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# Effects of Landscape Pattern on Pollination, Pest Control, Water Quality, Flood Regulation, and Cultural Ecosystem Services: a Literature Review and Future Research Prospects

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## Abstract

**Purpose of Review** This review highlights recent progress on how landscape pattern (composition, configuration, landscape context, keystone landscape, scaling, and nonlinearity) affects pollination, pest control, water quality, flood control, and cultural ecosystem services (ES)—landscape esthetics and recreation.

**Recent Findings** Landscape composition and configuration showed ES-specific effects. Recent studies confirmed that pollination increased in complex, heterogeneous landscapes with more surrounding natural/semi-natural habitats. Landscape pattern could also interact with local factors to affect pollination, with stronger effects at smaller spatial scales. For pest control, a comprehensive synthesis revealed inconsistent effects of non-crop habitat composition, perhaps due to diverse responses from different enemies and pests and complex tri-trophic interactions. Spatial configuration of land-covers, connectivity, and edge effects also mattered for pest control ES. Moreover, recent studies showed that configuration of land-covers could sometimes trump composition as the primary driver for water quality. Comparing across scales (e.g., riparian vs. watershed), landscape pattern effects on water quality tended to be more pronounced at small spatial scales. For flood control, studies showed that larger and less fragmented natural covers reduced peak runoffs, with a compositional threshold ~ 30–40%. Spatial location also mattered where imperviousness concentrated closer to outlet tended to increase peak runoffs. For cultural ES, landscape esthetics and recreation showed positive correlations with naturalness composition and landscape heterogeneity.

**Summary** Five overarching themes emerge for future research to advance understanding of landscape pattern effects on ES: (1) using social-ecological measures of ES; (2) assessing ES supply, flow, and demand; (3) considering interactions among multiple drivers across scales; (4) addressing ES interactions; and (5) enhancing predictive capacity of landscape models.

**Keywords** Landscape structure · Composition and configuration · Landscape metrics · Landscape heterogeneity · Spatial pattern · Natural capital

## Introduction

We are now living in an era that many scientists are calling the "Anthropocene"—a period in which humans and their activities dominate and reshape every ecosystem on Earth [1]. Since the advent of the Industrial Revolution, the majority of the terrestrial biosphere has been transformed from wild and semi-natural landscapes to predominantly agriculture and human settlements [2]. Such dramatic landscape modifications, on one hand, have enabled humans to appropriate an increasing share of the planet's resources for fulfilling desirable needs (e.g., food, fiber, and timber products), leading to an increased overall material well-being [3, 4]. However, these anthropocentric landscape changes also negatively affected biodiversity and natural capitals, producing tradeoffs with other vital ecosystem services (ES), such as water quality, climate regulation, soil retention, and cultural ES [5–8]. The loss of regulating ES is of particular concern, because it may compromise long-term ES resilience and lead to abrupt changes that exceed a "safe operating space" for humanity [9]. In the face of these unprecedented levels of anthropogenic landscape alterations,

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it is thus crucial to understand causal linkages between landscape pattern and ES from a holistic, dynamic, and mechanistic perspective [10••, 11••]. Such knowledge will improve our predictive capacity on social consequences of landscape changes and empower management to modify landscapes to sustain multiple ES in a changing world.

Landscapes, consisting of multiple interacting ecosystems over a watershed or geopolitically defined region, represent a pivotal scale for the research and management of ES [8, 12]. It is also the scale at which human society profoundly affects, interacts with and relies on nature's services. Landscape pattern (also termed as "landscape structure") encompasses two essential components: composition (i.e., relative abundance of different cover types) and spatial configuration (i.e., how different landscape elements are arranged spatially). These two components can interact to collectively affect connectivity, fragmentation and complexity of landscapes. Prior research has well demonstrated that landscape composition and configuration have myriad influences on the population dynamics, community structure, and ecosystem processes [13, 14], all of which underlie the potentials of landscapes to deliver ES to humans.

