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Os serviços das paisagens: uma abordagem teórica e aplicada para planejamento visando múltiplos benefícios

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Sumário

Resumo

Como descrito nos documentos e manifesto das Organização das Nações Unidas (ONU), para se alcançar o desenvolvimento sustentável há uma necessidade de se alinhar a segurança alimentar com a provisão de água limpa, a conservação biológica, a mitigação dos efeitos das mudanças climáticas, dentre outros objetivos sociais e ecológicos. Planejar paisagens que cumpram múltiplas funções é, portanto, uma estratégia a seguir. Como a intensificação das atividades econômicas ocorreu em muitas regiões em todo o globo, promovendo mudanças no uso da terra, esgotamento dos recursos naturais e comprometendo a oferta de serviços ecossistêmicos, projetos de restauração ambiental são necessários para aumentar a requerida multifuncionalidade. Estes projetos devem não somente considerar os tipos de ambientes a serem restaurados e as espécies a serem usadas, mas também a localização e a quantidade de áreas de restauração em relação aos outros elementos da paisagem, para que a produção e a entrega dos serviços sejam otimizadas. Isso decorre do fato de que os padrões e complexidade da paisagem, como por exemplo a quantidade e a conectividade de áreas naturais e antrópicas, influenciam nos processos e funções ecológicas envolvidos na provisão de serviços. Assim, gestores e proprietários de terra precisam de ferramentas adaptadas e informações práticas que já integrem conhecimento científico e que os auxiliem em tomadas de decisão em múltiplas escalas. O objetivo desta tese foi trazer uma abordagem tanto teórica quanto aplicada para o planejamento e manejo de paisagens que promovam múltiplos benefícios. O primeiro capítulo consiste na formulação de meta-análises para sintetizar e avaliar o conhecimento científico relacionado aos efeitos de diferentes padrões da paisagem sobre múltiplos serviços ecossistêmicos. Com base nestes resultados e nos trabalhos revistos da literatura, no segundo capítulo foi desenvolvido um framework que considera as percepções de diferentes grupos sociais de interesse, agrupa os serviços ecossistêmicos de acordo com sua resposta aos padrões de paisagem e possui uma ferramenta computacional e espacialmente explícita que usa dados prontamente disponíveis para identificar e priorizar locais para restauração. Portanto, os resultados desta tese têm o potencial de melhorar o planejamento e manejo das paisagens e ajudar a aumentar a implementação de projetos de restauração, por considerar os benefícios públicos e privados no processo de planejamento.

Palavras-chave: paisagem multifuncional; priorização espacial; restauração; LSRestoration; meta-análise; framework; serviços ecossistêmicos

Abstract

As described in the United Nations documents, in order to achieve sustainable development, there is a need to align food security with the provision of clean water, biological conservation, mitigation of the effects of climate change, and other social and ecological objectives. Planning landscapes that fulfill multiple functions is, therefore, a strategy to follow. As the intensification of economic activities has occurred in many regions around the globe, promoting land use/cover changes, depletion of natural resources and compromising the provision of ecosystem services, environmental restoration projects are needed to increase the required multifunctionality. These projects should not only consider the types of environments to be restored and the species to be used, but also the location and amount of restoration areas in relation to the other elements of the landscape, so that the production and delivery of services are optimized. This stems from the fact that landscape patterns and complexity, such as the quantity and connectivity of natural and anthropogenic areas, influence the ecological processes and functions involved in services provision. Therefore, land managers and landowners need adapted tools and practical information that already incorporate scientific knowledge and can assist them in the decisions-making process at multiple scales. The objective of this thesis was to bring a both theoretical and applied approach to the planning and management of landscapes that can promote multiple benefits. The first chapter consists of the formulation of meta-analyzes to synthesize and evaluate the scientific knowledge related to the effects of different landscape patterns on multiple ecosystem services. Based on these results and the literature reviewed, the second chapter developed a framework that considers the perceptions of different stakeholders, bundles ecosystem services according to their response to landscape patterns and has a computational and spatially explicit tool which uses readily available data to identify and prioritize locations for restoration. Therefore, the results of this thesis have the potential to improve the planning and management of the landscapes and to help increase the implementation of restoration projects, considering the public and private benefits in the planning process.

Keywords: multifunction landscapes; spatial prioritization; restoration; LSRestoration; meta-analysis; framework; ecosystem services

Introdução geral

Mantidas as condições atuais de uso dos recursos naturais e aumento populacional, a Organização das Nações Unidas (ONU) estima que, para 2050 serão necessários um incremento de 60% na produção de alimentos, 50% de energia e 40% de água (ONU, 2015). Entretanto, grande parte das paisagens hoje já se encontram sob atividades agrícolas ou outra forma de conversão da cobertura da terra para atividades humanas, com perda para biodiversidade e serviços ecossistêmicos (MEA, 2005; Braat & Brink, 2008; Iverson et al., 2014; Sanderson et al., 2002; Banco Mundial, 2016). Assim, a ONU clama por iniciativas que tornem as paisagens e as atividades mais sustentáveis, incorporando melhores práticas de manejo e gestão das regiões rurais e urbanas. Os países devem buscar alinhar segurança alimentar com a provisão de água limpa, a conservação da biodiversidade, a mitigação dos efeitos das mudanças climáticas, dentre outros objetivos sociais e ecológicos (CDB, 2010). O Brasil é um dos maiores produtores globais de *commodities* no mundo (FAOSTAT, 2015) e o país terá que aumentar sua produção para ajudar a manter as demandas futuras de alimentos à medida que a população humana cresce.

De acordo com Soares-Filho e colaboradores (2014), 53% da vegetação nativa brasileira ocorre em propriedades particulares e estocam 105 (± 21) Gt de CO2. Parte dessa vegetação se encontra protegida sob a legislação nacional modificada em 2012 (Lei de Proteção da Vegetação Nativa – popularmente chamada de Novo Código Florestal; Brasil, 2012). De acordo com ela, todo proprietário de terras rurais deve preservar com vegetação natural uma porcentagem mínima do total da área de sua propriedade, denominada reserva legal. Esse mínimo varia de acordo com o bioma e com a região política nos quais a propriedade está inserida, mas é de pelo menos 20%. Recentemente, foi avaliado o tamanho do déficit ambiental relacionado a essas reservas legais, calculando-se uma área total de cerca de 19Mha (Soares-filho et al., 2016) para as quais os proprietários terão que tomar medidas para se adequar à lei.

Um mecanismo que a lei estabelece para a adequação ambiental é o Programa de Regularização Ambiental (PRA) a ser implantado por cada estado brasileiro. Tal programa deve abordar as regras gerais de como os proprietários rurais podem restaurar, reflorestar ou compensar suas reservas legais. Dentro dessa última opção, a lei gera a possibilidade de compensação da reserva legal em outra propriedade que possua excedente de vegetação natural (ou área em recuperação) acima do exigido por lei (Brasil, 2012). A princípio, essa possibilidade parece benéfica por diminuir os custos de oportunidade para adequação à lei e por aumentar a efetividade da restauração ambiental. Entretanto, existem no Brasil regiões que concentram as terras com os menores custos de oportunidade, principalmente devido à baixa aptidão agrícola e regiões altamente lucrativas para a produção de *commodities* (Soares-Filho et al., 2016). Como as regras para essa compensação são amplas, possibilitando ao proprietário compensar seu déficit ambiental em qualquer outra região do mesmo bioma, provavelmente haverá paisagens muito fragmentadas e ambientalmente degradadas (as de maior custo de oportunidade) e outras paisagens mais conservadas (as de menor custo de oportunidade).

Essa discrepância no nível de conservação ambiental das paisagens rurais pode acarretar problemas sociais e econômicos e as consequências podem afetar não somente os proprietários rurais, mas também pessoas localizadas em outras regiões dentro ou mesmo fora dessas paisagens. Por exemplo, em uma escala regional a falta de vegetação nativa pode desencadear aumento dos períodos secos prejudicando a produção agrícola (Lawrence & Vandecar 2015), ou ainda ocasionar a diminuição da quantidade de água e assoreamento nos corpos hídricos prejudicando abastecimento à jusante (e.g. Mori et al., 2015; Uriate et al., 2011). Ainda, a intensificação das atividades agrícolas, com grandes áreas destinadas ao plantio de monoculturas e pecuária e poucas áreas de vegetação nativa, pode desencadear aumento de pragas e queda na produtividade, devido à perda dos inimigos de pragas que viviam nas áreas naturais (Chaplin-Kramer et al., 2011). Todos esses exemplos de externalidades negativas decorrem da perda de processos e funções ecológicas das paisagens e, por consequência, perda dos serviços ecossistêmicos. Como frequentemente esses riscos não são considerados por gestores e proprietários de terra, os remanescentes de vegetação nativa acabam possuindo uma área total pequena ou localizados em regiões da paisagem que não permitem a manutenção ou provisão de benefícios que os ecossistemas naturais promovem. Nesse sentido, tendo em vista a perda de vegetação nativa que já ocorreu no Brasil e em outras regiões do mundo (Lapola et al., 2014), são necessárias ações que ajudem a persuadir os proprietários rurais a restaurarem ou compensarem em suas próprias paisagens, para que elas possam garantir a provisão benefícios privados (para os próprios proprietários) e públicos (para a sociedade em geral; Silva, 2018).

Essas ações de restauração requerem não somente considerar os tipos de ambientes a serem restaurados e as espécies a serem usadas, mas também a localização das áreas de restauração em relação aos outros elementos da paisagem, para que a produção e entrega dos serviços sejam otimizadas (Fisher et al., 2009; Villamagna et al., 2013; Burkhard, et al., 2014). Nesse sentido os padrões e características da paisagem, como a quantidade e conectividade de áreas naturais e antrópicas, influenciam na escolha das áreas a serem restauradas para a promoção de serviços e benefícios aos seres humanos (Chaplin-Kramer et al., 2011; Kremen et al., 2011; Mitchell et al., 2013; Shackelford et al., 2013). Para planejar a paisagem de modo que ela possa prover múltiplos benefícios, gestores e proprietários de terra precisam de ferramentas adaptadas e informações práticas que já integrem conhecimento científico e que os auxiliem em tomadas de decisão em múltiplas escalas. Para tanto, dentro do processo de planejamento deve-se considerar o contexto da paisagem e sua relação com os processos ecológicos e sociais subjacentes à provisão de serviços ecossistêmicos (Cowling et al., 2008; Cimon-Morin et al., 2013).

Assim, o objetivo desta tese foi trazer uma abordagem tanto teórica quanto aplicada para o planejamento e manejo de paisagens que promovam múltiplos benefícios. A tese se encontra dividida em dois capítulos. O primeiro capítulo consiste em uma meta-análise para sintetizar e avaliar o conhecimento relacionado aos efeitos de diferentes padrões da paisagem sobre os serviços ecossistêmicos. Foi realizada uma revisão sistemática de artigos publicados em revistas científicas, que avaliaram as funções e serviços ecossistêmicos juntamente com métricas da paisagem que expressam tais padrões. Como resultado, obteve-se a mensuração do tamanho do efeito de certos padrões da paisagem, medidos através de grupos de métricas da paisagem (McGarigal et al., 2012), em determinados serviços como qualidade de água, controle de doenças, polinização, controle de pragas e beleza cênica.

O segundo capítulo foi desenvolvido com base nos resultados e nos trabalhos revistos da literatura, e consistiu na elaboração de uma estrutura conceitual (*framework*) que considera as percepções de diferentes grupos de sociais de interesse, agrupa os serviços ecossistêmicos de acordo com sua resposta aos padrões de paisagem e possui uma ferramenta computacional e espacialmente explícita que usa dados simples e prontamente disponíveis para identificar e priorizar locais para restauração. Este *framework* considera as principais características dos serviços que precisam ser identificados para apontar qual padrão de paisagem seguir nas ações de restauração. Os resultados da aplicação desta ferramenta indicam as áreas prioritárias para restauração com maior potencial para aumentar ou manter a provisão de múltiplos serviços ecossistêmicos.

Nesse sentido essa tese tem o potencial de auxiliar na elaboração e execução dos PRAs estaduais, pois demonstra que os gestores devem considerar a composição e a configuração da paisagem para garantir que múltiplos benefícios sejam mantidos e adaptar sua abordagem de acordo com aqueles de interesse. A tese ainda ajuda a reduzir a lacuna entre a pesquisa acadêmica em conservação e sua implementação, pois os resultados obtidos possuem implicações e ferramentas diretamente relacionados com a práticas de planejamento para promoção de serviços e benefícios ecossistêmicos (Dobrovolski et al., 2018). Portanto, essa tese tem o potencial de melhorar o planejamento das paisagens e ajudar a aumentar a implementação de projetos de restauração, por considerar os benefícios públicos e privados no processo de planejamento.

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Capítulo 1

The effects of landscape patterns on ecosystem services: meta-analyses of landscape services

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Abstract

Purpose

The recently introduced concept of 'landscape services' – ecosystem services influenced by landscape patterns – may be particularly useful in landscape planning by potentially increasing stakeholder participation and financial funding. However, integrating this concept remains challenging. In order to bypass this barrier, we must gain a greater understanding of how landscape composition and configuration influence the services provided.

Methods

We conducted meta-analyses that considered published studies evaluating the effects of several landscape metrics on the following services: pollination, pest control, water quality, disease control, and aesthetic value. We report the cumulative mean effect size (E++), where the signal of the values is related to positive or negative influences.

Results

Landscape complexity differentially influenced the provision of services. Particularly, the percentage of natural areas had an effect on natural enemies (E++ = 0.35), pollination (E++ = 0.41), and disease control (E++ = 0.20), while the percentage of no-crop areas had an effect on water quality (E++ = 0.42) and pest response (E++ = 0.33). Furthermore, heterogeneity had an effect on aesthetic value (E++ = 0.5) and water quality (E++ = -0.40). Moreover, landscape aggregation was important to explaining pollination (E++ = 0.29) and water quality (E++ = 0.35).

Conclusions

The meta-analyses reinforce the importance of considering landscape structure in assessing ecosystem services for management purposes and decision-making. The magnitude of landscape effect varies according to the service being studied. Therefore, land managers must account for landscape composition and configuration in order to ensure the maintenance of services and adapt their approach to suit the focal service.

Keywords: Landscape metrics; Spatial patterns; Structure; Management; Complexity; Ecological benefits

Introduction

Landscape patterns emerge from the composition and configuration of its basic elements, and these patterns influence both ecological processes and ecosystem functions (Turner 2005). This also holds true for ecosystem services, which heavily depend on the health of these functions, and on the spatial interactions and flow between ecosystems and anthropogenic areas (Termorshuizen and Opdam 2009; Syrbe and Walz 2012). To identify target areas for conservation, restoration, or enhancement of ecosystem services, decision-makers must consider spatial contexts and landscape patterns. Undoubtedly, human population growth has increased the demand for high-quality multifunctional landscapes (DeClerck et al. 2016; Garbach et al. 2016), and created an urgent need for more practical and applicable information to guide efficient decision-making toward this end.

The recently introduced concept of 'landscape services' is an essential part of the emerging field sustainability science (Termorshuizen and Opdam 2009). Its primary difference from the 'ecosystem services' concept is the dependence of rendered services on spatial configuration and the influence of elements external to the ecosystem (Bastian et al. 2014). The landscape services concept encompasses the notion that a complete landscape can provide services through its multi-functionality and the processes that emerge from a set of unique ecosystems (Frank et al. 2012; Hodder et al. 2014), in both natural and human-modified habitats. This concept may prove useful for landscape planning, as the integration of ecological services could increase stakeholder participation, financial funding, and encompass working landscapes (Chan et al. 2006, 2011; Goldman et al. 2008; Carpenter et al. 2009; Duarte et al. 2016). However, integrating this concept into the planning process remains a global challenge (de Groot et al. 2010). To bypass this barrier, we must improve our understanding of how particular landscape patterns influence its services (Mitchell et al. 2015).

Landscape metrics are widely used in studies describing landscape patterns and their relationship to land use/land cover changes, biodiversity distribution, ecological processes, and ecosystem functions (Uuemaa et al. 2013). However, such analysis requires an awareness of the metrics' interrelationships and redundancy (Cushman et al. 2008) and their consistency for landscape management. For this purpose, aggregating landscape metrics into more general groups can facilitate stakeholders' understanding of landscape management (Cushman et al. 2008).

Previous studies have investigated how specific landscape patterns and features relate to the provision of ecosystem services (e.g., Bastian et al. 2014; Hodder et al. 2014; Chaplin-Kramer et al. 2015; Mitchell et al. 2015). In addition, recent reviews and quantitative analyses have begun synthesizing available knowledge in this area (Chaplin-Kramer et al. 2011; Garibaldi et al. 2011; Mitchell et al. 2013; Shackelford et al. 2013); however, the focus remains on relatively few services and landscape features (e.g., landscape complexity). This study aimed to thoroughly review and evaluate the relationship between several aspects of landscape patterns and certain ecosystem services. The primary target of this research was to provide support for more practical decision-making in landscape planning and management in order to ensure the maintenance of key landscape services.

Meta-analysis is the quantitative, scientific synthesis of research results aiming to achieve broad generalizations across a large number of study outcomes (Gurevitch et al. 2018). Meta-analyses have largely been used in ecology, evolution, and conservation biology (Gerstner et al. 2017) to estimate the overall magnitude of effects, and to identify factors that modulate such effects. In this meta-analytical review, we considered published studies that evaluated indicators of ecosystem services and the landscape patterns to maintain or influence their provision. We hypothesized that (1) landscape complexity would have a significant effect on the provision of all services evaluated due to its relationship with high multi-functionality; (2) for services related directly to fauna biodiversity and water quality, we expected a positive relationship with both landscape aggregation and habitat quantity; and (3) we expected landscape heterogeneity to affect cultural services, as cultural landscapes involve both natural and anthropogenic land types.

Methods

Study Selection and Inclusion Criteria

For the present meta-analysis, we used three distinct approaches to conduct a systematic literature search aimed at collecting the most representative sample of existing primary research studies. First, we used articles already reviewed by Chaplin-Kramer et al. (2011; a meta-analysis of the effect of landscape complexity on pest control services), Garibaldi et al. (2011; a synthesis regarding landscape effects on the stability of pollination services), Shackelford et al. (2013; a meta-analysis of landscape and local effects on the abundance and richness of pollinators and natural enemies) and Uuemaa et al. (2013; a review of trends in the use of landscape metrics). We then performed an extensive search in the Web of Science database, using the keywords “landscape metrics,” “landscape indexes,” and “landscape indices” to complement the research by Uuemaa et al. (2013) – which reviewed studies between 2000 and 2010 using the same keywords – by adding studies published between 2011 and 2016. Finally, we reviewed relevant articles provided in the reference lists of all previously selected studies.

The present study only considered studies that used landscape metrics related to empirical data of functions or ecological indicators that directly benefit human well-being. We did not consider habitat function for biodiversity, except when primary studies explicitly cited biodiversity as being (or potentially being) directly related to certain ecosystem services (e.g., pollination and pest control). Furthermore, we chose to exclude habitat function, as this is not the focus of the present research and several previous scientific works and reviews have already studied the effect of landscape patterns on biodiversity and its conservation (Fahrig 2003, 2017; Uuemaa et al. 2013).

In addition, we restricted our research to terrestrial landscapes in rural, agricultural, mixed rural-urban or natural habitats regions, thus excluding strictly urban or marine landscapes. One study inclusion criterion was the reporting of statistical parameters (e.g., r, F, χ^2, Spearman-rho, t or R^2, and sample size) on the relationship between at least one landscape metric and one landscape function, or the partial contribution of at least one landscape metric. In some cases, we extracted and carefully reanalyzed the original raw data. When primary studies reported data in figures, we digitized them and extracted raw data using the Image J software version 1.46 (Schneider et al. 2012).

Landscape Explanatory Variables

The present study used landscape complexity variables, primarily those related to increasing the amount, spatial heterogeneity, and landscape connectivity of natural and semi-natural areas as predictors for explaining ecosystem services. These explanatory variables were grouped into four major groups according to the patterns they measured: a) percentage of natural areas; b) percentage of non-crop areas; c) landscape aggregation, which "refers to the tendency of patch types to be spatially aggregated; that is, to occur in large, aggregated or 'contagious' distributions" (McGarigal et al. 2012); and d) landscape heterogeneity, which refers to the degree of heterogeneity of landscape elements, including metrics such as diversity, evenness and richness indexes for natural and semi-natural land cover classes, and for the entire landscape (see example and metric definitions in McGarigal et al. 2012; Fig. 1). Additionally, landscape aggregation was also subdivided into: c1) landscape connectivity – metrics related to the proximity/connectance of landscape natural elements; and c2) landscape fragmentation – metrics related to the number of patches, edges, and the isolation of natural and semi-natural areas. By using these groups, it is possible to provide greater detail regarding manageable landscape characteristics that affect ecosystem services. The analyses in the present study evaluated the landscape metrics described in Fig. 1. However, only the groups that had at least five independent comparisons were included in the meta-analyses. In relation to the landscape metrics of natural area fragmentation and percentage of crops, we used inverted values of the reported statistical data, as these metrics are considered inversely related to the positive ecological effects of landscape complexity.

