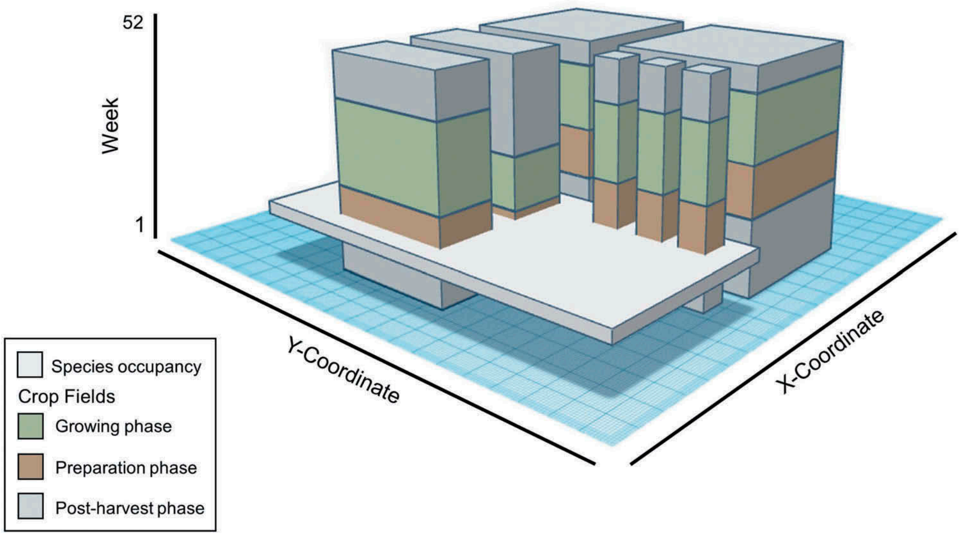

Figure 3. A conceptualization of a spatiotemporal classification of production phases of multiple crop types and utilization of those areas by a single migratory species. Columns represent different fields, and all fields are considered to comprise a single farm. The migratory species only occupy fields for a few weeks, and select to occupy fields which are in a production phase that provides their functional needs at that given time.

After identifying the influential social and environmental variables driving habitat dynamics in working landscapes, LSA can be used to optimize opportunities to increase multifunctionality by assessing tradeoffs and proposing novel interventions (Turner et al., 2013; Verburg et al., 2013; Figure 4). To do so, the conservation objective or species of interest must be well defined. The failure to use an objective driven approach to wildlife conservation in agricultural programs supported by the U.S. Farm Bill has led to mixed success (Burger, 2006). The range and habitat needs of some migratory species are intercontinental. However, assessments and interventions need to be local in nature (Turner, 2016). Many social-ecological systems exist across this space, and include a diversity of socioeconomic characteristics. Relying on a participatory approach may aid in tailoring an intervention to each system and scale up the conservation impact (Verburg et al., 2013).

To design spatiotemporal multifunctional landscapes that create dynamic conservation opportunities, principles of landscape ecology, SES, and LSA research can be utilized together (Figure 4). In doing so, managers can better: 1) map the temporal landscape mosaic and its benefit to target species (Figure 3); 2) identify design and management opportunities that may produce favorable outcomes for these species; 3) identify tradeoffs for social and environmental systems produced by a management action; and 4) identify the actors and institutions that may enable or hinder conservation success.

Discussion

We emphasize the need to integrate tools and principles developed in multiple land use paradigms to improve social and ecological sustainability and provide a working example specifically for the conservation of migratory species. In such systems, seldom will one set of tools be adequate to understand the complex interactions between humans and the environment to design land uses that produce desirable conservation outcomes. We rely on the principles of landscape ecology, SES, and LSA to provide a template to identify opportunities to improve biodiversity and agricultural production by allowing land use classification to move from static to dynamic. While the added temporal dimension