Over the past decade, there has been tremendous research towards investigating effects of landscape pattern on ES (Fig. 1) [10••, 15, 16], especially those sensitive to the movement of organisms and materials across the landscape [6]. Such an emerging trend in research interests from ecological consequences of landscape patterns to ES likely indicates a new research agenda that would require different approaches integrating social and ecological sciences [17••]. Prominent examples of ES studied include pollination [18, 19], biological control [20, 21, 22••], disease regulation [23, 24], carbon storage [25, 26], hydrological services [27, 28•], and recreational benefits [29]. However, most research thus far tended to focus a single or small set of ES, and not all types of ES were equally well represented (e.g., provisioning ES, and regulating ES such as pollination and pest control, are better studied than cultural ES) [10••]. In addition, most studies tended to incorporate one or few facets of landscape pattern (e.g., predominantly composition), and empirical studies to investigate diverse aspects of landscape configuration, and their interactions with composition to affect ES remain rare [30, 31•]. Nonetheless, different aspects of landscape structure could have varying effects on multiple ES (e.g., ES bundles), driving tradeoffs or synergies among ES as a consequence of altering landscape patterns [27, 32]. Moreover, effects on the biophysical production of ES have been the focus of prior research. Few studies have embraced the full spectrum of landscape effects from production to demand and use through flows of ES, which could be either complementary or even counteractive along the supply chains of ES provision [33].

In this paper, I first provided an overview of the current state of knowledge in how different aspects of landscape pattern (e.g., composition, configuration, landscape context, keystone landscape, scaling, and nonlinearities) affects ES. Selected ES to be reviewed include pollination, pest control, water supply and quality, cultural ES. ES were selected based on their significance to human society, sensitive to landscape