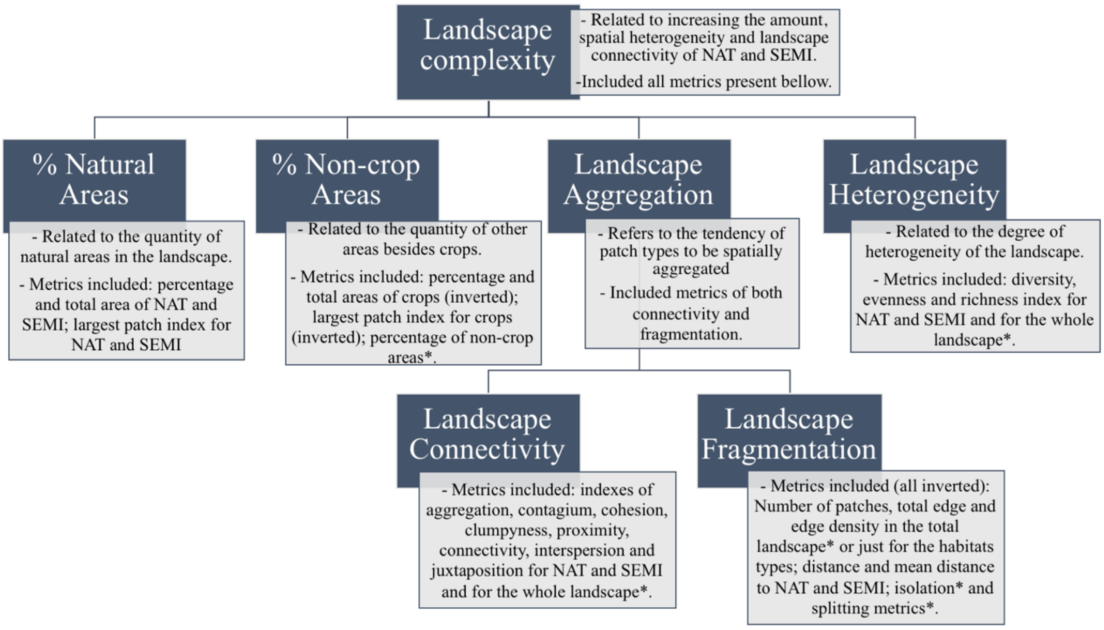

Figure 1. A flowchart representing the landscape-metric groups and subgroups. Group names are in the dark gray boxes. Descriptions of each group and subgroup, with their related landscape metrics, are in the light gray boxes. NAT and SEMI stand for natural and semi-natural areas, respectively. Descriptions for each landscape metric can be found in McGarigal et al. (2012). *at a landscape level, these metrics also account for anthropogenic (non-natural) areas.

Ecosystem Service Response Variables

Many ecosystem services related to water quality have been described by Keeler et al. (2012). Additionally, there is evidence to support landscape patterns influencing the provision of these services (Allan 2004). As response variables, we grouped several water functions, which are collectively referred to as 'water quality-related services' in the present study. Furthermore, we followed the study of Keeler et al. (2012) and searched for articles reporting concentrations of nitrogen, phosphorus, and sediments (including suspended solids and turbidity) as indicators of water quality. Based on these findings, we then inverted the sign of results from the meta-analysis in order to understand the effects of landscape complexity on the water quality indicators more easily.

The same approach was utilized to assess the service of disease control. This involved searching for primary studies reporting indicators of loss of disease control, such as disease prevalence, host and vector abundances, and infection levels. After the meta-analysis, the sign of its results was then inverted to assess the effects of landscape metrics on disease control indicators. To assess the service of pest control, two contrasting approaches were used. The first approach measured pest response through indicators related to pest abundance, richness, and damage. The second approach measured natural enemies' response through indicators such as natural enemy abundance, richness, diversity, and direct effects on pest reduction. As a result, two types of indicators of the effects of landscape complexity on pest control were available: one related to service providers (natural enemies) and other to disservice providers (pests). We also evaluated the service of pollination of agricultural areas using the abundance, richness, diversity, and effects of pollinators as indicators, as well as the service of aesthetic value using indicators from landscape preference studies.

For studies that exhibited a multi-scale approach (e.g., concentric radii to determine different landscapes) or multiple sampling seasons, we chose the most predictive scale or period of the year (following Chaplin-Kramer et al. 2011; Shackelford et al. 2013). For primary studies yielding results in different years, we considered every year for which authors reported a change in land use/land cover. Furthermore, following Shackelford et al. (2013), the mean of reported effect sizes for multi-subgroups of taxa was used (for example, spider families and bee genera).

Data analysis

Pearson product-moment correlation coefficients (r) were used as a measure of effect size, weighted by sample sizes for the meta-analyses. When studies did not report r values, the statistical results provided by the authors (F, $\chi 2$, Spearman-rho, t or R^2) were converted to the correlation coefficient (r). All r values were then converted into Fisher's Z (Rosenthal and DiMatteo 2001), as follows:

$$z = \frac{1}{2} ln\left(\frac{1+r}{1-r}\right)$$

and the asymptotic variance of z was calculated as:

$$v_z = \frac{1}{n-3}$$

where *n* represents the sample size. Fisher's z transforms ranges from -∞ to +∞, where negative values of z represent a negative effect, positive values of z represent a positive effect, and z=0 represents no effect. We calculated the 95% confidence intervals around a cumulative effect size for each variable of interest. Moreover, we considered estimates of the true effect size to be significant if confidence intervals did not overlap with zero. We conducted all analyses using MetaWin software version 2.0 (Rosenberg et al. 2000). In addition, we used mixed models to calculate the cumulative effect sizes (E++) for each group of landscape metrics, assuming that studies within a group share a common mean effect and that both random variation and sampling variation exists within a group. Then, the average of z values was weighted by the inverse of their variance.

Once the effect sizes for each landscape metric and service were calculated, we examined total and group heterogeneity among effects by partitioning variance within groups and testing whether categorical landscape groups were homogeneous with respect to effect sizes. We used the Q-statistic, and total heterogeneity (QT) was partitioned into within-class heterogeneity (QW) and between-class heterogeneity (QB). Total heterogeneity (QT) was calculated as QT= Σ w_i $(E_i\text{-}E_{++})^2$, where w_i is the reciprocal of the variance, E_i is the effect size for each study, and E_{++} is the cumulative effect size for the set of studies under evaluation. QT follows a chi-square distribution with k-1 degrees of freedom. Since we based our analyses on published studies alone, we checked for publication bias and the file-drawer problem by calculating Rosenthal's fail-safe number (Rosenthal and DiMatteo 2001). This number determines the hypothetical number of missing or unpublished studies that, if added, would change the effects from significant to non-significant. If this number is sufficiently high (larger than 5K +10, where k = number of independent comparisons), the results can be considered robust despite publication bias.

Results

A total of 121 articles fit the inclusion criteria and were used in the meta-analyses. Following a critical review and evaluation of data available for analysis, the services described in the *Ecosystem Services Response Variables* section were those that data could be located for, which included: a) water quality, b) disease control, c) loss of pest control by increase in pest response, d) pest control by increase of natural enemies' response, e) pollination, and f) aesthetic value.

Studies addressing natural enemies' response represented *c.a.* 30% of the articles included in the present review (N=36 articles), while 28% concerned water quality (N=34), and 21% evaluated pollination services (N=26), which was followed by pest response (N=11), disease control (N=8), and aesthetic value (N= 6). These selected studies generated 90, 327, 62, 40, 41, and 23 independent comparisons, respectively. Additional details regarding the primary data used for the present analyses is located in the supplementary material (Online Resource 1). Also, landscape complexity significantly influenced all services evaluated in this research, with the exception of disease control. The main results of each evaluated service are presented as follows:

- *Water quality:* Our results indicate an increase of nearly 30% [Cumulative mean effect size (E++) = 0.29, Confidence interval (CI) = 0.24 to 0.32, degrees of freedom (df) = 327], with an increase in landscape complexity (Fig. 2a). Furthermore, water quality varied significantly when various aspects of landscape metrics were evaluated (QB = 86.89, df = 3, $P<0.001$; Table 1), and the strongest (and most positive) effect was observed for the percentage of non-crop areas (E++ = 0.42, CI = 0.35 to 0.49, df = 120).

Landscape connectivity also positively influenced water quality (E++ = 0.35, CI = 0.20 to 0.50, df = 32), though landscape fragmentation did not (E++ = 0.06, CI = -0.08 to 0.20, df = 35). Landscape heterogeneity exhibited a significant and negative effect on water quality (E++ = -0.40, CI = -0.58 to -0.23, df = 20), indicating that heterogeneous matrices of non-natural areas, such as agricultural, urban, commercial and industrial areas, may decrease the effects of this service. Amongst the articles analyzed, approximately 90% evaluated water quality in landscapes that included a very heterogeneous matrix of non-natural areas within cited land use classes. In summary, these results suggest that an increase in landscape characteristics such as non-crop areas, the percentage of natural habitat, and landscape aggregation enhances the provision of services related to water quality.

- *Disease control*: The effect of landscape complexity on this service was slightly positive, though not significant (E++ = 0.04, CI = -0.01 to 0.1, df = 40). Amongst the landscape metrics evaluated, the percentage of natural areas in the landscape had a significant and positive effect on this service (Fig. 2b), enhancing disease control by approximately 20% (E++ = 0.20, CI = 0.07 to 0.33, df = 13) in areas with higher percentages of natural habitats. However, fail-safe values indicated that results were not robust (Table 1) and should be interpreted with caution. Furthermore, among the independent comparisons evaluated for disease control, heterogeneity analyses remained significant (QT = 154.60, $P<0.0001$), even after partitioning the mean effect into different landscape metrics.
- *Pest response*: An evaluation of pest response data (Fig. 2c) indicated that the percentage of non-crop areas increased pest response by nearly 35% (E++ = 0.33, CI = 0.09 to 0.57, df = 17), though the percentage of natural areas surrounding agricultural areas did not influence the loss of pest control (E++ = 0.08, CI = -0.23 to 0.40, df = 10).
- *Natural enemies' response*: With regard to pest control services by natural enemies, we determined that an increase in landscape complexity enhanced natural enemies' response by nearly 25% (E++ = 0.23, CI = 0.14 to 0.32, df = 89; Fig. 2d). However, although this service was influenced homogeneously within different landscape-metric groups (QB = 5.85, P = 0.11, df = 3; Table 1), an increase in the percentage of natural habitats (E++ = 0.35, CI = 0.15 to 0.54, df = 22) and non-crop areas (E++ = 0.30, CI = 0.14 to 0.44, df = 32) had the strongest effects on natural enemies' responses.
- *Pollination*: This service was 31% higher in complex landscapes (E++ = 0.31, CI = 0.21 to 0.42, df = 61; Fig. 2e). The percentage of natural habitats increased this service by 41% (E++ = 0.41, CI = 0.22 to 0.58, df = 24), whereas landscape aggregation increased pollination by 29% (E++ = 0.29, CI = 0.11 to 0.45, df = 24). However, the effects of landscape-metric groups similarly influenced pollination (QB = 5.61, P = 0.13, df = 3; Table 1).

- *Aesthetic value*: Relatively few studies evaluated aesthetic value (i.e., the perception of landscape as a cultural service) from a landscape perspective. Although this service increased due to landscape aspects such as heterogeneity (E++ = 0.50, CI = 0.10 to 0.90, df = 9; Fig. 2f), it did not differ amongst landscape-metric groups (QB = 1.42, P = 0.49).

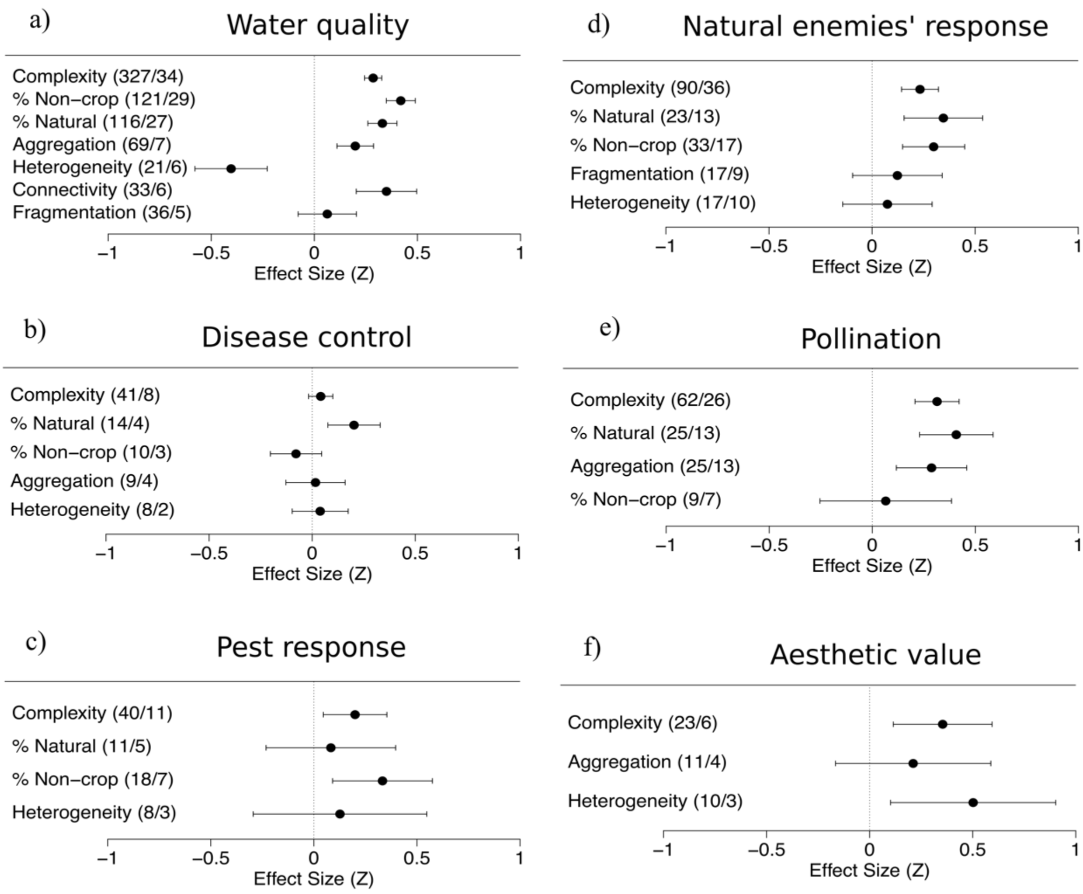

Figure 2. Effects of the selected landscape-metric groups (see Fig. 1 for more information regarding the groups) on the following ecosystem services: a) water quality; b) disease control; c) pest response; d) natural enemies' response; e) pollination; and f) aesthetic value. Values in parentheses denote the total number of independent comparisons/total number of primary studies, respectively. Lines indicate the 95% confidence interval around the effect size for each group.

Table 1. Results from heterogeneity analysis and Rosenthal's fail-safe number following a meta-analysis regarding the effect of landscape patterns on ecosystem services. Using Q statistics, total heterogeneity (QT) was partitioned into within-class heterogeneity (QW) and between-class heterogeneity (QB) following a chi-square distribution with k-1 degrees of freedom (df). The fail-safe number was calculated as $NR=([\Sigma\ z\ (pi)]^2\ /\ z^{\alpha 2})-n$, where z is the score of the normal distribution, $z\alpha$ is the z score associated with the chosen alpha (0.05), and n is the number of studies.

	Ecosystem services					
	Water quality	***Disease control***	***Pest response***	***Natural enemies***	***Pollination***	***Aesthetic value***
QB (P-value)	86.89 (<<0.001)	12.49 (0.006)	2.45 (0.48)	5.85 (0.12)	5.61 (0.13)	1.43 (0.49)
QW (P-value)	509.68 (<<0.001)	142.11 (<<0.001)	35.12 (0.51)	95.26 (0.23)	89.82 (0.004)	19.83 (0.47)
QT (P-value)	596.56 (<<0.001)	154.60 (<<0.001)	37.57 (0.53)	101.11 (0.18)	95.43 (0.003)	21.25 (0.50)
Fail-Safe Number	21,094	56	65	850	825	56

Evaluation of Publication Bias

For the majority of analyzed effects, fail-safe values were greater than 5k+10 (where k is the number of independent comparisons; Table 1). For water quality, natural enemies' response, and pollination services, these values were relatively large, indicating the robustness of results on the mean effect, which suggests the absence of publication bias. Scatter plots of effect sizes against sample sizes for all services separately exhibited a typical funnel shape (Online Resource 2), indicating that studies with small sample sizes had a large dispersion of effect sizes around the true effect value, whereas studies with larger sample sizes tended to possess effect sizes around the true mean value.

Discussion

We determined that specific groups of landscape patterns influenced the provision of ecosystem services differently. Composition landscape metrics, as the percentage of natural or no-crop areas and landscape heterogeneity, influenced all services evaluated in the present research, while configuration metrics such as landscape aggregation influenced two services: pollination and water quality. Our hypothesis regarding landscape complexity was confirmed for water quality, pollination, both pest control indicators, and aesthetic value. Therefore, the role of landscape complexity on increasing the provision of different services suggests that the restoration of natural areas using a land-sharing perspective could be important for the provision of multi-ecosystem functions, which corroborates with results from Barral et al. (2015).

We highlight that water quality can correspond to several different services (Keeler et al. 2012); for example, safe drinking water, commercial fishing, and recreational benefits, among others. A reduction in agricultural areas generally increases water quality through the reduction of fertilizers and pesticides in water bodies. Moreover, increased areas of natural vegetation results in increased soil nutrients, as well as decreased erosion. In the context of riverscapes, the importance of increased connectivity, shown in this study, is due to increased natural riparian vegetation (Allan 2004). Therefore, restoration programs should prioritize riparian areas in order to retain this set of ecosystem services.

Notably, both water quality and pest control by natural enemies' indicators exhibited a trade-off with food production services, as measured by the percentage of crop area. However, landowners and society could benefit from an increase in natural areas in rural regions, which consequently carries improved ecosystem services. For example, landowners could benefit from restoration strategies that increase habitat for natural enemies on their lands (Chaplin-Kramer et al. 2011), or water for irrigation of their crops. Therefore, land managers should consider the creation of mechanisms that lead to greater landowner cooperation on actions that improve landscape conservation and the provision of desired ecosystem services (Goldman and Tallis 2009).

This study also revealed that the reduction of crop areas (or increase in the non-crop percentage) could increase the loss of pest control due to greater pest abundance, richness, and/or damage. This study follows Tscharntke et al.'s (2016) hypotheses to this apparent contradiction, which stated that "the relative importance of natural habitats for biocontrol can vary dramatically depending on type of crop, pest, predator, land management, and landscape structure". For example, many primary studies included in our review did not differentiate between organic or conventional agricultural strategies, or did not report if natural enemies were present in the study region. Chaplin-Kramer et al. (2011) determined that neither the percentage of natural non-crop vegetation nor the percentage of crops has significant effects on pest responses.

Similar to findings by Shackelford et al. (2013), landscape complexity increased pollination service in the present study. This increase was primarily due to the percentage of natural areas, but also due to the positive relationship with landscape aggregation. Therefore, landscape managers should consider both restoration approaches in landscape planning processes for regions with naturally pollinated crops. Rickkets et al. (2008) and Garibaldi et al. (2011) also determined that the distance to habitat influences pollination services. Combined, these findings lend support to the theoretical design proposed by Brosi et al. (2008), who suggested that, in order to increase pollination services in agricultural landscapes, there should be areas large enough to sustain pollinator populations, with other smaller natural areas within the crop matrix with distances not much greater than pollinators' foraging distances. Although we observed a significant effect of aggregation metrics on one fauna-related service (pollination), this did not fully confirm our primary hypotheses. However, a recent review by Fahrig (2017) suggests that ecological responses to fragmentation typically have other influences aside from landscape structure.

With regard to disease control, although landscape composition has an important and significant impact, the determined fail-safe value was insufficiently robust. Additionally, articles related to disease control services were difficult to locate using our research method. Relatively few studies evaluated the impacts of landscape structure on epidemiological processes, though other reviews indicate that the integration of landscape ecological and epidemiological knowledge can be fruitful (e.g., Elliott and Wartenberg 2004; Graham et al. 2005; Ostfeld et al. 2005; Killilea et al. 2008). As disease risk and incidence are related to the communities and dynamics of their pathogens, vectors, reservoirs or hosts, the configuration and composition of landscapes has the potential to influence them, making this type of information useful for landscape managers in regions with high disease risk (Prist et al. 2017).