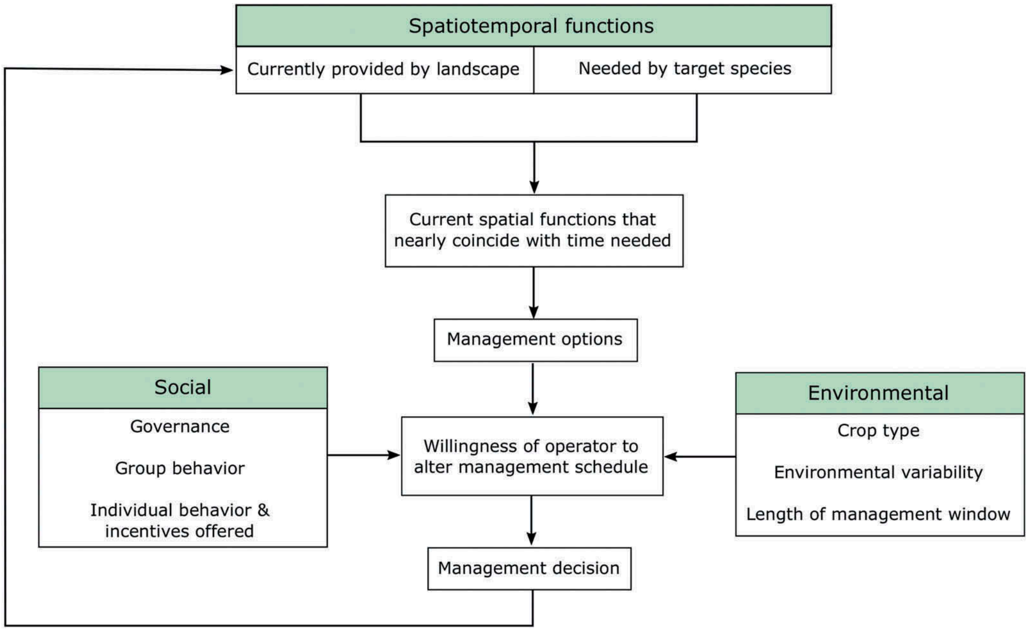

Figure 4. A flow diagram representing how dynamic conservation can be operationalized. This process relies on mapping spatiotemporal multifunctionality and the principles of landscape ecology, social-ecological systems, and land system architecture.

requires additional monitoring effort, it has the potential to further advance human-wildlife coexistence and improve resilience of human and ecological systems in the face of a changing climate.

The implementation of temporary wildlife conservation and multiple-land use practices presents unique design challenges and opportunities to researchers, stakeholders, and policy makers. The strength of the LSA approach is that the design of the landscape is embedded within the SES and landscape ecology of the study region (Verburg et al., 2013). The institutional capacity of the SES to accommodate the LSA design, enable conservation action, and understand the complex social-ecological feedbacks inherent within complex adaptive systems is vital to a successful intervention (Brown, 2003; Folke, 2006; Plummer & Armitage, 2007).

Effectively mobilizing a temporary and dynamic land use design will entail motivating agents at multiple scales of social activity and ensuring that agent goals are aligned with both conservation and land management. For instance, the CRP aims to motivate individual social actors, localities, and states to participate in conservation efforts through the use of monetary incentives (Schaible, Mishra, Lambert, & Panterov, 2015). However, the CRP has encountered difficulties in maintaining lifestyles that are at odds with agricultural conservation efforts, even when such efforts are in the financial interest of the farmer (Lambert, Sullivan, & Claassen, 2007).

Complexities also exist in creating conservation policy that considers both social and environmental outcomes across heterogeneous landscapes managed by decision-makers who are influenced by environmental, economic, and a hierarchy of social conditions (Daloğlu, Nassauer, Riolo, & Scavia, 2014). However, though critically important to the success of conservation efforts, U.S. federal conservation programs have social, political, or economic flexibility barriers that likely inhibit implementation of dynamic conservation programs. Non-governmental conservation organizations may provide a more effective medium to implement dynamic conservation programs due to their ability to create new policy or social mechanisms that match the undulating characteristics of the systems they are managing (Reynolds et al., 2017).

Despite the policy challenges presented by such an approach, the contextual specificity of dynamic conservation practices also present opportunities to: 1) reduce the cost historically associated with much of wildlife conservation (Hansen et al., 2015; Reynolds et al., 2017); 2) better understand characteristics of risks faced by farmers engaging in conservation activity (Ramsey, Bergtold, Canales, & Williams, 2016); and 3) improve the likelihood of recruiting and retaining conservation program participants (Reimer & Prokopy, 2014).

The inclusion of spatiotemporal multifunctionality to align conservation goals with resource demands can be applied to other groups with similar characteristics. Thorough knowledge of species movements and natural history will be necessary to expand these concepts to additional systems. The citizen science driven programs eBird and MoveBank are examples of ongoing efforts that collect such large scale information on wildlife movement (Sullivan et al., 2014). Advances in remote sensing will also support the near real-time assessment of production phases in working landscapes to identify alteration opportunities (Sakamoto et al., 2005).

A dynamic conservation approach may also prove useful when preparing for or reacting to environmental hazards. Following the Deepwater Horizon Spill of 2010, large areas of natural wetland habitat for migratory birds were lost (Corn & Copeland, 2010). In reaction to this disaster, the United States Department of Agriculture's Natural Resources Conservation Service launched the Migratory Bird Habitat Initiative, which provided economic and technical support to farmers to flood rice fields after harvest. While farmer response to the program was positive, evaluation assessments showed that the provision of habitat for birds varied greatly between regions and seasons (Sieges et al., 2014). The factors behind this variability were related to regional differences in landscape composition and bird occurrence and indicates the importance of understanding landscape ecology as it pertains to habitat selection and the alignment of intervention locations. Yet, mapping spatiotemporal functionality and identifying potential social barriers for implementing dynamic interventions as a preparation exercise could be useful when responding to environmental degradation caused by disasters.

Conclusion

We demonstrate how integrating principles of landscape ecology, social-ecological systems, and land system architecture enables a dynamic approach to landscape design and planning. The management of anthropogenic landscapes for multifunctional purposes is essential to supplement conservation efforts in the few remaining semi-natural and wild places on Earth. We should regard these landscapes as one and the same critical infrastructures that support human and non-human life. Utilizing land resources as spatiotemporal and multifunctional ultimately makes these landscapes more valuable to society. Optimizing landscapes for the sole purpose of increased production helps meet current food demands. But it may erode landscape multifunctionality and the ecosystem services that we depend upon, creating negative social and ecological consequences. Considering these challenges, government, private, and local institutions must work together to produce social systems that enable deliberate integration of existing fields to produce dynamic conservation design for human development and biodiversity conservation.

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