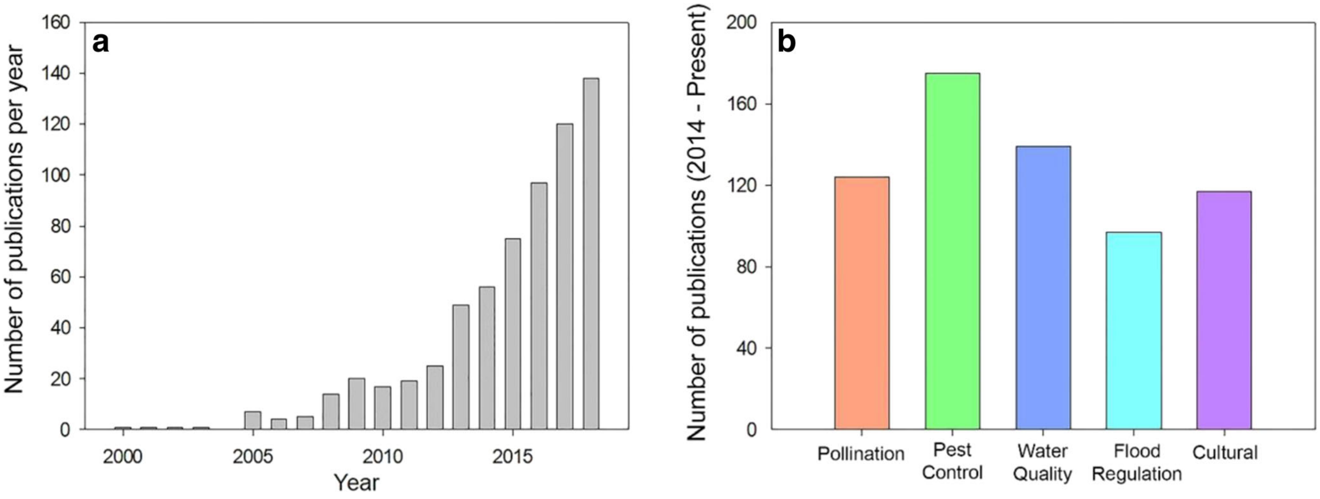

**Fig. 1** **a** Annual number of publications (2000–2018) from the ISI Web of Science database on landscape pattern (search term: "landscape pattern*" OR "landscape structure*" OR "landscape heterogeneity" OR "landscape composition" OR "landscape configuration" OR "spatial composition" OR "spatial configuration") effects on ecosystem services (ES) (search term: "ecosystem service*" OR "ecosystem good*" OR "ecological service*" OR "ecological good*" OR "environmental service*" OR "environmental good*"). **b** Cumulative publications over the past 5 years (2014–present) from the ISI Web of Science database on landscape pattern effects on pollination ("pollination*" OR "pollinator*"), pest control ("pest control" OR "biocontrol" OR "biological control"), water quality ("nutrient retention" OR "nutrient loss*" OR "nutrient loading*" OR "water quality"), flood regulation ("peak runoff*" OR "peak discharge*" OR "flood*"), and cultural ("cultural service*" OR "esthetics" OR "cultural heritage" OR "recreation" OR "tourism" OR "spiritual" OR "religious") ES. The search was conducted on 16 January 2019 using the science database only and including all document types

changes, and availability of empirical studies. This review is by no means an exhaustive analysis of all published studies, but rather vignettes highlighting most recent literature (i.e., past 5 years from 2015 to 2019) that evokes discussion and identification of future research directions. The study involves systematic search and reviewing of all published articles on relevant topics for each focused ES in the ISI Web of Science database (search terms shown in Fig. 1). The goal is to synthesize the most significant developments in the field, especially focusing on studies that attempted to address knowledge gaps as previously identified. Following the syntheses, I discussed directions of future research relevant to each individual ES. Finally, I concluded with five overarching themes for advancing the research on landscape pattern effects that are broadly relevant to all ES.

## Landscape Pattern Effects on Pollination Services

**Syntheses** Pollination is a vital ES that benefits more than three quarters of global food crops, with an estimated annual market value of $235–577 billion [34]. Pollination relies upon the movement of pollinators (often insects) from patches of natural habitats to adjacent agriculture fields, and thus landscape structure could exert profound influences. Prior studies have summarized that pollination ES (e.g., measured in fruit/seed sets, visitation, pollinator communities) tended to increase in complex, heterogeneous landscapes with higher proportion of surrounding natural/semi-natural habitats (e.g., forest, hedgerow, meadow) [15, 16•]. Recent empirical research confirmed positive effects of landscape heterogeneity, the amount of and proximity to adjacent habitats on visitation rate, abundance and richness of pollinators, especially for wild pollinators [35, 36]. Studies also revealed that favorable landscape patterns could interact synergistically with local factors (e.g., high-quality local floral resources) to bolster pollination ES [37•, 38] or buffer against negative consequences of "undesirable" local farming practices (e.g., pesticide use) on pollination [39]. Effects of landscape pattern on pollination ES are also scale dependent. Studies on bee visitation rates in coffee plantation [40] and apple orchard [41] showed that effects of landscape structure were stronger at smaller spatial scales, likely associated with the relative short foraging distances of insect pollinators. Moreover, keystone landscapes (e.g., functional biological corridors) also played a key role in enhancing habitat connectivity and thus pollination ES [15, 42]. In Costa Rica tropical forest, for example, corridors boosted forest-associated pollinator availability in fragments by 14.3 times of the unconnected equivalents, leading to overall increased pollination success [43].

**Outlook** (i) Research thus far has focused on effects of physical structure of landscapes, yet emerging studies suggested that a functional approach may better address effects of human-modified landscapes on pollination processes [44], which remains largely underexplored. In fragmented Atlantic Forest Region in Brazil, for example, functional landscape connectivity that accounts for landscape heterogeneity and functional costs associated each habitat type better explained variations of bee abundance and richness [45]. (ii) In addition to direct effects, landscape pattern can also exert indirect effects on pollinating ES through modifying microclimate (e.g., reduced urban heat island and temperature effects on bees from semi-natural habitats) [46], and/or altering plant communities (e.g., increased plant richness that in turn supports greater pollinator diversity) [47]. Disentangling direct and indirect pathways through which landscape patterns can affect pollination ES will need more future attention. (iii) Further, using network theory and methods (e.g., quantification of plant-pollinator networks or networks of diverse pollinator assemblage and their associations with landscape structure) represents a promising direction that accounts for intra- and inter-specific interactions to examine the cascading effects of landscape pattern on the stability and resilience of pollination ES [48, 49]. (iv) Finally, the majority of studies on landscape structure effects on pollination ES has been focused on wild and managed bees. However, effects on other pollinators (e.g., flies, beetles, wasps, birds, bats, etc.), which also play a significant role in global crop production, have been rarely explored. These non-bee pollinators may respond differently than bees to landscape structure and perhaps make the portfolio of pollination ES more robust to future landscape changes [50].