Notably, landscape heterogeneity had an important effect on the perception of aesthetic value reported by the interviewees in the selected studies, which confirms our hypothesis. However, due to the small sample size available (only six studies), this result was insufficiently robust. Although many other articles have studied this landscape service, their data was not adequately reported for inclusion in our meta-analysis. However, the conclusions of these excluded articles are similar in that landscape heterogeneity is important to peoples' perception of aesthetic value (e.g., Dramstad et al. 2001; De Groot and Van Den Born 2003; Franco et al. 2003; Sang et al. 2008; Herbst et al. 2009; Ode and Miller 2011; Frank et al. 2013; Surová et al. 2014). Furthermore, increased aesthetic value has the potential to increase satisfaction through regional tourism, and offers other spiritual and cultural benefits for society.

Overall, these meta-analyses reinforce the importance of considering landscape structure on assessing ecosystem services for management purposes and decision-making. The magnitude of landscape effect varies according to the landscape metrics and services. Therefore, the results presented in the present study advance our understanding of landscape patterns, and offer guidance for land management activities regarding the provision of landscape services. Land managers must account for landscape composition and configuration in ensuring that services are maintained, and adapt their approach depending upon the relevant focal services.

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Online Resources

Online Resource 1. Table showing the primary studies used in the meta-analyses by ecosystem service, with information about the authors, year of publication, the title of the article, journal source, country and region (when stated in the article) where the study was developed.

Table S1 – Primary studies used in the meta-analysis by landscape service. Information about the authors, year of publication, title of the article, the journal that it was published, the country and region (when stated in the article) where the study was developed.

Services	Authors	Year	Title	Journal	Country	Region
Water quality	Norton & Fisher	2000	The effects of forest on stream water quality in two coastal plain watersheds of the Chesapeake Bay	Ecological Engineering	United States of America	Chesapeake Bay
	Ometo et al.	2000	Effect of land use on water chemistry and macroinvertebrates in two streams of the Piracicaba river basin, southeast Brazil	Freshwater Biology	Brazil	Piracicaba River Basin
	Jones et al.	2001	Predicting nutrient and sediment loadings to streams from landscape metrics: A multiple watershed study from the United States Mid-Atlantic Region	Landscape Ecology	United States of America	Chesapeake Bay
	Ferrier et al.	2001	Water quality of Scottish rivers: spatial and temporal trends	Science of The Total Environment	Scotland	–
	Johnson et al.	2001	Predictability of surface water pollution loading in Pennsylvania using watershed-based landscape measurements	Journal of The American Water Resources Association	United States of America	Pennsylvania
	Buck et al.	2004	Scale dependence of land use effects on water quality of streams in agricultural catchments	Environmental Pollution	New Zeland	Otago
	Woli et al.	2004	Evaluating river water quality through land use analysis and N budget approaches in livestock farming areas	Science of The Total	Japan	Hokkaido

				Environment		
	King et al.	2005	Spatial considerations for linking watershed land cover to ecological indicators in streams	Ecological Applications	United States of America	Maryland
	Ahearn et al.	2005	Land use and land cover influence on water quality in the last free-flowing river draining the western Sierra Nevada	Journal of Hydrology	United States of America	The Cosumnes River Watershed
	Mehaffey et al.	2005	Linking land cover and water quality in New York City's water supply watersheds	Environmental Monitoring and Assessment	United States of America	Catskill/Delaware watersheds.
	Uuemaa et al.	2005	Scale dependence of landscape metrics and their indicatory value for nutrient and organic matter losses from catchments	Ecological Indicators	Estonia	–
	Dodds & Oakes	2006	Controls on nutrients across a prairie stream watershed: land use and riparian cover effects	Environmental Management	United States of America	Mill Creek watershed
	Davies & Neal	2007	Estimating nutrient concentrations from catchment characteristics across the UK	Hydrology & Earth System Sciences	United Kingdom	–
	Zampella et al.	2007	Relationship of land-use/land-cover patterns and surface-water quality in the Mullica River Basin	Journal of The American Water Resources Association	United States of America	Mullica River basin
	Poor et al.	2008	Testing the hydrological landscape unit classification system and other terrain analysis measures for predicting low-flow nitrate and chloride in watersheds	Environmental Management	United States of America	Willamette River Basin in western Oregon
	Tu & Xia	2008	Examining spatially varying relationships between land use and water quality using geographically weighted regression I: model design and evaluation	Science of The Total Environment	United States of America	watersheds in eastern Massachusett

	Amiri & Nakane	2009	Modeling the Linkage Between River Water Quality and Landscape Metrics in the Chugoku District of Japan	Water Resources Management	Japan	Chugoku district
	Lee et al.	2009	Landscape ecological approach to the relationships of land use patterns in watersheds to water quality characteristics	Landscape and Urban Planning	South Korea	–
	Rothwell et al.	2010	A spatial and seasonal assessment of river water chemistry across North West England	Science of The Total Environment	England	–
	Beckert et al.	2011	Characterization and comparison of stream nutrients, land use, and loading patterns in Maryland coastal bay watersheds	Water Air Soil Pollution	United States of America	Maryland coastal bays
	Hively et al.	2011	Relating nutrient and herbicide fate with landscape features and characteristics of 15 subwatersheds in the Choptank River watershed	Science of The Total Environment	United States of America	Chesapeake Bay
	Miller et al.	2011	Whole catchment land cover effects on water quality in the lower Kaskaskia River watershed	Water Air Soil Pollut	United States of America	The Lower Kaskaskia River Watershed
	Amiri et al.	2012	Linkage between in-stream total phosphorus and land cover in Chugoku District, Japan: an ANN approach	Journal of Hydrology and Hydromechanics	Japan	Chugoku
	Lowicki	2012	Prediction of flowing water pollution on the basis of landscape metrics as a tool supporting delimitation of Nitrate Vulnerable Zones	Ecological Indicators	Poland	Warta watershed.
	Bateni et al.	2013	Assessment of land cover changes and water quality changes in the Zayandehroud River Basin between 1997-2008	Environmental Monitoring And Assessment	Iran	The Zayandehroud river basin
	Sun et al.	2013	Effect of Land-Use Patterns on Total Nitrogen Concentration in the Upstream Regions of the Haihe River Basin, China	Environmental Management	China	The Haihe River basin,

	Bu et al.	2014	Relationships between land use patterns and water quality in the Taizi River basin, China	Ecological Indicators	China	The Taizi River
	Chen & Lu	2014	Effects of land use, topography and socio-economic factors on river water quality in a mountainous watershed with intensive agricultural production in East China	Plos One	China	The Cao-E River
	Ye et al.	2014	Seasonal water quality upstream of Dahuofang reservoir, China - the effects of land use type at various spatial scales	Clean-Soil Air Water	China	The Xiangxi River
	Haidary et al.	2015	Modelling the relationship between catchment attributes and wetland water quality in Japan	Ecohydrology	Japan	Higashi-Hiroshima
	Li et al.	2015	Modeling the relationship between landscape characteristics and water quality in a typical highly intensive agricultural small watershed, Dongting lake basin, south central China	Environmental Monitoring And Assessment	China	Jinjing River watershed
	Sangani et al.	2015	Modeling relationships between catchment attributes and river water quality in southern catchments of the Caspian Sea	Environmental Science And Pollution Research	Iran	Caspian sea
	Huang et al.	2016	Effects of land use patterns on stream water quality: a case study of a small-scale watershed in the Three Gorges Reservoir Area, China	Environmental Science And Pollution Research	China	The Heigou River
	Teixeira & Marques	2016	Relating landscape to stream nitrate-N levels in a coastal eastern-Atlantic watershed (Portugal)	Ecological Indicators	Portugal	The Mondego river basin
Natural enemies	Ostman et al.	2001	Landscape heterogeneity and farming practice influence biological control	Basic and Applied Ecology	Sweden	Uppsala
	Steffan-	2002	Landscape context affects trap-nesting bees, wasps, and	Ecological	Germany	Lower Saxony

	Dewenter		their natural enemies	Entomology		
	Tscharntke et al.	2002	Contribution of small habitat fragments to conservation of insect communities of grassland– cropland landscapes	Ecological Applications	Germany	Göttingen
	Kruess	2003	Effects of landscape structure and habitat type on a plant herbivore-parasitoid community	Ecography	Germany	Lower Saxony
	Steffan-Dewenter	2003	Importance of habitat area and landscape context for species richness of bees and wasps in fragmented orchard meadows	Conservation Biology	Germany	Lower Saxony
	Thies et al.	2003	Effects of landscape context on herbivory and parasitism at different spatial scales	Oikos	Germany	Lower Saxony
	Weibull et al.	2003	Species richness in agroecosystems: the effect of landscape, habitat and farm management	Biodiversity and Conservation	Sweden	Central East
	Prasifka et al.	2004	Relationships of landscape, prey and agronomic variables to the abundance of generalist predators in cotton (*Gossypium hirsutum*) fields	Landscape Ecology	United States of America	Texas
	Bianchi et al.	2005	Landscape factors affecting the control of by natural enemies in Brussels sprout	Agriculture, Ecosystems and Environment	Netherlands	–
	Miliczky & Horton	2005	Densities of beneficial arthropods within pear and apple orchards affected by distance from adjacent native habitat and association of natural enemies with extra-orchard host plants	Biological Control	United States of America	Washington and Oregon
	Purtauf et al.	2005	Landscape context of organic and conventional farms: influences on carabid beetle diversity	Agriculture, Ecosystems & Environment	Germany	Göttingen
	Purtauf et al.	2005	The response of carabids to landscape simplification differs between trophic groups	Agriculture, Ecosystems And	Germany	Giessen and Göttingen

				Environment		
	Roschewitz et al.	2005	The influence of landscape context and farming practices on parasitism of cereal aphids	Agriculture, Ecosystems & Environment	Germany	Göttingen
	Schmidt & Tscharntke	2005	Landscape context of sheetweb spider (Araneae: Linyphiidae) abundance in cereal fields	Journal of Biogeography	Germany	Göttingen
	Schmidt et al.	2005	Differential effects of landscape and management on diversity and density of ground-dwelling farmland spiders	Journal of Applied Ecology	Germany	Göttingen
	Thies et al.	2005	The landscape context of cereal aphid-parasitoid interactions	Proceedings of The Royal Society B	Germany	–
	Klein et al.	2006	Rain forest promotes trophic interactions and diversity of trap-nesting Hymenoptera in adjacent agroforestry	Journal of Animal Ecology	Indonesia	Napu valle
	Rand & Tscharntke	2007	Contrasting effects of natural habitat loss on generalist and specialist aphid natural enemies	Oikos	Germany	Lower Saxony
	Bianchi et al.	2008	Enhanced pest control in cabbage crops near forest in The Netherlands	Landscape Ecology	Netherlands	–
	Drapela et al.	2008	Spider assemblages in winter oilseed rape affected by landscape and site factors	Ecography	Austria	Agricultural region
	Oberg et al.	2008	Landscape effects on recolonization patterns of spiders in arable fields	Agriculture, Ecosystems and Environment	Germany	Central Hesse
	Schmidt et al.	2008	Contrasting responses of arable spiders to the landscape matrix at different spatial scales	Journal of Biogeography	Germany	Göttingen and Giessen
	Vollhardt et	2008	Diversity of cereal aphid parasitoids in simple and	Agriculture, Ecosystems and	Germany	Göttingen

	al.		complex landscapes	Environment		
	Werling & Gratton	2008	Influence of field margins and landscape context on ground beetle diversity in Wisconsin (USA) potato fields	Agriculture, Ecosystems and Environment	United States of America	Wisconsin
	Boccaccio & Petacchi	2009	Landscape effects on the complex of *Bactrocera oleae* parasitoids and implications for conservation biological control	Biological Control	Italy	Pisa
	Eilers & Klein	2009	Landscape context and management effects on an important insect pest and its natural enemies in almond	Biological Control	United States of America	Capay Valley
	Haenke et al.	2009	Increasing syrphid fly diversity and density in sown flower strips within simple vs. complex landscapes	Journal of Applied Ecology	Germany	Göttingen
	Schmidt-Entling & Dobeli	2009	Sown wildflower areas to enhance spiders in arable fields	Agriculture, Ecosystems and Environment	Switzerland	Solothurn and Bern
	Gardiner et al.	2009	Landscape diversity enhances biological control of an introduced crop pest in the north-central USA	Ecological Applications	United States of America	Iowa, Michigan, Minnesota, and Wisconsin
	Gardiner et al.	2009	Landscape composition influences patterns of native and exotic lady beetle abundance	Biodiversity Resarch	United States of America	Iowa, Michigan, Minnesota, and Wisconsin
	Anjum-Zubair et al.	2010	Influence of within-field position and adjoining habitat on carabid beetle assemblages in winter wheat	Agricultural and Forest Entomology	Switzerland	Solothurn and Bern
	Bailey et al.	2010	Effects of habitat amount and isolation on biodiversity in fragmented traditional orchards	Journal of Applied Ecology	Switzerland	north-eastern
	Ekroos et al.	2010	Responses in plant and carabid communities to farming practises in boreal landscapes	Agriculture, Ecosystems and Environment	Finland	South
	Gardiner et al.	2010	Landscape composition influences the activity density of	Biological	United States of	Iowa, Michigan, Minnesota,

			Carabidae and Arachnida in soybean fields	Control	America	and Wisconsin
	Pluess et al.	2010	Non-crop habitats in the landscape enhance spider diversity in wheat fields of a desert agroecosystem	Agriculture, Ecosystems and Environment	Israel	Northwest Negev Desert
	Thomson et al.	2010	Effect of woody vegetation at the landscape scale on the abundance of natural enemies in Australian vineyards	Biological Control	Australia	BarossaValey abd Wrattonbully region
Pest response	Ostman et al.	2001	Landscape heterogeneity and farming practice influence biological control	Basic and Applied Ecology	Sweden	Uppsala
	den Belder et al.	2002	Effect of woodlots on thrips density in leek fields: a landscape analysis	Agriculture, Ecosystems and Environment	Netherlands	North Barbant and Limburg
	Thies et al.	2003	Effects of landscape context on herbivory and parasitism at different spatial scales	Oikos	Germany	Göttingen
	Kruess	2003	Effects of landscape structure and habitat type on a plant herbivore-parasitoid community	Ecography	Germany	Göttingen
	Roschewitz et al.	2005	The influence of landscape context and farming practices on parasitism of cereal aphids	Agriculture, Ecosystems & Environment	Germany	Göttingen
	Thies et al.	2005	The landscape context of cereal aphid-parasitoid interactions	Proceedings Of The Royal Society B	Germany	Göttingen
	Zaller et al.	2008	Insect pests in winter oilseed rape affected by field and landscape characteristics	Basic and Applied Ecology	Austria	Lower Austria
	Eilers & Klein	2009	Landscape context and management effects on an important insect pest and its natural enemies in almond	Biological Control	United States of America	Capay Valley
	Zaller et al.	2009	Parasitism of stem weevils and pollen beetles in winter oilseed rape is differentially affected by crop	Biological Control	Austria	Lower Austria

			management and landscape characteristics			
	Bailey et al.	2010	Effects of habitat amount and isolation on biodiversity in fragmented traditional orchards	Journal of Applied Ecology	Switzerland	north-eastern
	Noma et al.	2010	Relationship of soybean aphid (Hemiptera: Aphididae) to soybean plant nutrients, landscape structure, and natural enemies	Environmental Entomology	United States of America	Iowa, Michigan, Minnesota, and Wisconsin
Pollination	Kremen et al.	2002	Crop pollination from native bees at risk from agricultural intensification	PNAS	United States of America	Central Valley
	Steffan-Dewenter et al.	2002	Scale-dependent effects of landscape context on three pollinator guilds	Ecology	Germany	Lower Saxony
	Steffan-Dewenter	2002	Landscape context affects trap-nesting bees, wasps, and their natural enemies	Ecological Entomology	Germany	Göttingen
	Steffan-Dewenter	2003	Importance of habitat area and landscape context for species richness of bees and wasps in fragmented orchard meadows	Conservation Biology	Germany	Lower Saxony
	Klein et al.	2003	Pollination of *Coffea canephora* in relation to local and regional agroforestry management	Journal of Applied Ecology	Indonesia	Lore-Lindu National Park
	Westphal et al.	2003	Mass flowering crops enhance pollinator densities at a landscape scale	Ecology Letters	Germany	Göttingen
	Kremen et al.	2004	The area requirements of an ecosystem service: crop pollination by native bee communities in California	Ecology Letters	United States of America	Yolo, Solano and Sacramento counties
	Ricketts	2004	Tropical forest fragments enhance pollinator activity in nearby coffee crops	Conservation Biology	Costa Rica	San Isidoro del General
	Westphal et al.	2006	Bumblebees experience landscapes at different spatial scales: possible implications for coexistence	Oecologia	Germany	Göttingen

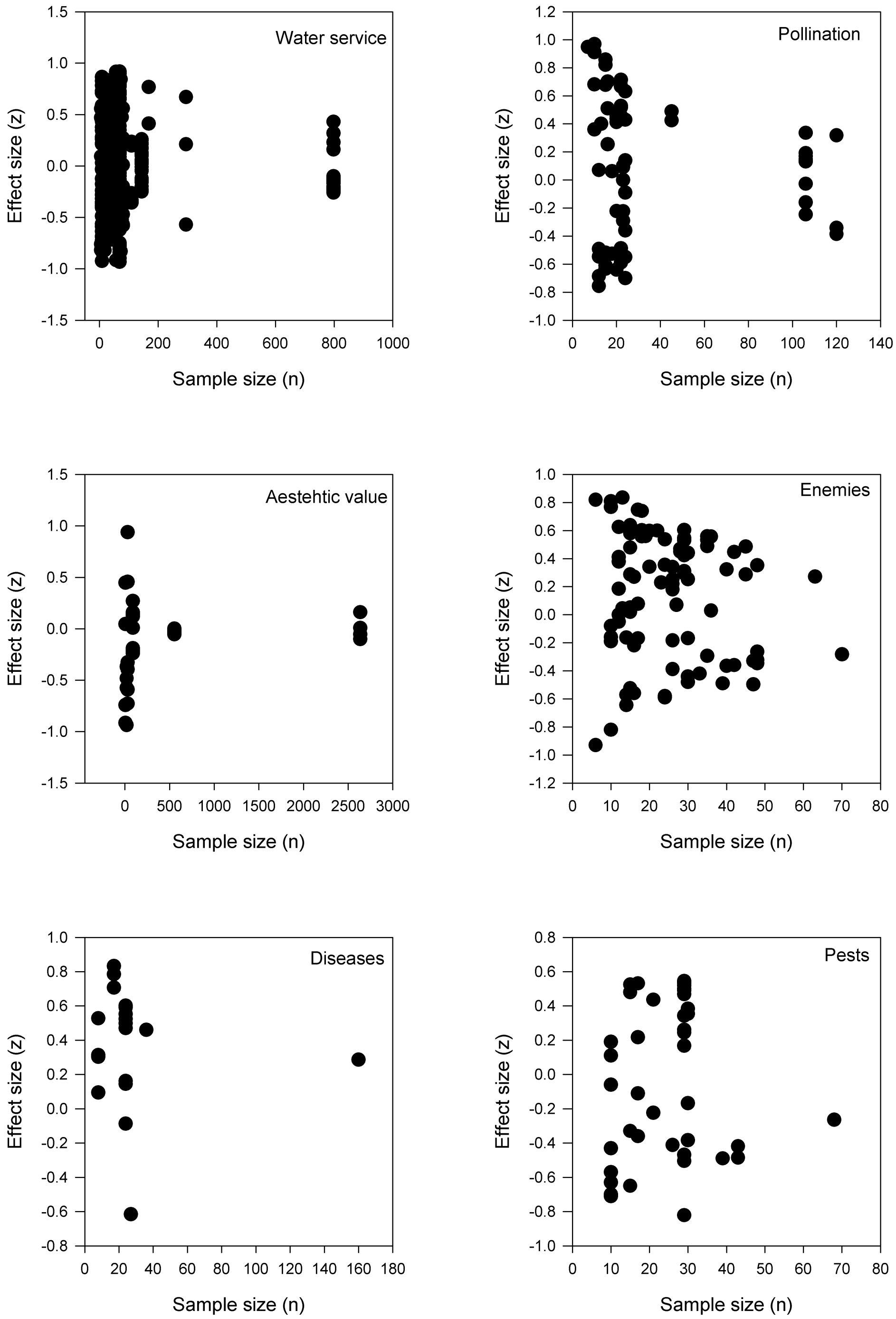
	Morandin & Winston	2006	Pollinators provide economic incentive to preserve natural land in agroecosystems	Agriculture, Ecosystems and Environment	Canada	Alberta
	Greenleaf & Kremen	2006	Wild bee species increase tomato production and respond differently to surrounding land use in Northern California	Biological Conservation	United States of America	Northern California
	Greenleaf & Kremen	2006	Wild bees enhance honey bees pollination of hybrid sunflower	PNAS	United States of America	Central Valley
	Klein et al.	2006	Rain forest promotes trophic interactions and diversity of trap-nesting Hymenoptera in adjacent agroforestry	Journal of Animal Ecology	Indonesia	Lore-Lindu National Park
	Morandin et al.	2007	Can pastureland increase wild bee abundance in agriculturally intense areas?	Basic and Applied Ecology	Canada	Alberta
	Winfree et al.	2007	Native bees provide insurance against ongoing honey bee losses	Ecology Letters	United States of America	Pennsylvania
	Rundlof et al.	2008	Interacting effects of farming practice and landscape context on bumble bees	Biological Conservation	Sweden	Skäne
	Chacoff et al.	2008	Proximity to forest edge does not affect crop production despite pollen limitation	Proceedings of The Royal Society B	Argentina	Upper Bermejo River Basin
	Winfree et al.	2008	Wild bee pollinators provide the majority of crop visitation across land-use gradients in New Jersey and Pennsylvania, USA	Journal of Applied Ecology	United States of America	New Jersey and Pennsylvania
	Carré et al.	2009	Landscape context and habitat type as drivers of bee diversity in European annual crops	Agriculture, Ecosystems and Environment	France, Germany, Poland, Sweden and UK	Mediterranean north (France), Atlantic central (Germany and the UK), continental (Poland), and nemoral (Sweden).

	Klein	2009	Nearby rainforest promotes coffee pollination by increasing spatio-temporal stability in bee species richness	Forest Ecology and Management	Indonesia	Lore-Lindu National Park
	Jauker et al.	2009	Pollinator dispersal in an agricultural matrix: opposing responses of wild bees and hoverflies to landscape structure and distance from main habitat	Landcape Ecology	Germany	Wetterau
	Julier & Roulston	2009	Wild bee abundance and pollination service in cultivated pumpkins: farm management, nesting behavior and landscape effects	Journal of Economic Entomology	United States of America	North Virginia and Maryland
	Arthur et al.	2010	Influence of woody vegetation on pollinator densities in oilseed Brassica fields in an Australian temperate landscape	Basic and Applied Ecology	Australia	Boorowa
	Brittain et al.	2010	Organic farming in isolated landscapes does not benefit flower-visiting insects and pollination	Biological Conservation	Italy	the Meolo basin
	Carvalheiro et al.	2010	Pollination services decline with distance from natural habitat even in biodiversity-rich areas	Journal of Applied Ecology	South Africa	farming region of located between Blyde River Canyon Nature Reserve and Kruger National Park
	Diaz-Forero et al.	2013	Influence of local and landscape factors on bumblebees in semi-natural meadows: a multiple-scale study in a forested landscape	Journal of Insect Conservation	Estonia	Ida-Virumaa
Disease control	Page et al.	2001	Changes in transmission of *Baylisascaris procyonis* to intermediate hosts as a function of spatial scale	Oikos	United States of America	Indiana
	Overgaard et al.	2003	Effect of landscape structure on anopheline mosquito density and diversity in northern Thailand: Implications for malaria transmission and control	Landscape Ecology	Thailand	Pang Mai Daeng village, Mae Taeng district, Chiang Mai province, Mae Mok village, Ban Tae village and Huay Chang Kham village

	Brownstein et al.	2005	Forest fragmentation predicts local scale heterogeneity of Lyme disease risk	Oecologia	United States of America	Connecticut
	Horobick et al.	2007	Abundance and *Borrelia burgdorferi* infection prevalence of nymphal *Ixodes scapularis* ticks along forest-field edges	Ecohealth	United States of America	Dutchess County
	Ezenwa et al.	2007	Land cover variation and West Nile virus prevalence: patterns, processes, and implications for disease control	Vector-Borne and Zoonotic Diseases	United States of America	St. Tammany Parish
	Yang et al.	2008	An integrated approach to identify distribution of *Oncomelania hupensis*, the intermediate host of *Schistosoma japonicum*, in a mountainous region in China	International Journal For Parasitology	China	Cibihu Lake
	Degroote et al.	2008	Landscape, demographic, entomological, and climatic associations with human disease incidence of West Nile virus in the state of Iowa, USA	International Journal of Health Geographics	United States of America	Iowa
	Wang et al.	2013	Environmental determinants of *Opisthorchis viverrini* prevalence in northeast Thailand	Geospatial Health	Thailand	Khorat Plateau
Aesthetic value	Clay & Daniel	2000	Scenic landscape assessment: the effects of land management jurisdiction on public perception of scenic beauty	Landscape and Urban Planning	United States of America	Southern Utah
	Franco et al.	2003	The impact of agroforestry networks on scenic beauty estimation - The role of a landscape ecological network on a socio-cultural process	Landscape and Urban Planning	Italy	Venice drainage basin
	Arriaza et al.	2004	Assessing the visual quality of rural landscapes	Landscape and Urban Planning	Spain	Andalusia
	Dramstad et al.	2006	Relationships between visual landscape preferences and map-based indicators of landscape structure	Landscape and Urban Planning	Norway	–
	De la Fuente	2006	Relationship between landscape visual attributes and spatial pattern indices: a test study in Mediterranean-	Lanscape and	Spain and Chile	Sierra de Guadarrama(Madrid, Spain)

	de Val et al.		climate landscapes	Urban Planning		and the Andean foothills (Santiago,Chile).
	Ode et al.	2009	Indicators of perceived naturalness as drivers of landscape preference	Journal of Environmental Management	Europe	–

Online Resource 2. Funnel plots of effect sizes against sample sizes for each ecosystem service evaluated in the present study.



Capítulo 2

A framework and rapid assessment tool for multifunctional landscapes - incorporating landscape services in restoration planning

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Abstract

As international aims for sustainable development, there is a current need to align food security with the provision of clean water, biological conservation, climate change mitigation and other socioecological benefits. Multifunctional landscapes are, therefore, a way forward to achieve these goals. As economic activities intensification occurred in many landscapes all over the globe, jeopardizing the provision of natural ecosystems services (ESs) that benefit human well-being, restoration projects are necessary to increase multifunctionality. The scientific community is describing a number of landscape structure and patterns, such as its complexity, connectivity, composition and configuration, that lead to the stability of ESs. If restoration planners want to increase or sustain the provision of ESs, they should consider the potential of the resultant landscape structure – i.e., the landscape composition and configuration after the restoration – to optimize the ecological and social process involved in the service provision and delivery. In this work, we developed a spatially explicit modelling framework that considers stakeholders interests, bundles ecosystem services according to their response to landscape patterns, and has a tool that uses simple, readily available data to rapidly identify locations for restoration across landscapes. The framework states the main features of the ESs that need to be identified to know which landscape pattern to pursue in restoration actions. The outputs of our tool indicate priority areas for restoration that have the greatest potential to increase or maintain the provision of multiple ESs. We believe that our framework and tool have a great potential to support landscape planning and management decisions that aim to increase landscape multifunctionality.

Keywords: *Ecosystem services; Restoration; Spatial patterns; LSRestoration; Ecological Benefits; Bundles;*

Introduction

According to the international aims for sustainable development (CBD, 2010), there is a current need to align food security, provision of clean water, biological conservation, and other socioecological benefits. Planning for multifunctional landscapes are a way towards achieving these goals, as they do not only maintain biodiversity but also sustain multiple ecological processes and functions, including the ones that benefit human well-being, known as ecosystem services (ESs; Pretty, 2008; Garbach et al., 2016; Rockström et al., 2016). In agricultural landscapes, the integration of ecological principles, such as agroforests and organic management, can increase win-win situations for crop yield and ESs (Jose, 2009; Garbach et al., 2016). As economic activities intensification occurred in many landscapes all over the globe, promoting land use change, natural assets depletion and jeopardizing the provision of ESs from natural systems (MEA, 2005), restoration projects are necessary to increase landscape multifunctionality and can be a profitable investment (De Groot et al., 2013).

Planning restoration to create multifunctional landscapes requires accounting not only for the capacity of ecosystems to provide services for humans, but also for the spatial variation of the location and quantity of ES supply and demand areas, as well as the connection between them - that is the ES flow (Fisher et al., 2009; Villamagna et al., 2013; Burkhard, et al., 2014; Mitchell et al., 2015). The scientific community is describing a number of landscape structure and patterns, such as complexity, connectivity, composition and configuration, that influence the provision of ESs (Chaplin-Kramer et al., 2011; Kremen et al., 2011; Mitchell et al., 2013; Shackelford et al., 2013; Duarte et al., 2018). For example, the provision of fisheries, water quality, and flood protection are all directly related to the preservation of natural ecosystems in riparian areas (Allan, 2004; Keeler et al., 2012). On the other hand, the provision of pollination, natural pest control and microclimate regulation are related to interspersed anthropogenic and natural ecosystems (Brosi et al., 2008; Liu & Weng, 2009; Duarte et al., 2018). Therefore, the maintenance of multiple ESs depend on the spatial arrangement and interaction between natural habitats and between natural and anthropogenic areas (Termorshuizen & Opdam, 2009; Syrbe & Walz, 2012).

Once budgets for restoration projects are limited and need to be efficiently allocated, landscape planners are increasingly trying to prioritize restoration efforts that can enhance multiple benefits (Benayas et al., 2009; Trabucchi et al., 2012; Metzger & Brancalion, 2016). Accounting for the effects of the spatial arrangement of restoration areas on the potential for positive ecological outcomes provides a way forward this prioritization (Metzger & Brancalion, 2016). In other words, if restoration planners want to increase or sustain the provision of ESs, they should consider the effects of the resultant landscape structure – i.e. the landscape composition and configuration after the restoration – on the ecological and social process involved in the service provision and delivery. To do so, planners and managers could use mechanisms that enable them considering the landscape context in the restoration planning process and its link to ecological and social processes that underlie ES provision (Cowling et al., 2008; Cimon-Morin et al., 2013).

In this sense, although there are several successful approaches to model individual ESs provision, demand and flow (Martínez-harms & Balvanera, 2012; Villamagna et al., 2013; Cimon-Morin et al., 2014), these information has not been used to formulate practical tools that land managers can easily use. Building on a recent review and meta-analysis regarding the effects of landscape patterns on multiple ESs (Duarte et al., 2018), we developed a spatially explicit modelling framework that considers stakeholders interests, bundles ecosystem services according to their response to landscape patterns, and has a tool that uses simple, readily available data to rapidly identify locations for restoration across landscapes. The framework identifies the main features of the ESs that need to be identified to know which landscape pattern to pursue in restoration actions. The outputs of our tool indicate priority areas for restoration that have the greatest potential to increase or maintain the provision of multiple ESs. With this work, we intend to support landscape planning and management decisions that aim to increase landscape multifunctionality.

Framework description

The general goal of the framework is to identify bundles of ESs that respond similarly to landscape structure and provide a tool to assist landscape planners in the allocation of restoration efforts in order to increase or maintain ES provision. In this way, using spatial data inputs landscape planners will receive information on priority areas for restoration. By identifying ES that respond in similar ways to landscape patterns, planners can make it simpler to manage landscapes for multiple benefits. This framework focus on local to regional landscapes, as for example subwatersheds up to 10^5 km^2, so that the landscape patterns have an effect on ES provision (Duarte et al., 2018). Indeed, most of the ES mapping studies were done at the regional scale (Martínez-Harms & Balvanera, 2012).

To increase chances of implementation of restoration plans, landscape planners should use a participatory approach with different stakeholders, including both the ones who have power to influence restoration initiatives and the ones that will be influenced by them (Metzger et al., 2017). To fairly consider stakeholders' different points of view enables the conditions for ES knowledge to lead to practical actions, as it creates a sense of legitimacy of the whole process within the parts involved (Posner et al., 2016). Thus, this framework integrates ESs preferences of different stakeholders and incorporates landscape management options that are easily understandable to a broad audience of planners, landowners and decision-makers. It aims to facilitate the assessment and identification of areas for restoration that have the greatest capacity to create landscape patterns that positively influence the provision of multiple ESs. The framework consists of:

1. Stakeholders consultation and assessment of ES of concern (fig. 1a) along with other context dependent information throughout the entire process of restoration planning.
2. Determining bundles of ESs that respond similarly to landscape structure, through the assessment of three different ES characteristics (fig. 1b, c and d).
3. Applying the proposed tool for each bundle, which takes readily available spatial data and identifies areas that are most likely to lead to a landscape structure that favors the provision of ES of that specific bundle (fig. 1e).
4. Guiding the application of these outputs in the decision-making process with stakeholders' participation. In this step, we discuss the information derived from the tool and how to use multiple services in the planning process (fig. 1f).

We describe below each one of these steps of the framework.

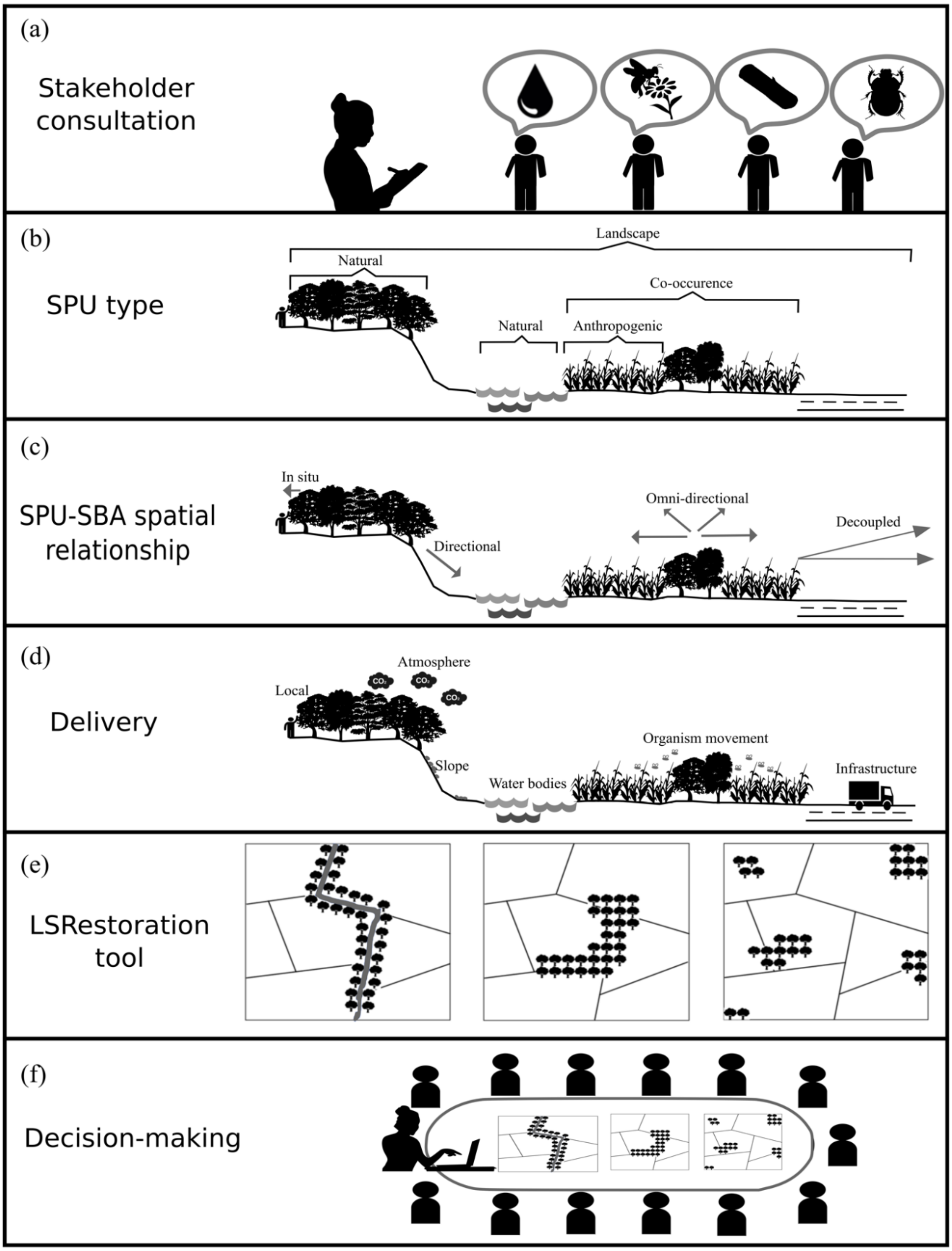

Figure 1. Scheme representing the steps of the proposed framework. The first step is related to stakeholder consultation regarding the ecosystem services of interest and of concern (a); Steps relating to the characteristics of the ecosystem services and the corresponding Service Providing Unit (SPU), Service Beneficiary Area (SBA), and Delivery (b, c and d) – the definitions and categories of these characteristics are text body; Then the usage of the Landscape Service Restoration tool (LSRestoration) to map priority areas for restoration (e); Last, the decision-making

step with participation of stakeholders regarding the tool results (f). See the text and table 1 for more information.

Stakeholders consultation

As stated before in this work, landscape planners need to engage with stakeholders and assess their ESs of interest. Therefore, we designed this framework to be based on the stakeholders' opinions regarding the provision of ESs in the landscape and also on scientific knowledge (Reed, 2008; Reed et al., 2009). When engaging with stakeholders, especially with landowners, landscape planners will encounter private interests that the ecosystems provide (or have the potential to provide) – such as wood, pest control and pollination on private farms. Although these private ESs can persuade landowners to restoration actions in their own landscape, the landscape planner should also consider the public interests of others ES provided in that landscape (or with the potential to be provided) – such as drinking water, scenic beauty and flood control. As the focus here is the restoration of natural areas, landscape planners should address not only the importance of the service to stakeholders, but also their concern about ES maintenance through time in the landscape.

Within this stakeholders' consultation, planners should assess which ES are most valued or of concern by different stakeholders and understand how people interact with ecosystems to obtain ESs. In this consultation process, the different characteristics to bundle ES in that landscape will become clearer to planners. Specifically, after assessing the ES of interest, planners should address:

a) the service providing units type (SPU). That is, the types of spatial units that are the source of an ESs (Syrbe & Walz, 2012). Alternatively, the landscape planner should understand the type of SPU that have the potential, if restored, to increase service provision. Understanding this with stakeholders' consultation and with scientific knowledge will inform to planners what are the areas that are already providing the ES and the type of ecosystem that they will need to restore.
b) the spatial relation between the SPU and the service beneficiary area (SPU-SBA). The types of SPU-SBA spatial relationships address the distances and directions that the services can spread or reach throughout the landscapes (Fisher et al., 2009; Syrbe & Walz, 2012; Burkhard et al., 2014; table1). In this case, the ecological process underlying the service will define its capacity to percolate the landscape.
c) how the delivery of the ES occurs, that is, what mechanisms are needed for a benefit to be realized. Therefore, planners should understand, with the stakeholders, how the benefits actually flow to them, or how they interact with the ecosystems that are providing the service.

d) the information regarding the areas available for restoration within the landscape and, if possible, a surface map with values of restoration feasibility/suitability. With the consultation of stakeholders, especially with landowners, this information can translate the actual areas available for restoration and their feasibility/suitability - perhaps include the different opportunity and restoration costs. This could increase the probability of implementation of the restoration plan, as it creates a more participatory approach with the stakeholders (Reed et al., 2009; Metzger et al., 2017).

As different stakeholders can have their own nomenclature for the ES of interest, this framework focus in the three ES characteristics described above (a, b and c). This creates a more flexible approach and helps the landscape planners using our framework to understand the ES behavior and define the landscape structure that will attend their needs. These three characteristics are described in details in the following sections.

Bundling ecosystem services

SPU type

In this framework, we propose four different types of SPUs to aggregate different services: anthropogenic, natural, co-occurrence and landscape (table 1; fig. 1b). ES with anthropogenic SPUs are those that are primarily produced within human-dominated ecosystems. This includes ES like food production from croplands or timber production from plantation forests. ES with natural SPUs are the those primarily produced within natural ecosystems, such as forests, savannas, rivers and lakes. Examples of ESs with this type of SPUs are fruits and wood from natural areas, water-related services, bioremediation, carbon sequestration, ecotourism and maintenance of habitat for species of interest. SPUs of the co-occurrence type are the systems that need both natural and anthropogenic areas co-occuring for the provision of the ESs. For example, for services such as pollination, pest control, and micro-climate regulation to occur, natural areas (as forest patches) must be interleaved or within an anthropogenic area (as crops, pastures and urban area). The same goes for sediment retention and landslide control, as they only are considered ecosystem services if they occur within anthropogenic areas. Last, SPUs of landscape type are the ones in which the system, or spatial unit, that provides the service is the whole landscape. For example, cultural services of scenic beauty and spiritual and religion values.

Table 1 – The description of attributes and its possible categories that we used in the framework to bundle ecosystem services (ESs).

Attributes	Categories	Description
SPU (ecosystem service providing units)	Anthropogenic	The production of the service primarily occurs in anthropogenic ecosystems.
	Natural	The production of the service primarily occurs in natural or semi-natural ecosystems.
	Co-production	For service production, it is necessary that both natural and anthropogenic ecosystems are interspersed.
	Landscape	The landscape as a whole is the provision unit of the service.
SPU-SBA (ecosystem services providing units and benefiting areas spatial relation)	In situ	SPU and SBA are realized in the same location.*
	Directional	SBA in a specific location due to flow direction from the SPU.*
	Omni-directional	SPU in one location, SBAs in the surrounding landscape without directional bias.*
	Decoupled	Ecosystem service can be traded over long distances.*
Delivery (how the ecosystem service is delivered to society)	Local	The flow of the ES occurs in one location.
	Infrastructure	Some infrastructure (for example roads and processing plants) are necessary for the occurrence of ES flow.
	Organism movement	The flow of the ES occurs through organism movement.
	Water Bodies	The flow of the ES occurs through water bodies.
	Slope	The flow of the ES occurs downslope.
	Atmosphere	The flow of the ES occurs through the atmosphere.