## Landscape Pattern Effects on Pest Control Services

**Syntheses** Pest predation and suppression by natural enemies is an important biological control ES, in particular in agroecosystems, estimated at ~US$4.5 billion annually in avoided crop damage in the United States alone [51]. Similar to pollination, pest control depends on the movement of herbivores and predators across landscapes from natural patches to adjoining agricultural fields, and thus responds to the composition and configuration of landscapes [6, 52]. Previous reviews and syntheses have concluded that biological control (e.g., measured as abundance, diversity and activity of natural enemies) tended to increase in landscapes with more non-crop habitats [21, 53, 54]. However, a recent comprehensive analysis [22••] composed of data from 6759 sites across the globe showed inconsistent effects of the composition of non-crop habitats on pest and enemy abundance, predation rates, crop damage, and yields. In other words, unlike pollination, it is difficult to generalize effects of landscape context and composition on pest control ES. Such large variations are perhaps due to diverse and sometimes contrasting landscape responses of multiple natural enemies (e.g., birds, bats, ants, spiders, flies, etc.) and pest species [22••, 55••, 56]. It might also have to do with effects of local farming practices (e.g., organic vs. conventional) and complex tri-trophic interactions (i.e., enemies, pests, crops) that are highly context specific [22••], thus overwhelming effects of landscape composition [57–59].

The composition of surrounding landscapes has been traditionally the focus in studies on pest control ES. Yet an increasing number of studies alluded to the importance of spatial configuration, connectivity, and edge effects [60–62]. For example, Dominik et al. [59] showed positive effects of structural connectivity of rice bunds on parasitoids and predators in rice-dominated landscapes in Philippines. In addition, in a study in western France, spatial configuration and connectivity of spring and winters crops increased the abundance of carabids [63], thus enhancing pest control ES. Edge effects (e.g., edge type, and proximity to edges of natural habitats) and patch (field) size also had important effects for the abundance and functional diversity of natural enemies, as shown for spiders, carabids and stalk borer [64–66]. Moreover, linear structures like hedgerows, perennial fallow strips also served as the critical landscape elements that help sustain pest control ES [67, 68].

**Outlook** (i) Given the highly variable landscape pattern effects on pest control ES as revealed in previous studies, it may be challenging or impractical to make generalization across diverse taxa. Rather, generalization or synthesis might be more feasible for each separate groups of pests/natural enemies (e.g., of similar guilds or functional traits). (ii) Most published studies have either taken a snapshot approach or averaged across multiple sampling time throughout the growing season to determine landscape pattern effects on pest control ES. Few studies have investigated inter- and intra-annual dynamics of landscape pattern effects, which could associate with temporal variations in the population, activities and interactions among pests and enemies. For example, substantial seasonal differences were found regarding effects of landscape structure on activity and density of predators [69–71]. Future research on fine-scale temporal dynamics of pest control can help pinpoint specific mechanisms determining the abundance and diversity of pests and natural enemies [72]. (iii) Effects of landscape pattern on pest control ES are likely scale dependent [73]. Yet few studies have adopted a multi-scale perspective (e.g., within field, neighboring, and surrounding landscapes) to assess relative importance of landscape structure at different spatial scales and any cross-scale interactions for pest control ES. One example is that, across multiple natural enemy taxa, Martin et al. [61] demonstrated that effect sizes of landscape configuration, habitat amount, and landscape diversity tended to increase with spatial scales. Hence, whether there are generalized scaling rules, and what factors (e.g., mobility, body size, functional traits, and habitat preference) explain variations of landscape pattern effects across scales deserve more future research. (iv) Not surprisingly, most research on pest control has been focused on agroecosystems. Nevertheless, this ES is also vital in urban settings (e.g., ornamental plants, urban gardens), but remains relatively understudied [74]. Improved knowledge on what kind and level of spatial heterogeneity will promote urban pest control ES is thus needed to help conserve and manage urban landscapes.