* Definitions from Fisher et al. 2009 and Burkhard et al. 2014.

SPU-SBA spatial association

Here, we follow Burkhard et al. (2014) and propose four different types of SPU-SBA relationship to aggregate different services: in situ, directional, omni-directional, decoupled (table 1; fig. 1c). The *in situ* relationships occur when the provision and the benefit are realized in the same location (e.g. bioremediation, fruits, wood and animals for subsistence or local consumption, and natural plants for traditional medicine). A directional relationship occurs when SPU and SBA have different locations due to flow direction (e.g. water quality regulation for downstream population and erosion control for downslope crops). An omni-direction relationship occurs when the SPU is in one location and SBAs in the surrounding areas without directional bias (e.g. pollination, pest control, seed dispersal, and microclimate regulation). A decoupled relationship corresponds to situations when the benefit can percolate long distances that go beyond the landscape of interest. A common example is the carbon sequestration that promotes global climate regulation. However, this type of relationship is also related to services as wood, natural fruits, crops production and other natural products that will be sold in regional, national or global markets.

Delivery

Here, we propose six different types of delivery to aggregate different services: local, infrastructure, organism movement, water bodies, slope, and atmosphere (table 1; fig. 1d). Local delivery corresponds to services with *in situ* relationship and, therefore, the flow is limited to one location. Delivery through infrastructure is related to services that need some human-made structure before reach their beneficiaries. For example, production services as crops outputs, timber and no-timber materials from natural areas that will be sold in markets could need to go to processing-plants and/or to be transported through roads to reach these markets. In addition, for many ecotourism activities in natural areas to occur they need to be close to roads or other infrastructure. Delivery through organism movement occurs when species need to percolate the landscape for the service to flow to their beneficiaries. For examples, pollinators and natural enemies of pest need to percolate crop areas so the respective services can be realized. Or individuals of species with conservation interest need to move through different habitat patches so their population can survive. Delivery through water bodies is related to services with flows occurring through hydrological systems. Examples are all water quality and quantity related services, including flood control, drinking water and fisheries (see Keeler et al. 2012 for more examples). Slope delivery is related to services that flow downslope, such as erosion control, sediment and nutrient retention. Atmosphere delivery is related to processes occurring in the atmosphere, like micro and global climate regulation.

Services bundles

Using the CICES classification (version 4.3) of ESs as a starting point (Haines-Young & Potschin, 2013), we created bundles of services according to the three different features described above. Landscape planners do not need to use the CICES classification of the ES as we did. They only need to determine the type of their ES of interest on each characteristic above. We can see that services characteristics types are context dependent, and therefore, different landscape patterns could influence ESs with the same classification/name depending on the local or regional context. For example, in one region the maintenance of nursey habitats for species of economic interest could be delivered through water bodies and have a directional SPU-SBA relationship (e.g. fisheries). In another region, the same service (or same classification/name) could have an in-situ SPU-SBA relation and be delivered locally (e.g. crabs captured in mangrove areas for subsistence). In these examples, the landscape management to improve the service provision would be different and, therefore, potential areas for restoration would likely differ. Using the CICES system, we could fit 24 different ESs into ten different bundles (Table 2). We did not aim to fulfill all possible combinations of the three characteristics, but instead focused on the ones that we judge have scientific support to be manageable from a landscape structure perspective.

Table 2 – Possible bundles of ecosystem services, that are manageable at the landscape scale, with their respective categories regarding the Service Providing Unit (SPU) type, the spatial relationship between SPUs and Services Beneficiary Areas (SPU-SBA), and how the spatial delivery of the ecosystem service occurs. We provide examples of ecosystem services that could fit into these bundles, and some references that support our decision.

Bundle Number	SPU	SPU-SBA	Delivery	Ecosystem Services Examples	References examples
1	Anthropogenic	Decoupled	Infrastructure	Cultivated crops; Reared animals and their outputs; Plant-based resources	Herrero et al., 2010; Tilman et al., 2011
2	Natural	Decoupled	Infrastructure	Wild plants, algae, animals and their outputs; Fibres and other materials from plants, algae and animals for direct use or processing; Materials from plants, algae and animals for agricultural use; Genetic materials from all biota Experiential use of plants, animals and land-/seascapes in different environmental settings	Wickens, 1991; Belcher et al., 2005; Zhu et al., 2017
3	Natural	In Situ	Local	Bio-remediation by all biota; Filtration/sequestration/storage/accumulation by all biota; Maintaining nursery populations and habitats; Wild plants, algae, animals and their outputs; Fibres and other materials from plants, algae and animals for direct use or processing; Materials from plants, algae and animals for agricultural use	Fahrig, 2013; Schaafsma et al., 2014; Magioli et al., 2015; da Silva et al., 2016; Zhu et al., 2017
4	Natural	Directional	Water bodies	Flood protection; Storm protection; Surface water for drinking; Surface water for non-drinking purposes	Allan, 2004; Keeler et al., 2012; Li et al., 2014; Duarte et al., 2018
5	Natural	Omni-direction	Organism movement	Maintaining nursery populations and habitats; Genetic materials from all biota	Mitchell et al., 2013; Ayram et al., 2015
6	Natural	Decoupled	Atmosphere	Global climate regulation by reduction of greenhouse gas concentrations	Laurance et al., 1997; Santos et al., 2008; Tabarelli et al., 2008; Numata et al., 2011; Melito et al., 2018
7	Co-occurrence	Omni-direction	Atmosphere	Micro and regional climate regulation	Bolund & Hunhammar, 1999; Liu & Weng, 2009; Xu, 2009; Zhao et al., 2010
8	Co-occurrence	Omni-direction	Organism movement	Pollination; Seed dispersal; Pest control; Disease control	Overgaard, et al., 2003; Brosi et al., 2008; Pradier et al., 2008; Chaplin-Kramer et al., 2011; Kremen et al., 2011; Shackelford et al., 2013; Duarte et al., 2018
9	Co-occurrence	Directional	Slope	Mass stabilisation and control of erosion rates	Ouyang et al., 2010; Capon et al., 2013; Frank et al., 2014
10	Landscape	Omni-direction	Infrastructure	Experiential use of plants, animals and land-/seascapes in different environmental settings; Physical use of land-/seascapes in different environmental settings; Aesthetic	Franco et al., 2003; Palmer, 2004; Chan et al., 2006; Dramstad et al., 2006; Tveit, 2009

LSRestoration

In our framework, we developed a tool that takes spatial data related to the ESs bundles described above, and combines this with spatially explicit functions to identify restoration locations that are most likely to improve ESs provision (fig. 1e). These restoration locations are recognized in this framework as priority areas for restoration. To increase the availability and generality of the tool, we used two open source software for the programming and data processing: R (R Core Team, 2017) and Grass GIS (GRASS Development Team, 2015), respectively. We then created the Landscape Services Restoration tool (LSRestoration), which provides an output map with priority areas for restoration, aiming at improving the landscape pattern that affects each ESs bundle described in the "Service bundles" section (table 2). The tool does not contain a function for bundles 1 and 10, as the production of services in the first bundle does not directly relate to restoration of natural ecosystems, and the latter corresponds mostly to cultural ESs influenced by landscape heterogeneity that we judge too context depended to model.

For each function on LSRestoration, a common input required is a restoration map containing the delimitation or boundaries of the areas available for restoration within the landscape and, if possible, a surface of restoration feasibility/suitability. This restoration map is the one constructed with the consultation and participation of stakeholders. The other inputs correspond to maps of easily available information (like vegetation, roads and water bodies) and context-dependent parameters. Below, we provided the aims, explanations, assumptions and the landscape pattern that drives the services for each one of the tool functions related to the ESs bundles. For more details, graphs, necessary inputs and the codes for the tool, see the User Guide on Online Resource 1. The tool is freely available at the https://github.com/LEEClab/LSRestoration link.

For comparison purposes, we generated restoration priority maps of each one of the bundle functions in LSRestoration using a rural landscape as case study, located in mid-west of Brazil, within the savannah biome (called Cerrado biome). In this study area the main economic activity is agriculture, with pastures and crop areas covering the majority of the landscape. However, there are also conservation units which serve as habitat for threatened species (ICMBio, 2015; Figure 2a). Moreover, in this landscape there is a plan for the implementation of a Payment for Ecosystem Service program, a program led by the local city hall and the Federal University of Goiás. All maps used in this comparison are available online (https://worldmap.harvard.edu/maps/peld_silvania). The supplementary material 2 contains the input parameters for each bundle function used here. Figure 2, shows the restoration priority maps for each one of the bundle functions.

- *Bundle 2 (SPU = natural, SPU-SBA = decoupled, and Delivery = infrastructure)*: The aim of this function is to create a landscape pattern that prioritizes restoration in areas near the infrastructure needed for the service flow and near the already established SPUs in the landscape. We assumed that the areas restored within this bundle will need to be near infrastructure to guarantee ES delivery, and near already established SPU so that species of interest could more easily recolonize them. The delivery of services through infrastructure is a crucial feature of this service bundle and, therefore, the marginal benefit obtain through restoration of natural areas will decrease with the distance from the infrastructure. This is also the case for distance from already established SPU, as species of interest are more likely to recolonize restored areas near their ongoing habitats. Figure 2b contains an example of restoration priority areas for this bundle.

- *Bundle 3 (SPU = natural, SPU-SBA = in situ, Delivery = local)*: The aim of the function is to give restoration priority to areas around the specific sites that need the ecosystem service to increase of be maintained. Examples of these sites could be the areas needing bioremediation, or already established SPUs that we want its areas to increase. As this is a local service with *in situ* delivery, we assume that the main landscape pattern contributing to the maintenance and improvement of the production of the service will be the quantity of natural areas surrounding specific sites. Therefore, the marginal benefit obtain through restoration of natural areas will decrease with the distance from the sites. Figure 2c contains an example of restoration priority areas for this bundle.
- *Bundle 4 (SPU = natural, SPU-SBA = directional, Delivery = water bodies)*: The aim of the function is to give restoration priority to areas buffering water bodies. We assume that areas surrounding water springs, rivers and lakes, will serve as the main source of water delivered services. The delivery of services through water bodies is a crucial feature of this service bundle, as its ecological process occur in these systems. Therefore, the marginal benefit obtain through restoration of natural areas will decrease with the distance from the infrastructure. Figure 2d contains an example of restoration priority areas for this bundle.
- *Bundle 5 (SPU = natural, SPU-SBA = omni-directional, Delivery = organism movement)*: The aim of this function is to give restoration priority to regions that can connect the already established SPUs, as movement of organisms between natural areas need to be increased or maintained for the service flow. A more connected landscape can provide the increase of maintenance of biodiversity populations. Figure 2e contains an example of restoration priority areas for this bundle.
- *Bundle 6 (SPU = natural, SPU-SBA = decoupled, Delivery = atmosphere)*: The aim of this function is to give restoration priority to areas around already established SPUs and consider the shape of the fragments to reduce edge effects, the matrix extension and the contrast between the SPU and the adjacent matrix. We assume that fragments with

fewer edge effects, lower adjacent matrix extension and contrast will retain more carbon in the above and belowground biomass, contributing to mitigate the greenhouse effects (Laurance et al., 1997; Tabarelli et al., 2008; Numata et al., 2011; Melito et al., 2018). Figure 2f contains an example of restoration priority areas for this bundle.

- *Bundle 7 (SPU = co-occurrence, SPU-SBA = omni-directional, Delivery = atmosphere)*: The aim of the function is to give restoration priority to areas near and within SBA, spaced apart, and sparse from the already established SPUs. We assume that the benefit of restoration is smaller near the already established SPUs, as these areas are already under the effects of the ESs that the SPUs provide. What the function of this bundle does is to create a solution with new restoration patches that are interleaved within and near the SBA areas. Each one of these patches will benefit the area surrounding it. The distance between the restoration areas should be thought to minimize the overlap between benefited areas of different patches (Brosi et al., 2008). Figure 2g contains an example of restoration priority areas for this bundle.
- *Bundle 8 (SPU = co-occurrence, SPU-SBA = omni-directional, Delivery = organism movement)*: The bundle 8 function is similar to the bundle 7. They both aim to give restoration priority to areas near and within SBA, spaced apart, and sparse from the already established SPUs. However, in this bundle, we assume that the benefit of restoration is higher in areas near the already established SPUs, as these SPU areas will serve as the source of the organism that can potentially colonize the new restored areas. What the tool does for this bundle is to create a solution with new restoration patches that are interleaved within and near the SBA areas. Each one of these patches will benefit the area surrounding it. The distance between the restoration areas should be thought to minimize the overlap between benefited areas of different patches (Brosi et al., 2008). Figure 2h contains an example of restoration priority areas for this bundle.
- *Bundle 9 (SPU = co-occurrence, SPU-SBA = directional, Delivery = slope)*. The aim of this function is to give restoration priority to areas with steeper and longer slopes. We assume that the benefit from restoration will increase with the increase of erosion potential, which is related to the slope length-gradient factor in the Universal Soil Loss Equation (Wischmeier & Smith, 1978). The function uses an already established tool in the GRASS GIS software to calculate the slope length-gradient factor (LS factor) for each cell in the landscape. With everything else equal, the higher the LS factor, the higher the long-term average annual soil loss and, therefore, the increased need to restore natural areas on that site to maintain the retention of soil, nutrients and other services. Figure 2i contains an example of restoration priority areas for bundle.

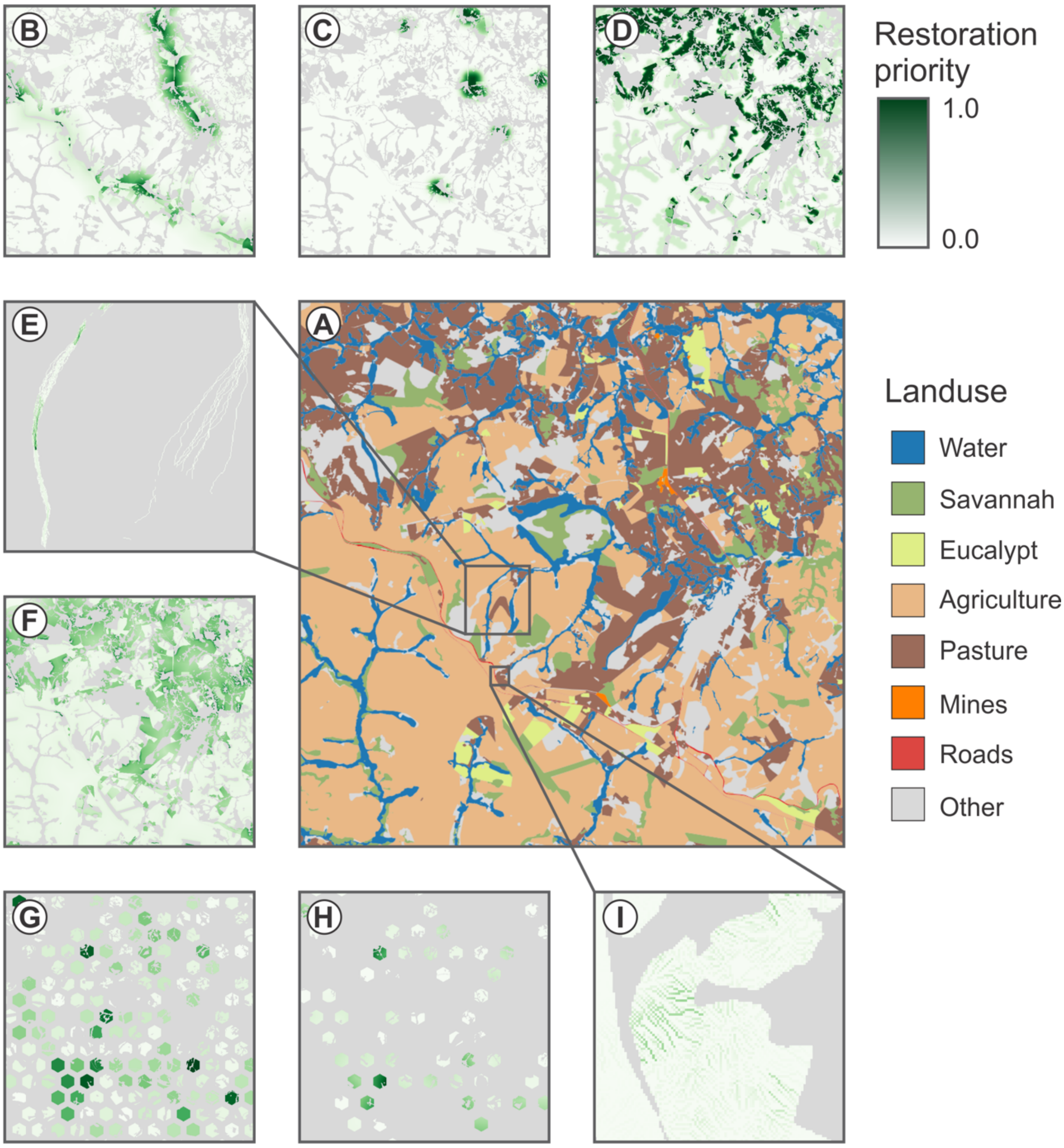

Figure 2. Representation of the outputs from LSRestoration for each one of the bundles present in this study (from B to I), using a real rural landscape as case study (A).

Recommendations

The output maps of the tool, with different landscape patterns for each one of the ESs bundle could be used as guideline for decisions in restoration programs. As financial support for these activities are scarce the prioritization provided with LSRestorationis also necessary for defining target areas for restoration. As we stated before in this work, stakeholder consultation of adequacy of this priority areas to their interests and costs should be reviewed even after the generation of LSRestoration outputs (fig. 1f), to increase chances of implementation of the restoration plan and reduce conflicts between stakeholders (Reed, 2008; Reed et al., 2009; Metzger et al., 2017).

In this sense, we highlight that each bundle described here will respond to landscape structure in similar ways. Therefore, different services of concern could be more easily managed together if they fall in the same bundle, differing just in some function parameters, as distance and patch area. However, the stakeholders can be interested in different bundles. In both cases (same bundle or not), the landscape planner should produce a final restoration priority map for each ES of concern, and these LSRestoration output maps can be overlapped (e.g. summing the maps), generating a final map considering multiple services. Moreover, the maps that will be overlapped can be weighted by their importance or level of concern, for example, giving higher weights for services that produce public benefits than the ones that have private interests. These weights should be discussed with stakeholders in the decision-making process, in a participatory approach, as trade-offs will likely occur and not all services provision can be prioritized (Howe et al., 2014).

Limitations of the proposed framework and tool

In this work, as we wanted to accomplish a certain level of generalization and rapid applicability of the proposed tool, our input variables are easily available remoted-sensed, hydrological and land cover data. That is, they are maps derived from readily available information not verified in the field. In addition, our framework does not consider spatial biophysical variation in the ecosystem services derived from variables other than those related to landscape patterns. We do not consider variables such as the quality of restored habitats, species used, soil properties, and others local factors that could influence the provision of the ESs bundle, unless they are previously quantified and integrated in the restoration input map. Therefore, the inclusion of restoration and opportunity costs in this framework are as precise as the information that the landscape planner uses in the restoration map.

Another limitation in our framework is that we do not quantify the benefits of restoring in a certain area of the input landscape. Therefore, we do not differentiate areas with high or low provision of ESs. However, we argue that the landscape planners using this framework are looking for an output with redundancy and diversity of provision areas that could increase or maintain bundles of ESs (Biggs et al., 2012), not areas with quantitatively high provision of multiple services. In this framework, what matters is that the restoration plan as a whole achieves the desired benefits to stakeholders, and we do not have a focus on individual additionality (Chan et al., 2017).

Conclusion

The scientific community is recognizing that there is an urgent need to reduce the gap between conservation research and its implementation, and to value use-inspired research (Knight et al., 2008; Keeler et al., 2017). Our framework represents a strategy towards this end, as it considers stakeholders interests, is easy to understand by people outside the academia, and do not depend of ESs classifications and nomenclature. The bundles proposed here reflect the effects of landscape patterns on ESs provision and are, therefore, directly applicable to many landscape planning processes in different contexts. The tool is for general use, with easily available information, and can combine multiple ESs. Additionally, our framework and tool facilitate the incorporation of scientific knowledge in the process related to decision-making for restoration and can be used worldwide. Therefore, this framework has the potential to improve landscape and restoration planning and increase its implementation, persuading people to restoration as it considers their private interests, but also raising people's awareness to consider public benefits in the planning process.

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Online Resources

Online Resources 1. The User Guide of Landscape Restoration tool (LSRestoration).