## Landscape Pattern Effects on Hydrologic Services

Water quality and quantity are two components of hydrologic ES crucial for supporting human well-being [75] but are susceptible to landscape changes such as agricultural expansion or urbanization. Landscape pattern can affect hydrologic ES either directly by altering processes such as hydrologic flows or lateral fluxes of nutrients, or indirectly by changing biotic communities. Here, in this review, I focused on nutrients/contaminants retention or loadings into downstream waterbodies (as proxies for water quality ES) and flood regulation (a key aspect of water flow regulation) ES.

**Water Quality—Syntheses** Prior research has contributed to understanding of the effects of land-use pattern on water quality and nutrient dynamics across different landscapes [76] and further elucidated the spatial scales over which these effects are manifest [77, 78••]. However, there has been a historical interest and emphasis on effects of landscape composition, other than their spatial arrangement. Nevertheless, empirical and theoretical evidence indicates that landscape configuration (e.g., connectivity, distribution, proximity, or contagion of source and buffer ecosystems) could mediate the transport of water and nutrients across landscape, therefore affecting water quality ES [79–81]. Indeed, Qiu and Turner [27] showed that after accounting for effects of composition, landscape configuration mattered for phosphorus loading, where subwatersheds with higher wetland patch density, higher grassland patch density, more disaggregated forest patches and lower contagion had greater supply of water quality ES. Similar findings were also reported in [82] that wetland and forest edge density had positive effects on stream water quality, likely because more edges of natural cover reduced the rate of surface flow and promoted interactions of water with soils and vegetation, thus increasing nutrient uptake and retentions. Chaplin-Kramer et al. [28•] showed that spatial configuration of agricultural expansion could even trump composition as the primary driver for water quality in a range of geographic contexts (e.g., USA, Brazil, and China). To properly analyze effects of landscape configuration, it is important to be cognizant of constraints and confounding effects of composition over configuration and to control for effects of composition, which has not been consistently adopted [83] and may produce conflicting or sometimes even misleading results. Moreover, studies are also emerging to address how landscape pattern effects on water quality vary across spatial scales and over time. For instance, recent studies demonstrated that overall landscape metrics (composition plus configuration) explained greater variations on water quality indicators at the scale of riparian buffers than the catchment or watershed scales [84–86], and effects were stronger in the wet or flooding season as compared with dry season [87, 88]. However, opposite results were reported in Zhang et al. [89], perhaps due to different variables of water quality being measured. Thus, in assessing, comparing, and generalizing landscape pattern effects, it is important to note differences in water quality indicators and underlying ecological and/or hydrological processes that may respond fundamentally different to landscape patterns.

**Water Quality—Outlook** (i) While numerous indicators have been used to quantify water quality ES (e.g., nutrients, contaminants, organic matter, chemical, biotic communities), some (e.g., macroinvertebrates richness, level of glyphosate) might have limited direct influence on human use of freshwater. Future research is encouraged to selected indicators that are mostly relevant to human use of freshwater (e.g., drinking, irrigation, recreational uses) [90]. (ii) Many water quality indicators have well-known ecological or human-related thresholds (e.g., phosphorus thresholds for eutrophication, or contaminating threshold for human diseases) [91], yet relatively few studies have investigated how landscape pattern affects the probability of exceeding such water quality thresholds, which would deserve more future research. (iii) Most studies thus far have focused on spatial patterns of land use/cover to calculate landscape metrics. Nevertheless, spatial patterns of other landscape features, e.g., road network or drainage infrastructure density, may exert greater influences than traditionally landscape patterns quantified based on land use/cover, especially in urbanized and agricultural watersheds with high level of anthropogenic modifications [92]. (iv) Some water quality indicators may have nonlinear responses to landscape metrics, yet most studies tended to use linear statistical models [93]. Understanding the nonlinear responses to landscape pattern may suggest ecological leverage points where small management investments can yield large benefits in water quality ES [27]. Nonetheless, detection of such nonlinearities as well as exploration of underlying mechanisms that account for the nonlinearities remains challenging, and the empirical evidence is scant.