Landscape Services Restoration tool (LSRestoration) - incorporating landscape patterns and ecosystem services in decisions for restoration

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Introduction

Ecological restoration of natural areas is necessary in landscapes that suffered from natural habitat loss and, consequently, have their capacity to provide ecological benefits to humans and high-quality habitats for biodiversity reduced (Barral et al., 2015). Often, these landscapes host people in private properties and evoke different economic interests, which create trade-offs with natural habitats conservation strategies. To encompass these landscapes and, at the same time, create more opportunities for funding restoration actions, the concept of ecosystem services (ES) can be fruitful (Goldman et al., 2008). ES are the benefits that people gain from ecosystems, including the production of goods (e.g. food, wood and honey), maintenance of processes (e.g. water purification, pollination of crops and disease control) and conditions (e.g. recreation in nature, scenic beauty and spiritual benefits) (MEA, 2005).

The provision of ES often depends on the composition, configuration and interaction of landscape elements (e.g. the different anthropic and natural areas; Duarte et al., 2018), and, in this case, they can be called landscape services (Termorshuizen & Opdam, 2009). Therefore, it is necessary to plan the location of natural areas to be restored that have the potential to increase or maintain the provision of these services in the landscape. In this sense, we developed the Landscape Services Restoration tool (LSRestoration), a landscape design tool with spatial explicit functions that generate different maps with areas of interest for restoration depending on the ES of concern. As the provision of different ES can be influenced by the same landscape pattern (composition and configuration), they can form bundles of services with similar important areas for restoration. Therefore, this tool follows the framework provided by Duarte et al. (in prep) that describes criteria to bundle different services based on the location of service providing units, the beneficiaries areas relationship with these units and type of the service flow.

To increase the availability and generality of the tool, we used two open source software for the programming and data processing: R (R Core Team, 2017) and Grass GIS (GRASS Development Team, 2015), respectively. Here we briefly describe the framework, but we encourage users to check the work of Duarte et al (in prep.) for better understanding.

Framework – bundling ecosystem services

The corresponding bundle of a specific ES will depend on the answer regarding 3 characteristics of the ES of concern. These characteristics and answers are better exemplified in the Duarte et al. (in prep) work:

1) What is the type of Service Providing Unit (SPU)? The following categories can be used to answer this question:
    a. Anthropogenic - the production of the service occurs in anthropogenic ecosystems.

b. Natural - the production of the service occurs in natural or semi-natural ecosystems.
c. Co-occurrence - for service production, it is necessary that both natural and anthropogenic ecosystems are interleaved.
d. Landscape - the landscape is the providing unit of the service

2) What is the type of interaction between the Service Providing Unit and the Service Beneficiary Area (SPU-SBA)? The following categories can be used to answer this question (Fisher et al. 2009; Burkhard *et al*. 2014):
   a. In situ - SPU and SBA are realized in the same location.
   b. Directional - SBA in a specific location due to flow direction from the SPU.
   c. Omni-directional - SPU in one location, SBAs in the surrounding landscape without directional bias.
   d. Decoupled - ecosystem service can be traded over long distances.
3) How does the Delivery of the service occur? The following categories can be used to answer this question:
   a. Local - the flow of the ES occurs in one location.
   b. Infrastructure - some infrastructure (for example roads and processing plants) are necessary for the occurrence of ES flow.
   c. Organism movement - the flow of the ES occurs through organism movement.
   d. Water Bodies - the flow of the ES occurs through water bodies.
   e. Slope - the flow of the ES occurs downslope.
   f. Atmosphere - the flow of the ES occurs through the atmosphere.

You should understand that the answer to these questions is context dependent. We encourage the inclusion of stakeholders in the assessment of each one of them, to better capture all ES of concern. In addition, we did not aim to fulfill all possible combinations of answers for the three questions, instead, we focused on the ones we judge have scientific support and that are manageable from a landscape structure perspective.

We described in Table 1 the bundles described in Duarte et al. (in prep.) article, with examples of ES that can follow in each bundle. As state in the article, the tool does not contain a function for bundles 1 and 10, as the first bundle does not benefit from natural restoration, and the latter corresponds mostly to cultural ES influenced by landscape heterogeneity that we judge too context depended to model.

Table 1 – Proposed bundles of ecosystem services that are manageable at the landscape scale, with their respective categories regarding the Service Providing Unit (SPU) type, the spatial relationship between SPUs and Services Beneficiary Areas (SPU-SBA), and how the spatial delivery of the

ecosystem service occurs. We provide examples of ecosystem services that could fit into each bundle.

Bundle Number	SPU	SPU-SBA	Delivery	Ecosystem Services Examples
1	Anthropogenic	Decoupled	Infrastructure	Cultivated crops; Reared animals and their outputs; Plant-based resources
2	Natural	Decoupled	Infrastructure	Wild plants, algae, animals and their outputs; Fibres and other materials from plants, algae and animals for direct use or processing; Materials from plants, algae and animals for agricultural use; Genetic materials from all biota
3	Natural	In Situ	Local	Bio-remediation or Filtration/sequestration/storage/ accumulation by micro-organisms, algae, plants, animals, and ecosystems; Maintaining nursery populations and habitats; Wild plants, algae, animals and their outputs; Fibres and other materials from plants, algae and animals for direct use, processing or agricultural use
4	Natural	Directional	Water bodies	Flood protection; Storm protection; Surface water for drinking; Surface water for non-drinking purposes
5	Natural	Omni-direction	Organism movement	Maintaining nursery populations and habitats; Genetic materials from all biota
6	Natural	Decoupled	Atmosphere	Global climate regulation by reduction of greenhouse gas concentrations
7	Co-occurrence	Omni-direction	Atmosphere	Micro and regional climate regulation
8	Co-occurrence	Omni-direction	Organism movement	Pollination; Seed dispersal; Pest control; Disease control
9	Co-occurrence	Directional	Slope	Mass stabilisation and control of erosion rates
10	Landscape	Omni-direction	Infrastructure	Experiential use of plants, animals and land-/seascapes in different environmental settings; Physical use of land-/seascapes in different environmental settings; Aesthetic

Getting started

LSRestoration tool runs as a script packaged in R environment. To run LSRestoration, you must have installed previously:

1. R software (version 3.X or above). The software should be installed following the procedures on the website: https://www.r-project.org
2. GRASS GIS (version 7.X or above). The software should be installed following the procedures on the website: http://grass.osgeo.org. For Mac OSx users, note that GRASS GIS should be installed in Application Folder of the user that is using the R software.
3. The R packages “rgrass7”, “raster”, “rgeos”, “akima”, “rgdal” and “maptools”. Please, make sure that this packages are already installed in R (using the install.packages() command), before running LSRestoration.
4. If running bundle #5, LSCorridors GRASS package is required. The software should be installed following the procedures on the website: https://github.com/LEEClab/LS_CORRIDORS.

Both softwares above (R, GRASS GIS) are open source and free. Running LSRestoration does not require further R programming skills, but it does require basic skills in R like knowing how to import and export raster files in R environment and following scripts (for some examples see Martello, 2016). We provide in this User Guide the commands for installing the R packages and LSRestoration.

To use the tool for a specific context, you must compile data described in the bundles' section below that you wish to run and format them as indicated.

Formatting your data

Before running LSRestoration, it is necessary to format your data. Although subsequent sections of this guide describe how to prepare input data for each bundle, there are several formatting guidelines common to all models:

1. Spatial data should be in raster format, preference to tiff files (.tif).
2. All input data for a given bundle should be in the same Datum and projection. This projection should be in meters.
3. All input data for a given bundle should have the same spatial resolution (cell size) and extension. Depending on the resolution and extension of your raster data, the bundle function could take too long to run.
4. The raster files must have no missing data.

Basic inputs needed for all bundles

All the functions described below need three general information to work. They should be input in the R environment before running the function using the same object name as provided here:

1 – “dir.input”: a character vector, corresponding to the absolute filepath representing the working directory of the R process, where the input raster files are, and where the output will be saved.

2 – “dir.grass”: a character vector, corresponding to the absolute filepath representing the folder where Grass GIS is installed.

3 – “output.name”: a character vector, corresponding to the name of the output raster map.

4 – “rest.map”: the restoration map, in a raster file format, which should contain the delimitation (or boundaries) of the area available for restoration in the landscape or a surface of restoration feasibility/suitability. Although the restoration map can reflect the restoration feasibility/suitability in a cell on the map, its values should be relative. That is, a specific group of cells has a higher (or lower) restoration feasibility/suitability/cost compared to another group. For example, if a region in the landscape has 3 times less suitability (or 3 times higher cost) for

restoration than the rest of the landscape, due to soil properties, the group of cells that correspond to that region should have a value of 1 and the rest of the regions available for restoration in the landscape a value of 3. In this example, the models will prioritize areas more likely to be restored (value 3), as they have higher suitability for restoration (or lower costs). If a region in the landscape has, for any reason, no restoration feasibility/suitability, the cell values in the rater map should correspond to zero. For example, if there is an urban region, a road, or a river in the landscape, the values in that cells should be zero for the rest.map input. The bundle functions below, will not consider in the prioritization regions with zero values in the rest.map, and the output maps will show these regions with Not Available (NA) values.

Therefore, the R commands to begin working with the bundle functions are:

install.packages(c("maptools", "rgdal", "rgeos","akima","rgrass7","raster"))

install.packages("~\\lsrestoration_1.0.2.tar.gz", repos = NULL, type="source") # This is just an example of filepath. Please give the correct filepath to the latest LSRestoration .tar.gz file in work computer.

library(lsrestoration)

dir.input<-"C:\\Users\\User_Name\\LSRestoration\\BundleX" #This is just an example of filepath. You should change to your own inputs filepath. An example for Mac OSx users, is "~/Applications/GRASS-7.4.0.app/Contents/Resources".

setwd(dir.input)

dir.grass<-"C:\\Program Files\\GRASS GIS 7.4.0" # This is just an example of filepath. Make sure that you change it for the correct filepath where GRASS GIS is installed.

output.name<-"rest.benf.bundleX " #This is just an example of file name. You should change to your own preference.

rest.map<- raster("rest_surface.tif") #use here the correct file name. This raster file should be saved in the same input folder described in the "dir.input".

Below we described other inputs and necessary information for each one of the bundles functions.

Bundle 2 (SPU = natural, SPU-SBA = decoupled, Delivery = infrastructure)

Bundle purpose and parameters

This function creates a restoration surface that prioritizes areas near the infrastructure needed for the service flow and near the already established SPUs in the landscape. We assumed that the areas restored within this bundle should be near infrastructure to guarantee ES delivery, and near already established SPU so that species of interest could more easily recolonize them. You have the option to input a maximum distance from the infrastructure and from the already established SPUs, in a way that areas further than this maximum distance will have no value for restoration, that is, a value equal to zero. The flowchart represented in figure 1 contains the inputs, process and outputs of this bundle function. Therefore, for this bundle, you need to input:

1. "infra.map": a raster map with the location of the infrastructures needed for the service delivery. It should be a binary map with cells corresponding to the infrastructure sites with values equal 1 and the other cells with values equal to zero.
2. "spu.map": a binary raster map with the already established SPUs in the landscape. Cells in the map corresponding to SPU areas should have a value equal to 1 and everything else with a value equal to zero.
3. "dist.infra" (optional): an integer number corresponding to the maximum distance (in meters) from the infrastructure where the restoration areas should be located.
4. "dist.spu" (optional): an integer number corresponding to the maximum distance (in meters) from the already established SPUs where the restoration areas should be located.

Bundle operation and outputs

The function will create a raster map with the Euclidian distances from the already established SPUs and another Euclidian distance map from the infrastructure sites. Both resultant distances maps will integrate a Generalized Linear Model (GLM) analysis that will predict the restoration priority for each one of the landscape cells. Therefore, these priority values are response variables in function of distance from SPU and infrastructure (with interaction between predictors). As both maximum distances are optional inputs, if you choose not to input one or both variables, the function will use the highest value in the corresponding distance map. The final step is to multiply the resultant map from the GLM analysis with the restoration map ("rest.map"). These final values are standardized from zero to one. The function gives two outputs:

1. "rest.priority2": a raster map with the restoration priorities for the ecosystem services of interest.
2. a plotted graph in R environment, that corresponds to the response variables of the GLM model (restoration priority) plotted with two maximum distances used in the model. We give an example of a graph in figure 2.

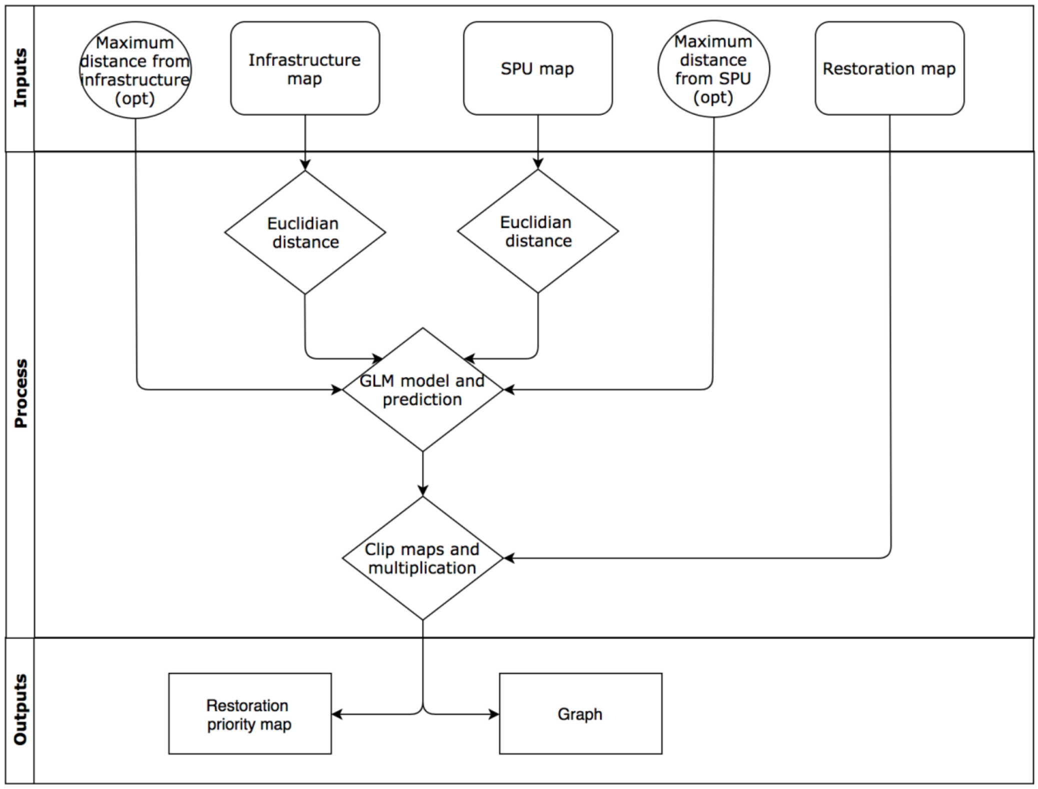

Figure 1 - Flowchart representing the inputs, process and outputs for the function from bundle number 2

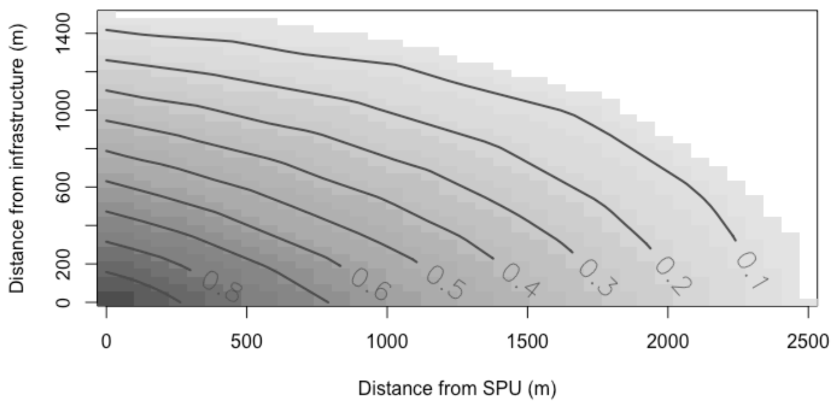

Figure 2 - Graphic representing the restoration priority values in relation to the distances from the Service Providing Units (SPU) and from the Infrastructure. Darker gray colors in the cells represent higher restoration priority values. The gray lines are isolines of the corresponded restoration priority value.

Bundle example

For running this bundle function, you need to type the following R commands:

```
##Inputs for bundle 2. The raster names and distance values are examples. Use the correct file name when inputting a raster file and change the distance value according to your context.

spu.map<-raster("spu.tif")

infra.map<-raster("roads.tif")

dist.spu<-850

dist.infra<-1000

#Running the bundle 2 function

bundle2.results<- bundle2(dir.grass, rest.map, spu.map, infra.map, dist.spu, dist.infra, output.name)
```

Bundle 3 (SPU = natural, SPU-SBA = in situ, Delivery = local)

Bundle purpose and parameters

The aim of the function is to give restoration priority to areas around the specific sites that need the ecosystem service. As this is a local service with in-situ delivery, we assume that the main landscape pattern contributing to the maintenance and improvement of the production of the service will be the quantity of natural areas surrounding specific sites. Figure 3 shows a flowchart representing the inputs, process and output for this bundle. To create a restoration priority map, you need to input:

1. “site.map”: a raster map with the location of the sites that need the service. It should be a binary map with cells corresponding to the specific sites with values equal 1 and the other cells with values equal to zero.
2. “dist.site”: an integer value related to the maximum distance (in meters) from the site. This distance corresponds to the radius of the area of influence of the ecosystem service. For example, if it is necessary a bioremediation on specific sites, the distance would be the maximum length that could influence the bioremediation through restoration. Another example is for food production that has local consumption (as natural fruits, nuts and meat for subsistence). In this case, the distance would be the maximum radius necessary to create a habitat for the species of interested.

Note that the function will prioritize areas closer to the input sites. For this, we created a distance-decay function follows a sigmoid curve (figure 4), that can have different shapes according to your preference. To the sigmoid curve adapt to your study area context, it is necessary to input the following parameter:

3. “alpha”: an integer value, between 1 and 5, that corresponds to the alpha parameter for the sigmoid curve. This parameter will change the inclination and shape of the curve (see figure 4 for alpha examples). The higher the alpha, the sigmoid curve will decay more similar to a linear function. With lower alpha values, the distribution of priority values will follow a sigmoid curve, and you will have a group of cells in the restoration map closer to the inputted sites with priority values with high values, and a group of cells with low values. We recommend a sigmoid distance-decay curve with alpha near 1, especially in cases when the user wants to prioritize restoration in the site proximity and also think in a buffer area around this priority region that will be restored after, or partially.

Bundle operation and outputs

First, the function will create a raster map with the Euclidian distances from the sites. Then, it will use these values of maximum distance and the alpha value, to construct a sigmoid function that gives new values to the cells. The final step is to multiply the resultant map from the sigmoid function with the restoration map (“rest.map”). These final values are standardized from zero to one. This function has two outputs:

1. “rest.priority3”: a raster map with the restoration priorities for the ecosystem services of interest.
2. two plotted graphs in R environment, that correspond to the relationship between the distance from the sites and the restoration priority. One graph corresponds to the maximum distance from sites found in the whole landscape. The other one corresponds to the maximum distance from sites selected by the user. With these graphs, the user can do simulations and compare different maximum distances, and different alpha values. We give an example of graphs in figure 5.