**Flood Regulation—Syntheses** Compared with water quality, studies investigating effects of landscape pattern on flood regulation ES (often quantified as flood damage, reduction in peak runoffs, or integrated score-based assessment) were infrequent [94], most of which were focused on urbanized landscapes. It is not surprising that percent impervious or pervious cover is a key factor that regulates peak runoffs and flooding risks. For example, pervious cover has been shown as most effective in controlling rainstorm floods when its proportion increased to 30–40%—a threshold presumably associated with critical transitions in the spatial configuration of pervious patches from fragmented to highly connected [95]. Similar findings were also reported in Kim and Park [96] that larger, less fragmented, and more connected urban green infrastructure mediated peak runoffs, whereas larger development covers with more clustered pattern were likely to augment peak runoffs. Composition and configuration also interacted to affect flooding risks. In a mountainous landscape in Puerto Rico, for example, more edges from forest fragmentation led to more effective inception of subsurface flow by forest root systems, promoted forest transpiration, and reduced stream flows [97]. Hence, reduced forest fragmentation accompanied with reforestation may offset impact of reforestation on lessening flooding risk. Spatial location also mattered; in an urban catchment in Beijing, China, impervious cover concentrated closer to the outlet increased peak runoffs than that concentrated upstream [98]. Similarly, another study showed that floodplain forest restoration in areas of the upper and middle reach of the catchment tended to show reductions in peak magnitude at the catchment outflow [99].

**Flood Regulation—Outlook** (i) Most research has focused on spatial pattern of land use/cover on flood regulation. However, spatial characteristics of other biophysical factors (e.g., soil, geology) are as equally important (if not more) as land use/cover. Indeed, Amiri et al. [100] revealed that regularity of landscape, pedoscape, and lithoscape were all significant predictors to explain the variation in the flood magnitudes at the catchment scale. Hence, in examining landscape pattern effects on flood regulation ES, it is imperative to consider other factors (e.g., soil, geology) or critical landscape features (e.g., depression wetlands, stream network, artificial drainage) that altogether influence the hydrologic connectivity of landscapes [101, 102]. (ii) Most studies have used biophysical indicators to quantify flood regulation (e.g., peak runoffs, peak discharges)—i.e., intermediate indicators underpinning the potentials of regulating floods. More research is needed to connect them to final ES that are directly relevant to human wellbeing (e.g., inundation area, flood economic damage, etc.). One example is that, using time-series analysis and controlling for socioeconomic, and development-based factors, Brody et al. [103] demonstrated that large, expansive and continuous patches of naturally occurring open spaces were most effective in reducing economic losses from flood events.

## Landscape Pattern Effects on Cultural Services

**Syntheses** Cultural ES are consistently recognized, but inadequately studied and underrepresented in the literature [104]. Here I focus two cultural ES – landscape esthetics and recreation that have reasonable number of studies to review. Landscape esthetics refers to natural or scenic value of landscapes (e.g., landforms, vegetation, water features) [105]. Esthetics has mostly been assessed by perceptual surveys using quantitative measures of esthetic quality by averaging choices or ratings across observers within statistically coherent groups [106]. Prior research has demonstrated that both composition and configuration can affect esthetics across different landscapes. In northwestern U.S. forests, for example, perceived beauty (after timber harvest practices) increased with the amount of green trees remained and diversity of landscapes in terms of tree species and sizes (i.e., composition), and was rated higher in evenly dispersed rather than clumped tree patterns (i.e., configuration) [107, 108]. In urban settings, using in situ captured eye-tracking data of mobile devices, Cottet et al. (2018) [109•] revealed positive effects of naturalness composition (i.e., street tree, river) on gaze fixation (a proxy for landscape esthetics) in the urban riverine systems (Yzeron, France). Similarly, using questionnaire-based surveys, Chen et al. (2015) [110] revealed the importance of specific landscape elements (e.g., freely growing trees, individual houses, gable roofs and mixed design of green spaces) for esthetic preference in two cities in U.K. and China. In agricultural landscapes, using preference surveys, Klein et al. (2015) [111] found that perceptional scenic quality increased with the amount of buffer strip vegetation. Based on empirically estimated effects of landscape variables, further efforts have been taken to quantify esthetics at large landscape scales using spatial modeling [112] or composite indicators [113]. Such spatially explicit assessment could serve as the basis for landscape-scale evaluation of cultural ES to better inform urban and regional planning, especially in areas where cultural ES are fundamental to the regional economies.