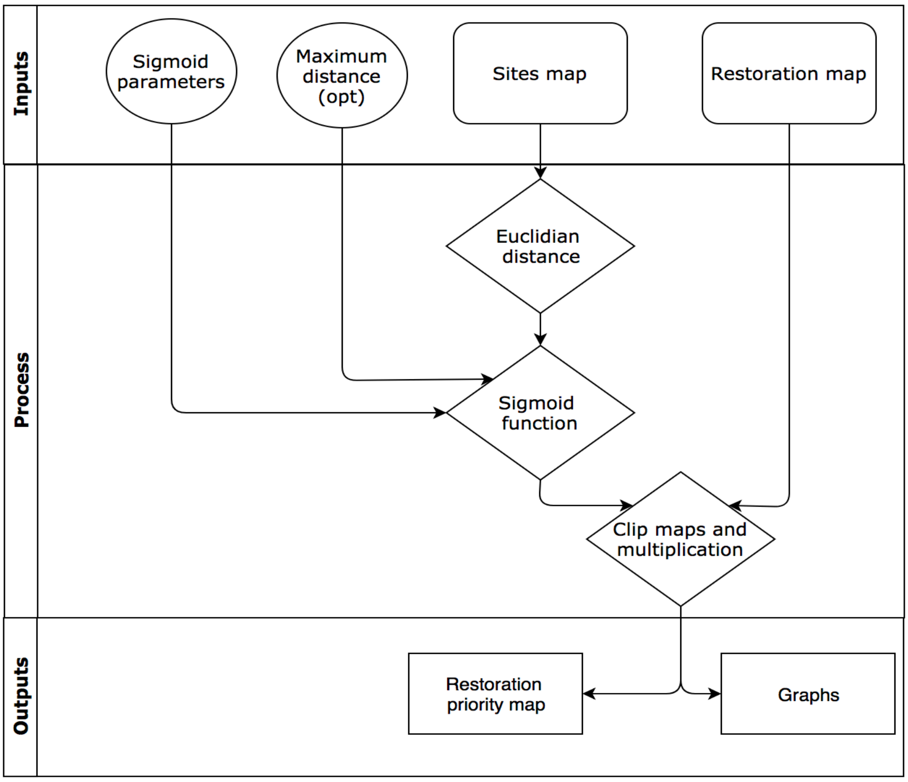

Figure 3 - Flowchart representing the inputs, process and outputs for the function from bundle number 3

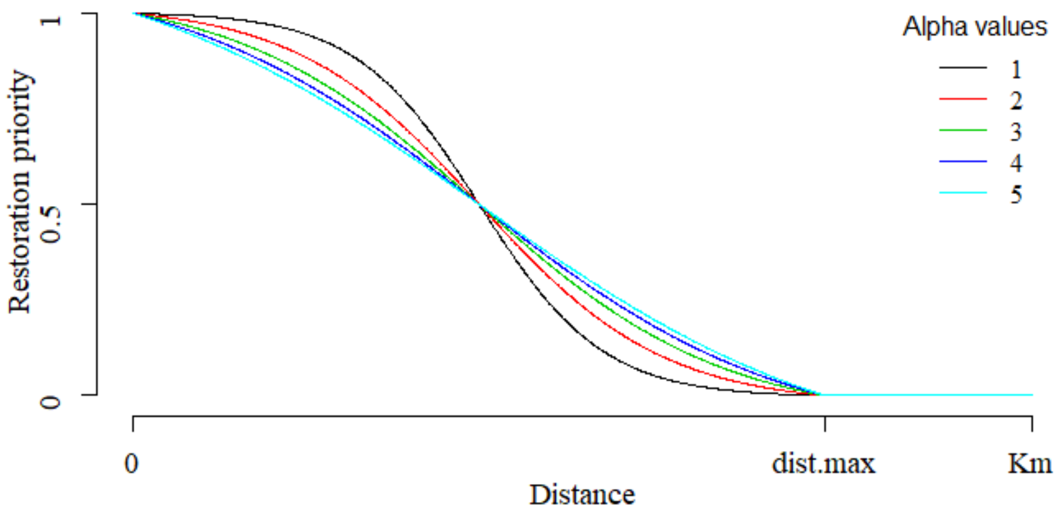

Figure 4 - Graph with exemplification of sigmoid curves for different values of the alpha parameter, with distance as the explanatory variable and the restoration priority as the response variable. Different values of the alpha parameter will change the shape of the curve. The "dist.max" is the maximum distance set by the user (named "dist.site" in bundle 3, and "dist.water" in bundle 4).

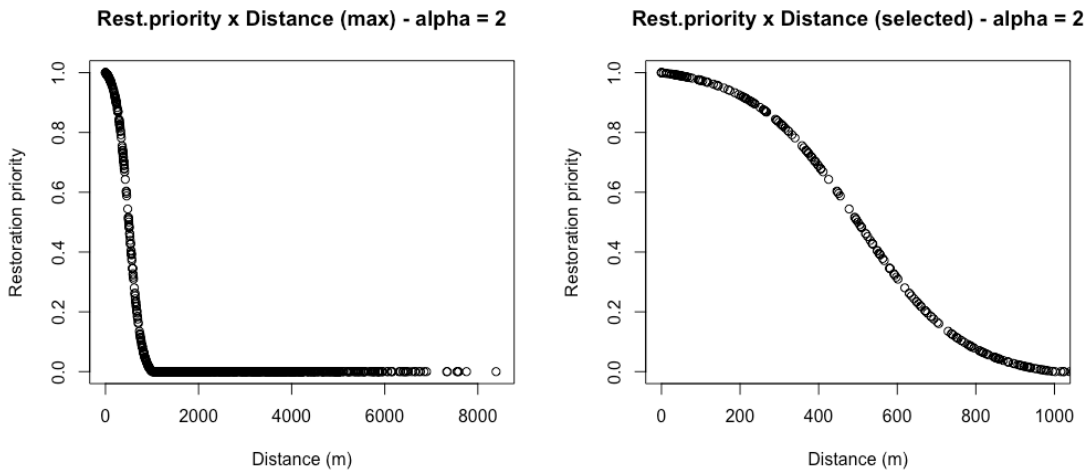

Figure 5 - Graphs with exemplification of the relationship between restoration priority values and the maximum distance from sites (or water bodies in the case of bundle 4) in the landscape (left) and maximum distance from the site (or water bodies in the case of bundle 4) selected by the user (right).

Bundle example

For running this bundle function, you need to type the following R commands:

##Inputs for bundle 3. The raster names, alpha and distance values are examples. Use the correct file name when inputting a raster file and change the distance and alpha values according to your context.

site.map<-raster("mines.tif")

dist.site<-500

alpha<-0.5

#Running the bundle 3 function

bundle3.results<- bundle3(dir.grass, rest.map, site.map, dist.site, alpha, output.name)

Bundle 4 (SPU = natural, SPU-SBA = directional, Delivery = water bodies)

Bundle purpose and parameters

The aim of the function is to give restoration priority to areas buffering water bodies. We assume that areas surrounding water springs, rivers and lakes, will serve as the main source of water delivered services. The flowchart for this function is shown in figure 6. The function for this bundle works very similar to the function for bundle 3. The main difference here is that you need to input a raster map with the water bodies of interest instead of the site's map. Therefore, the inputs for this function are:

1. “water.map”: a raster map with the location of the water bodies that need or deliver the service. This is a binary map with cells corresponding to the water bodies with values equal 1 and the other cells values equal zero.
2. “dist.water”: an integer value related to the maximum distance (in meters) from the water body. This distance corresponds to the maximum width of the buffer area that can influence the process occurring in water bodies. This is very context depend, and to define this distance you should consider the types of water bodies, their own size and width, soil types, etc.

Like the previous bundle, this function will give priority for areas closer to water bodies and the distance-decay function follows a sigmoid curve (examples in figure 4). Therefore, it also needs:

3. “alpha”: an integer value, between 1 and 5, that corresponds to the alpha parameter for the sigmoid curve. This parameter will change the inclination and shape of the curve (see figure 4 for alpha examples). The higher the alpha, the sigmoid curve will decay more similar to a linear function. The same principles for the alpha parameter in bundle 3 apply here.

Bundle operation and outputs

First, the function will create a raster map with the Euclidian distances from the water bodies. Then, it will use these values of distance and the alpha value, to construct a sigmoid function that gives new values to the cells. The final step is to multiply the resultant map from the sigmoid function with the restoration map (“rest.map”). These final values are standardized from zero to one. This function has two outputs:

1. “rest.priority4”: a raster map with the restoration priorities for the ecosystem services of interest.
2. two plotted graphs in R environment, that correspond to the relationship between the distance from the water bodies and the restoration priority. One graph corresponds to the maximum distance from water bodies found in the whole landscape. The other one corresponds to the maximum distance from water bodies selected by the user. With these graphs, the user can do simulations and compare different maximum distances, and different alpha values. We give an example of graphs in figure 5.

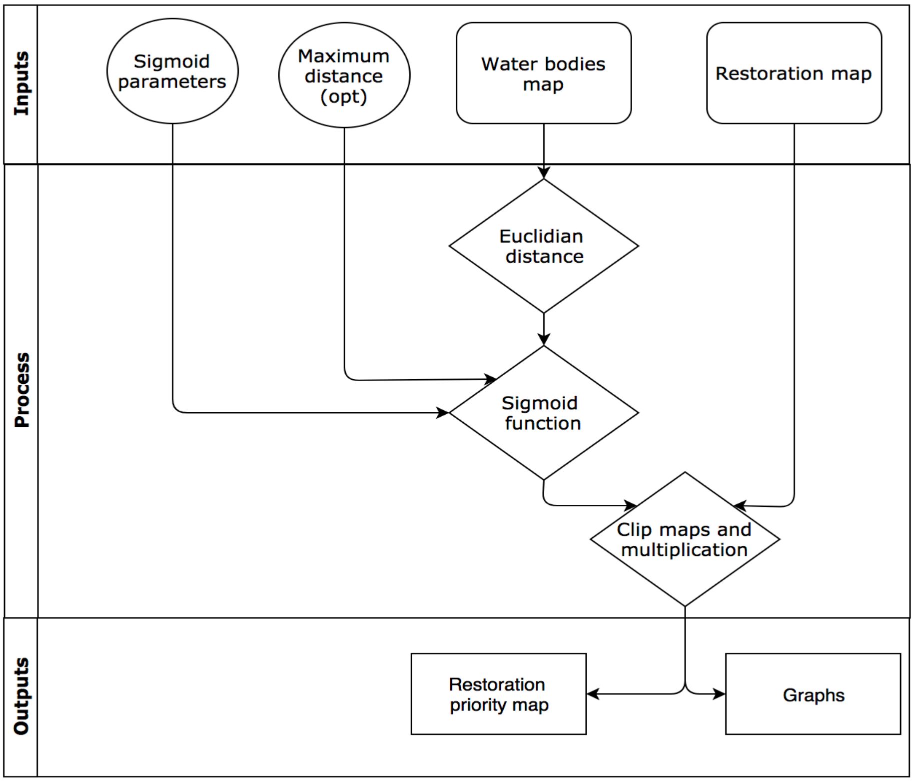

Figure 6 - Flowchart representing the inputs, process and outputs for the function from bundle number 4

Bundle example

For running this bundle function, you need to type the following R commands:

##Inputs for bundle 4. The raster names, alpha and distance values are examples. Use the correct file name when inputting a raster file and change the distance and alpha values according to your context.

water.map<-raster("water.tif")

dist.water<-350

alpha<-1

#Running the bundle 4 function

bundle4.results<- bundle4(dir.grass, rest.map, water.map, dist.water, alpha, output.name)

Bundle 5 (SPU = natural, SPU-SBA = omnidirectional, Delivery = organism movement)

Bundle purpose and parameters

The aim of this function is to give restoration priority to regions that can connect the already established SPUs, as movement of organisms between natural areas need to be increased or maintained for the service flow. For this function, we recommend that you install and use the recently released LSCorridors software (Ribeiro et al., 2017). It is also possible that you use other corridors simulation software. Here, we will describe the LSCorridors output and how your bundle function uses it, but few free to use any software you want.

Bundle operation and outputs

After running LSCorridors, the software will give, as one of its outputs, a raster map showing how many of the corridor simulations passed through each pixel of the map. The authors call these values the Route Selection Frequency Index (RSFI), and state that "high RSFI values indicate areas (pixel) that are more likely to be used as corridors according to species requirements included in the resistance surface and should, therefore, receive special attention of the decisions makers". For comparisons purposes with the other bundles, the bundle 5 function takes the RSFI map resultant from a simulation in the LSCorridors software, multiplies it with the restoration map and rescales the product from zero to 1. Therefore, higher the value in the RSFI map, the higher is the restoration priority of that pixel in the final map. Figure 7 has the flowchart for this bundle function.

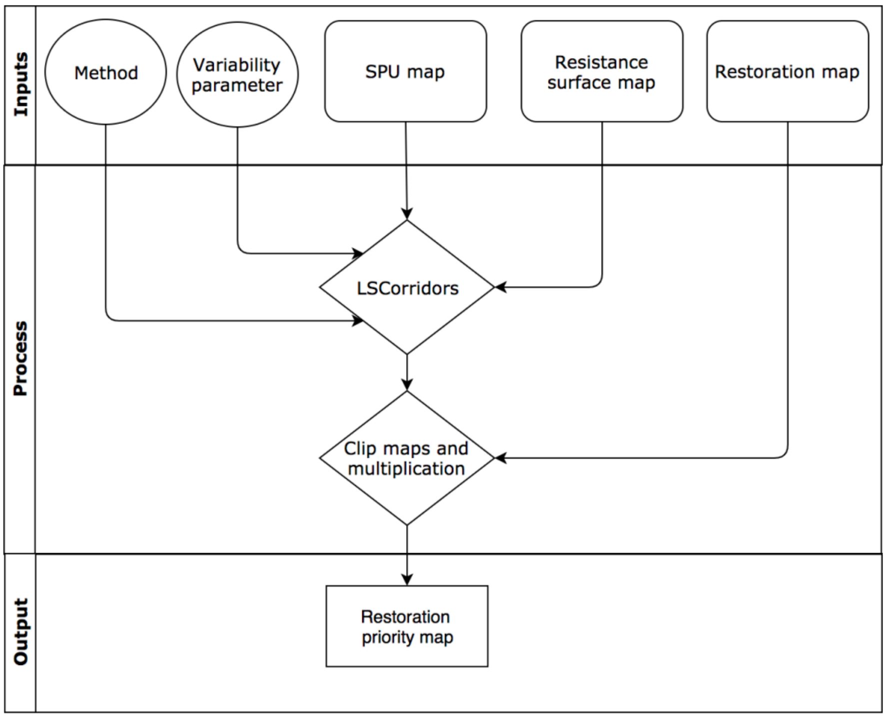

Figure 7 - Flowchart representing the inputs, process and outputs for the function from bundle number 5

Bundle example

For running this bundle function, you need to type the following R commands:

##Inputs for bundle 5. The raster name is an example. Use the correct file name when inputting a raster file.

corridors.map<-raster("RSFI_lscorridors.tif")

#Running the bundle 5 function

bundle5.results<- bundle5(rest.map, corridors.map, output.name)

Bundle 6 (SPU = natural, SPU-SBA = decoupled, Delivery = atmosphere)

Bundle purpose and parameters

The aim of this function is to give restoration priority to areas around already established SPUs, considering the shape of the fragments to reduce edge effects, the matrix extension and the contrast between the SPU and the adjacent matrix. We assume that fragments with fewer edge effects, lower adjacent matrix extension and contrast will retain more carbon in the above and belowground biomass, contributing to mitigate the greenhouse effects. For this function you should input:

1. "spu.map": a binary raster map with the already established SPUs in the landscape. Cells in the map corresponding to SPU areas should have a value equal to 1 and everything else with a value equal to zero.
2. "dist.edge": an integer number corresponding to the distance (in meters) that the expected edge effects could percolate inside the SPUs and decrease carbon stock and sequestration.

Bundle operation and outputs

The function will create a raster map with the Euclidian distances from the SPUs in the "spu.map". After it, the function also takes spu.map for a move-window analysis, where the central pixel will have the sum value of its neighbors. The "dist.edge" value corresponds to half of one of the move-window sides. In the last step, the function multiplies the new map created after the move-window analysis, the Euclidian distance map and the restoration map. These final values are standardized from zero to one (Figure 8).

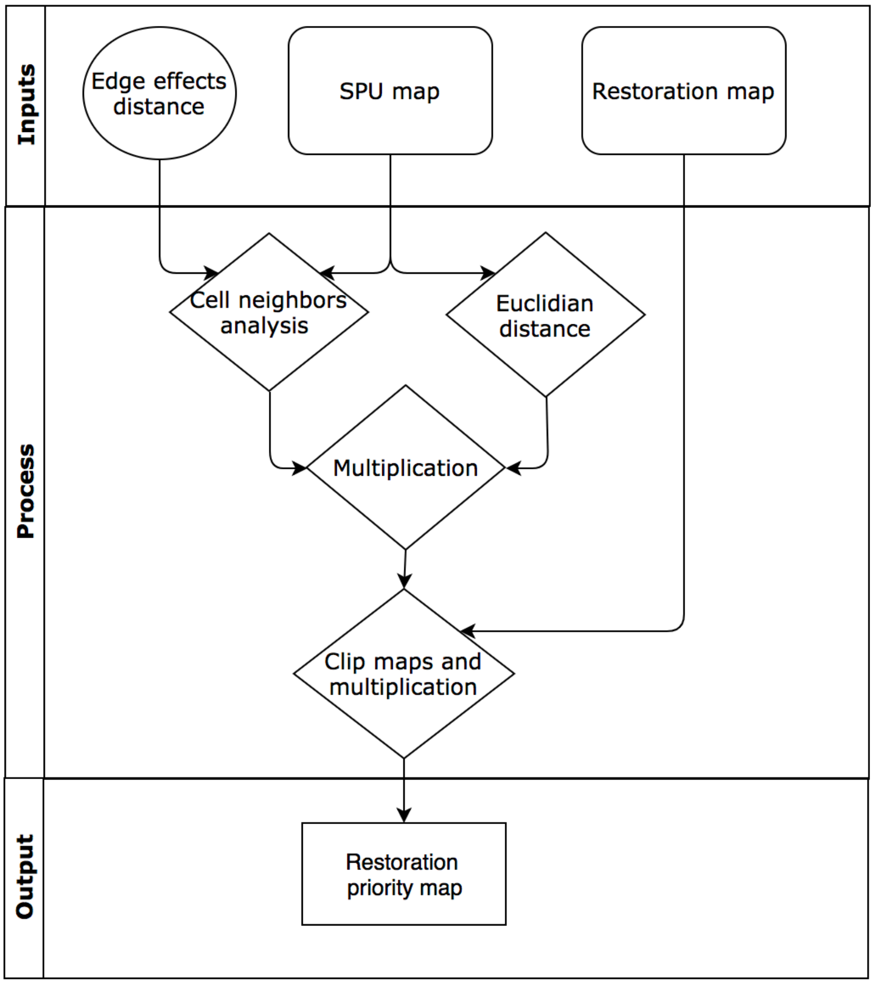

Figure 8 - Flowchart representing the inputs, process and outputs for the function from bundle number 6

Bundle example

For running this bundle function, you need to type the following R commands:

##Inputs for bundle 6. The raster name and distance values are examples. Use the correct file name when inputting a raster file and change the distance values according to your context.

spu.map<-raster("spu.tif")

dist.edge<-150

#Running the bundle 6 function

bundle6.results<- bundle6(dir.grass, rest.map, spu.map, dist.edge, output.name)

Bundle 7 (SPU = co-occurrence, SPU-SBA = in-situ, Delivery = atmosphere)

Bundle purpose and parameters

The aim of the function is to give restoration priority to areas near and within SBA, spaced apart, and sparse from the already established SPUs. We assume that the benefit of restoration is smaller near the already established SPUs, as these areas are already under the effects of the ESs that the SPUs provide. The function of this bundle creates a solution with new restoration patches that are interleaved within and near the SBA areas. Each one of these patches will benefit the surrounding area. The distance between the restoration areas should be thought to minimize the overlap between benefited areas of different patches (Brosi et al., 2008). Therefore, the inputs necessary for this function are:

1. “spu.map": a binary raster map with the already established SPUs in the landscape. Cells in the map corresponding to SPU areas should have a value equal to 1 and everything else with a value equal to zero.
2. “sba.map”: a raster map with SBA location in the landscape. Cells in the map corresponding to SBA areas should have a value different than zero and everything else with a value equal to zero. The values of SBA cells should be relative and represent the demand for an ecosystem service. For example, if a region in the landscape needs twice more of that service than another region, the cells in the first region should have values equal to 2 and the other region values equal to 1.
3. “patch.max”: the maximum size of a patch that will be restored, in square meters. This size is context dependent and should be defined as the sufficient area to provide the benefit for that distance of influence. Therefore, larger areas than the one inputted in this parameter will not have higher benefits.
4. “patch.min”: the minimum size of a patch that will be restored, in square meters. This size is context dependent and should be defined as the minimum area to be restored. That is the minimum area that can provide the service. Therefore, areas smaller than the one inputted in this parameter does not provide sufficient benefits.
5. “dist.inf”: the distance of influence, in meters, that the benefit of the service can percolate in the landscape from the already established SPU and/or from new restored patches. The area surrounding the SPU and patches within this distance will be considered as the area benefiting from the services of this bundle. Therefore, the distance between two adjacent new patches corresponds to twice the dist.inf parameter.

Bundle operation and outputs

Figure 9 contains the flowchart with the inputs, process and outputs of this bundle function. In the first step, the function uses the “dist.infl” parameter to create a buffer around the “spu.map” and excludes the SBA areas that are already benefiting from the established SPUs. Then, the function creates a hexagonal grid, with the distance between the centers of this hexagons equals the sum of the radius of the “patch.max” area and the “dist.infl” parameter. After, the function creates two regions for each hexagon: a) the core region, where the restored patches are proposed to fall in – thus including the “rest.map” cell values to formulate this core region; b) the benefited region, that represents the region benefited from the corresponded core region – thus including the “dist.infl” parameter and the “sba.map” cell values to formulate this benefited region. The function excludes the core regions that have areas smaller than the “patch.min” parameter, and that the corresponded benefited region do not overlap with the “sba.map”. Then, it multiplies the sum of values in the core region with the sum of values in the respective benefited region. The results are standardized from zero to one. This creates a restoration priority index, and it is attributed to all cells in the same core region. Therefore, this function has two outputs:

1. “rest.benf7”: raster map with the remaining core regions, with its values corresponding to the restoration priority index.