Recreational opportunities, such as hiking, camping, boating, represent a major cultural ES that human benefits from ecosystems, in the form of contributions to the physical, mental, intellectual and psychological well-being [104]. It is obvious that availability of recreational sites, often as composition of natural areas like forest, water and open green space and their ecological conditions, have positive effects on recreation ES [114]. Recent studies also showed positive relationships between landscape heterogeneity (or landscapes with varying levels of land use intensity) and recreational ES in agricultural landscapes [115, 116•]. Size of landscape elements also mattered for the perception and use of recreation ES; an interview of >100 park visitors in Delhi indicated the importance of large, well-maintained, publicly accessible parks (as compared with small parks in the vicinity) [117].

**Outlook** (i) Research on ES requires the integration of concepts, theories, and methods from social and ecological sciences [7]. This is in particular true for cultural ES, where stronger and more seamless interdisciplinary collaborations are needed that extend to broader domains of ecology, economics, environmental and social sciences [104]. Such interdisciplinary perspectives can help better understand the direction, magnitude and mechanisms of landscape pattern effects on the supply, use and perceptions of cultural ES. (ii) Given the "intangible" nature of many cultural ES that are challenging to measure spatially and empirically, innovative use of methods and integrated technologies (e.g., social media, eye-tracking device, virtual reality, agent-based modeling, geo-visualization) [109•, 118] is highly encouraged. (iii) Cultural ES are likely affected by other social-economic and human-related factors besides landscape patterns. Future research teasing apart effects of individual factors (i.e., demographics, value), social norms and contexts and their interactions with landscape factors on affecting cultural ES is thus needed.

## Path Forward

**Social-Ecological Measures of ES** Although ES research has proliferated over the past two decades, its earlier development has been predominantly isolated within disciplinary silos (e.g., ecology vs. economics) [17••]. Given that ES results from the interplay among social and ecological factors, research has called for a transdisciplinary and social-ecological approach to measuring ES using production function and benefit flows to link ES with human wellbeing of diverse beneficiaries [119, 120, 121••]. With such a framework, researchers will not only quantify effects of landscape pattern on biophysical production of ES but also determine how these effects transfer to societal and community benefits and to the resilience of social-ecological systems. In turn, people and decision-makers are thus more compelled to incorporate such knowledge into management and policies.

**ES Supply, Flow, and Demand** The majority of research has focused on landscape pattern effects on biophysical production of ES (i.e., capacity of landscapes to produce ES). Yet, more research is needed to address the multifaceted roles of landscape patterns in the flow, demand, and use of ES. In fact, for some ES, landscape pattern can have complementary or opposing influences on ES supply and flow, leading to contrasting net effects and thus complicating predictions of landscape pattern effects on ES provision [33, 122]. One example is that road construction in a pristine forest can lead to forest fragmentation, and thus negatively affect ES supply such as esthetics, water quality, and carbon sequestration [123]; on the other hand, road construction could also increase forest access, and thus foster the use and flow of forest-based ES [33, 124]. By considering ES from supply to flow and demand (e.g., [124]), as well as the co-production of ES between social and natural capitals, the full spectrum of landscape pattern effects can be better unraveled. Novel integration and uses of diverse approaches (e.g., biophysical model, system dynamics model, agent-based model, social network analysis) from different disciplines present one possible path forward to addressing these knowledge gaps.

**Interaction Among Multiple Drivers Across Scales** In addition to landscape pattern, ES are also responsive to other drivers of change that often occur at different spatial and temporal scales. Hence, it is important to consider how different drivers (either global processes such as climate and international trade that operate above landscape scales, or local factors such as local farming practices and fine-scale soil processes that operate below landscape scales) interact with landscape patterns to affect ES, and whether there are any cross-scale dynamics [125, 126]. One example is that climate variability could overwhelm local land-use and management effects on water quality [127] and quantity [128]. Besides aboveground processes and factors, belowground drivers (e.g., groundwater), which are often underappreciated and less well understood, could also interact with landscape patterns to affect ES, with nonlinear consequences for ES [129]. Hence, in examining landscape pattern effects, in particular to generalize results across geographic regions and social-ecological systems, it would be helpful to consider and account for these potentially confounding and interacting factors across scales (e.g., via use of networks [130••]). Such understanding will inform how to adapt our landscapes through local management to build resilience and buffer against undesirable broad-scale environmental changes.

**Interactions among Multiple ES** Different ES likely respond differently to landscape patterns (e.g., responses of water quality vs. crop production to agricultural expansion). Hence, altering landscapes could exert simultaneous effects on multiple ES, causing tradeoffs (i.e., increases in one ES at the expense of others) or synergies (i.e., multiple ES enhanced altogether). While ES trade-offs and synergies have been active areas of research [32], only until recently studies have started to examine how and when composition and configuration of land covers contribute to bundles of ES and their interactions [31•, 131, 132]. For example, in an agriculture, peri-urban region in South Quebec, Canada, Lamy et al. (2016) [31•] found that both composition and configuration played a key role in explaining variations in the supply of multiple ES; e.g., configuration of forest cover was an important determinant in the provision of four ES including pork production, water quality, tourism, and soil phosphorus retention ES. Hence, it is critical to take a multi-functional perspective to examine effects on multiple ES, or "ecosystem service cascade", where changes in one ES due to landscape patterns lead to consequences for other ES and ultimately the benefits to human welfare [133].

**Enhancing Predictive Capacity of Landscape Pattern Effects** Research empirically exploring landscape pattern effects on ES across space or time is growing, yet fewer studies have linked these effects to underpinning mechanisms [11••]. Linking social and ecological mechanisms of ES dynamics to landscape patterns provides an effective means to enhancing predictions that are essential for sustainable management of ES. To achieve this goal, functional traits (e.g., either using proper functional traits as ES proxies or predicting ES indicators) have emerged as a powerful approach to understanding the ecological mechanisms underlying ES production, tradeoffs or synergies among ES, and thus have potentials to better predict effects of landscape patterns [134, 135]. Developing scaling functions is another effective pathway to linking ecological mechanisms gleaned from small-scale manipulative experiments to improved predictions of landscape consequences for ES (Qiu and Cardinale, in review).

## Concluding Remarks

Sustaining multiple ES in a global changing context presents as one of the most pressing challenges in sustainability science and contemporary landscape ecology. It requires enhanced knowledge of when, how and what aspects of landscape structure affect ES in social-ecological systems. This review highlights recent progress on effects of landscape structure on pollination, pest control, water quality, flood control, esthetics and recreation ES. It demonstrates that both landscape composition and configuration affect the provision of ES, with ES- and context-specific effects that vary based on landscape metrics. Despite these remarkable progresses, our understanding still remains at an infancy stage. In particular, more research is need to advance our understanding of landscape pattern effects on ES from a social-ecological lens that accounts for the supply, flow, and demand of multiple ES, their interactions, and contributions to different aspects of human welfare. Future research to address interactive effects of landscape pattern with other drivers of global change, and to develop mechanistic models to improve predictions how future landscape changes affect ES across scales is also desired. I hope that this review could catalyze additional discussions and help promote new research on this topic anchored on the theories of landscape ecology and social-ecological sciences, by considering ES as a consequence of human-environment interactions, and adopting multi-pronged approaches (e.g., theoretical, empirical, modeling, and other innovative methods). As ES framework is increasingly incorporated into decision-making and policies, our improved knowledge and syntheses of landscape structure effects on ES will inform management practices to sustain the capacity of landscapes to provide ES and enhance their resilience for the decades to come.

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## Compliance with Ethical Standards

**Conflict of Interest** The author declares that he has no conflict of interest.

**Human and Animal Rights and Informed Consent** This article does not contain any studies with human or animal subjects performed by any of the authors.

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•• Of major importance

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