2. "hex.grid": a hexagonal grid corresponding to the locations of the restoration patches, with a shapefile format. It shows in the attribute table the total area of each core region, the total area of its respective benefited region, and the restoration priority index.

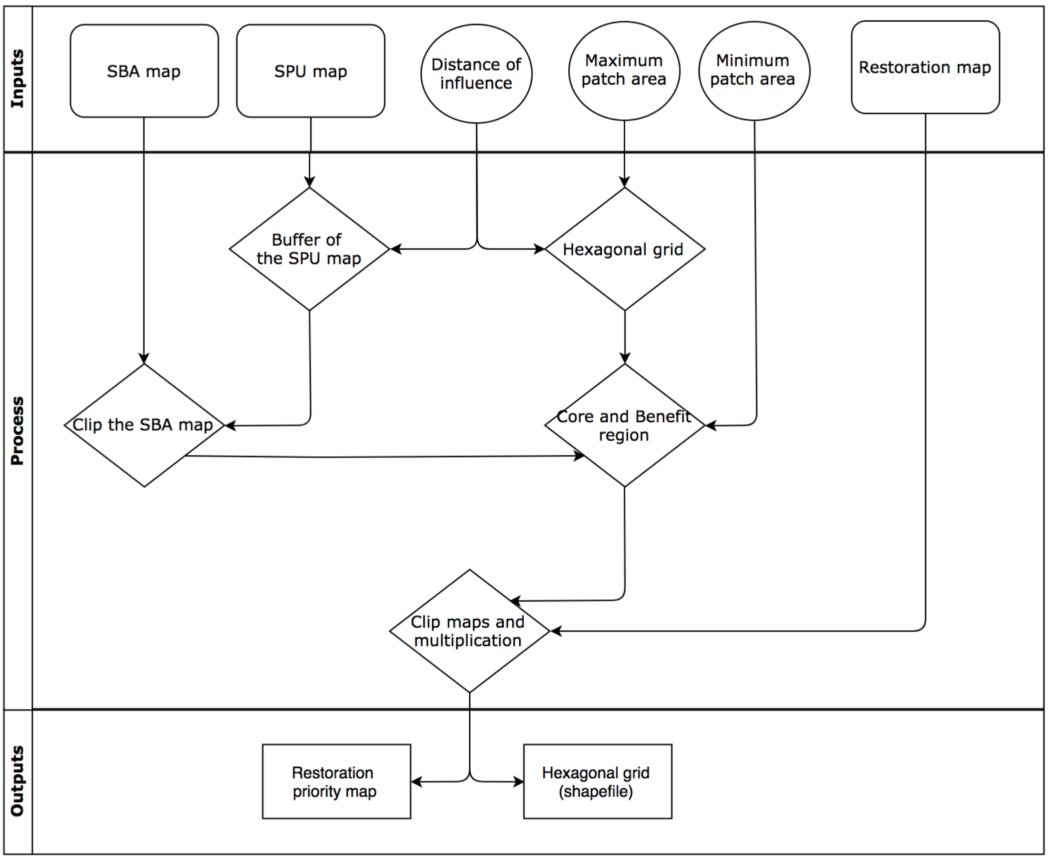

Figure 9 - Flowchart representing the inputs, process and outputs for the function from bundle number 7

Bundle example

For running this bundle function, you need to type the following R commands:

##Inputs for bundle 7. The raster names, patch area and distance values are examples. Use the correct file name when inputting a raster file and change the distance and area values according to your context.

spu.map<-raster("spu.tif")

sba.map<-raster("sba.tif")

patch.max<- 2000

patch.min<- 1500

dist.inf<- 350

#Running the bundle 7 function

bundle7.results<- bundle7(dir.grass, rest.map, spu.map, sba.map, patch.max, patch.min, dist.inf, output.name)

Bundle 8 (SPU = co-occurrence, SPU-SBA = in-situ, Delivery = organism movement)

Bundle purpose and parameters

The bundle 8 function is similar to the bundle 7. They both aim to give restoration priority to areas near and within SBA, spaced apart, and sparse from the already established SPUs. However, in this bundle, we assume that the benefit of restoration is higher in areas near the already established SPUs, as these SPU areas will serve as the source of the organism that can potentially colonize the new restored areas. What the tool does for this bundle is to create a solution with new restoration patches that are interleaved within and near the SBA areas. Each one of these patches will benefit the area surrounding it. The distance between the restoration areas should be thought to minimize the overlap between benefited areas of different patches (Brosi et al., 2008). Therefore, the inputs necessary for this function are:

1. “spu.map": a binary raster map with the already established SPUs in the landscape. Cells in the map corresponding to SPU areas should have a value equal to 1 and everything else with a value equal to zero.
2. “sba.map”: a raster map with SBA location in the landscape. Cells in the map corresponding to SBA areas should have a value different than zero and everything else with a value equal to zero. The values of SBA cells should be relative and represent the

demand for an ecosystem service. For example, if a region in the landscape needs twice more of that service than another region, the cells in the first region should have values equal to 2 and the other region values equal to 1.

3. “patch.max”: the maximum size of a patch that will be restored, in square meters. This size is context dependent and should be defined as the sufficient area to provide the benefit for that distance of influence. Therefore, larger areas than the one inputted in this parameter will not have higher benefits.
4. “patch.min”: the minimum size of a patch that will be restored, in square meters. This size is context dependent and should be defined as the minimum area to be restored. That is the minimum area that can provide the service. Therefore, areas smaller than the one inputted in this parameter does not provide sufficient benefits.
5. “dist.inf”: the distance of influence, in meters, that the benefit of the service can percolate in the landscape from the already established SPU and/or from new restored patches. The area surrounding the SPU and patches within this distance will be considered as the area benefiting from the services of this bundle. Therefore, the distance between two adjacent new patches corresponds to twice the dist.inf parameter.

Bundle operation and outputs

Figure 10 contains the flowchart with the inputs, process and outputs of this bundle function. In the first step, the function uses the “dist.infl” parameter to create a buffer around the “spu.map” and excludes the SBA areas that are already benefiting from the established SPUs. Then, the function creates a hexagonal grid, with the distance between the centers of this hexagons equals the sum of the radius of the “patch.max” area and the “dist.infl” parameter. After, the function creates two regions for each hexagon: a) the core region, where the restored patches are proposed to fall in – thus including the “rest.map” cell values to formulate this core region; b) the benefited region, that represents the region benefited from the corresponded core region – thus including the “dist.infl” parameter and the “sba.map” cell values to formulate this benefited region. The function excludes the core regions that have areas smaller than the “patch.min” parameter, and that the corresponded benefited region do not overlap with the “sba.map”. Then, it multiplies the sum of values in the core region with the sum of values in the respective benefited region. The results are standardized from zero to one. This creates a restoration priority index, and it is attributed to all cells in the same core region. A different step from bundle 7, is that this function multiplies the remaining core regions cells with Euclidian distance values from the already established SPUs. The results are standardized from zero to one.

Therefore, this function has two outputs:

1. “rest.benf7”: raster map with the remaining core regions, with its values corresponding to the product between the restoration priority index and the Euclidian distance from the already established SPUs.

2. "hex.grid": a hexagonal grid corresponding to the locations of the restoration patches, with a shapefile format. It shows in the attribute table the total area of each core region, the total area of its respective benefited region, and the restoration priority index.

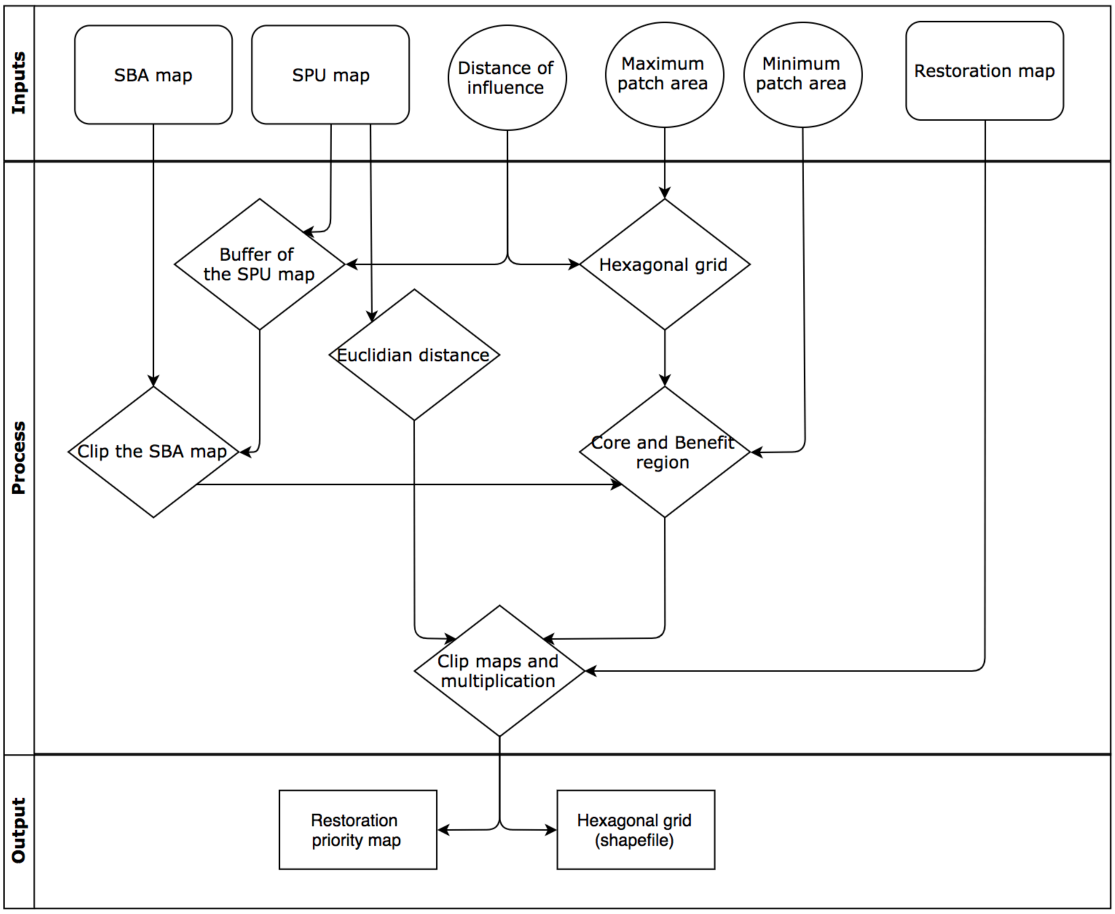

Figure 10 - Flowchart representing the inputs, process and outputs for the function from bundle number 8

Bundle example

For running this bundle function, you need to type the following R commands:

##Inputs for bundle 8. The raster names, patch area and distance values are examples. Use the correct file name when inputting a raster file and change the distance and area values according to your context.

spu.map<-raster("spu.tif")

sba.map<-raster("sba.tif")

patch.max<- 120

patch.min<- 90

dist.inf<- 300

#Running the bundle 8 function

bundle8.results<- bundle8(dir.grass, rest.map, spu.map, sba.map, patch.max, patch.min, dist.inf, output.name)

4.5. Bundle 9 (SPU = co-occurrence, SPU-SBA = directional, Delivery = slope)

Bundle purpose and parameters

The aim of this function is to give restoration priority to areas with steeper and longer slopes. We assume that the benefit from restoration will increase with the increase of erosion potential, which is related to the slope length-gradient factor in the Universal Soil Loss Equation (Wischmeier & Smith, 1978). The function uses an already established tool in the GRASS GIS software to calculate the slope length-gradient factor (LS factor) for each cell in the landscape. With everything else equal, the higher the LS factor, the higher the long-term average annual soil loss and, therefore, the increased need to restore natural areas on that site to maintain the retention of soil, nutrients and other services. Figure 11 contains the flowchart with the inputs, process and output of this bundle function. For this tool to work, it is necessary to input:

1. "dem.map": a raster file with the digital elevation model for the landscape of interest.
2. "threshold": a threshold value, which specifies the minimum size of an exterior watershed basin in cells number. As defined in the GRASS GIS manual, "the minimum size of drainage basins, defined by the threshold parameter, is only relevant for those watersheds with a single stream having at least the threshold of cells flowing into it. These watersheds are called exterior basins" (https://grass.osgeo.org/grass75/manuals/r.watershed.html).

Bundle operation and outputs

We suggest that the restoration map includes, if available, weights for the different soil erodibility rates (which indicates the susceptibility of soil particles to be detached and carried by the rain). The higher the erodibility rate, the higher the benefit to restore in that cell. The others USLE factors (Rainfall erosivity index, Support practice factor, Cover-management factor) can also be included in the restoration map. Keep in mind that the USLE equation corresponds to the multiplication of these factors, and their product can integrate the restoration map. Last, we advise that having a well-prepared digital elevation model is critical and it must have no missing data.

The function will first calculate the slope length gradient factor and, then, multiply the resultant map with the restoration map ("rest.map").

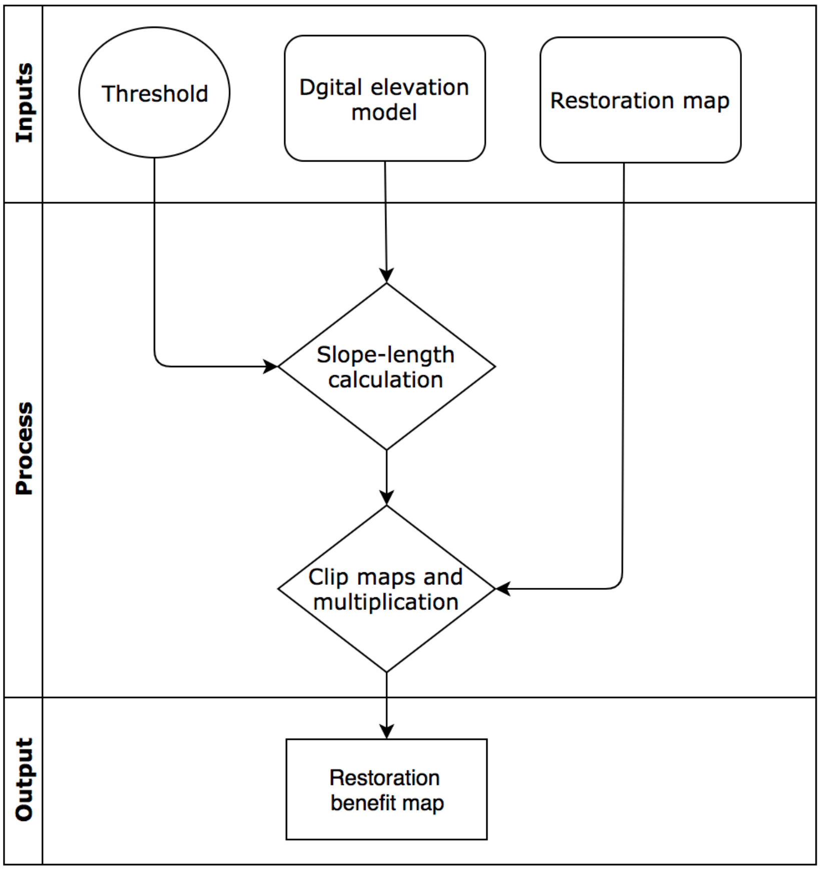

Figure 11 - Flowchart representing the inputs, process and outputs for the function from bundle number 9

Bundle example

For running this bundle function, you need to type the following R commands:

##Inputs for bundle 9. The raster names and the threshold value are examples. Use the correct file name when inputting a raster file and change the threshold value according to your context.

dem.map<-raster("dem.tif")

threshold<- 100

#Running the bundle 9 function

bundle9.results<- bundle9(dir.grass, rest.map, dem.map, threshold, output.name)

5. Reporting errors

If you encounter any issues, please post to the user's support forum at https://github.com/LEEClab/LSRestoration with the following information:

1. LSRestoration bundle you're having difficulty with
2. Explicit error message or behavior
3. If possible, a screenshot of the state of your R environment when you get the error.

6. Acknowledgments

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Online Resource 2. Table with the input parameters used as an example to run the bundle functions of LSRestoration.

Bundle number	Input Variable Codename	Values
all	rest.map	0 – others 2 – crops 5 - eucalyptus 10 - pastures
2	infra.map	0 – others 1 - roads
	spu.map	0 – others 1 – savanna
	dist.infra	1500
	dist.spu	2500
3	site.map	0 – others 1 - mines
	dist.site	1000
	alpha	2
4	water.map	0 – others 1 - water
	dist.water	350
	alpha	1
5	corridors.map	LSCorridors output
6	spu.map	0 – others 1 – savanna
	dist.edge	150
7	spu.map	0 – others 1 – savanna
	sba.map	0 – others 20 – crops 5 – grass meadow
	patch.max	800000
	patch.min	600
	dist.inf	250
8	spu.map	0 – others 1 – savanna
	sba.map	0 – others 20 – crops 5 – grass meadow
	patch.max	800000
	patch.min	600
	dist.inf	500
9	dem.map	Altitude values
	threshold	100

Considerações Finais

Esta tese coloca em foco as influências da composição e configuração das paisagens para a provisão de diferentes serviços ecossistêmicos e desenvolve uma abordagem espacial para o planejamento da restauração de áreas naturais visando incorporar tais influências, juntamente com as percepções de diferentes grupos de interesse. Embora haja evidências crescentes na literatura de que paisagens mais complexas tem efeitos positivos na provisão de determinados serviços, neste trabalho desmembrou-se o fator complexidade em padrões e características que podem ser diretamente aplicados em projetos de manejo e planejamento de paisagens. Por exemplo, o aumento da complexidade da paisagem para promoção de serviços relacionados à qualidade de água acarreta aumento da conectividade de áreas naturais próximas aos corpos hídricos. Já para serviços relacionados à beleza cênica, paisagens mais complexas estão ligadas à maior heterogeneidade dos elementos das paisagens. Nesse sentido, esta tese ajudou a responder perguntas sobre como e quando a complexidade da paisagem está relacionada ao aumento da provisão de serviços, o que é útil em tomadas de decisão que precisam de indicações mais precisas sobre quais padrões da paisagem almejar.

Embora existam diferentes modelos para se espacializar e quantificar a produção de determinados serviços ecossistêmicos, este trabalho estende os esforços recentes para também incorporar aspectos específicos da configuração da paisagem em planejamentos de restauração e conservação de grupos de serviços ecossistêmicos. Os modelos e ferramentas já existentes são geralmente restritos a posições como montante-jusante na forma de fluxo descendente em modelos hidrológicos, ou relações entre habitat e área de forrageio para polinizadores. Esta tese expande esses modelos para múltiplos serviços ao desenvolver um framework que agrega características contexto-dependentes que se relacionam diretamente com estruturas e padrões da paisagem capazes de ter efeitos positivos em sua provisão. Assim, gestores de paisagens podem planejar a restauração e conservação ambiental visando atender múltiplos benefícios, levando em consideração mudanças na configuração e composição da paisagem em múltiplas escalas espaciais. À medida que serviços ecossistêmicos se tornam amplamente utilizados para orientar na tomada de decisão relacionadas ao uso da terra, ferramentas como o LSRestoration serão necessárias para melhorar o manejo e a sustentabilidade das paisagens.

Como os sistemas agrícolas fornecem e influenciam muitos serviços ecossistêmicos que são essenciais para o bem-estar humano e que, por sua vez, podem afetar a produtividade agrícola, a gestão desses territórios é essencial para a sustentabilidade a longo prazo. Para manter o equilíbrio entre os benefícios providos por ambos sistemas natural e agrícola, as soluções normalmente envolvem regulamentação governamental, como a Lei de Proteção da Vegetação Nativa - LPVN (antigo Código Florestal brasileiro, citada na introdução desta tese), ou mecanismos de mercado, como os programas de pagamentos por serviços ambientais. Esta tese reforça a ideia de que as soluções devem incluir abordagens em escala de paisagem, pois essa escala é determinante para a manutenção desses benefícios. Nesse sentido, são necessárias abordagens que encorajem a cooperação entre proprietários rurais para restaurar e/ou compensar áreas naturais dentro de suas próprias regiões, formando os padrões e estruturas da paisagem que os beneficiem e também à sociedade. Por exemplo, os Programas de Regularização Ambiental (PRAs) estabelecidos na LPVN, podem incluir incentivos extras para proprietários que desejarem compensar ou restaurar em áreas próximas (e.g. dentro da mesma microbacia) de sua propriedade. O framework e a ferramenta desenvolvidos nesta tese podem auxiliar no planejamento e priorização das áreas a serem recuperadas e/ou compensadas dentro dos PRAs. Nessas abordagens, os gestores de paisagens agrícolas podem procurar considerar não a adicionalidade que cada parcela, ou cada propriedade, possui para a provisão de determinados serviços, mas sim o resultado ou padrões finais que a paisagem terá. Esse tipo de abordagem pode contribuir mais para a sustentabilidade dos sistemas agrícolas, do que abordagens a níveis individuais, e se tornar uma forma de atingir tanto benefícios privados quanto públicos.