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Research paper

Using dimension reduction PCA to identify ecosystem service bundles

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ABSTRACT

The concept of ecosystem services (ES) has facilitated the identification, mapping and communication about the many non-marketable benefits of green infrastructure. These benefits are important to consider during a spatial planning process. For spatial prioritisation of sites with a high societal importance, there is need to filter this information to insightful spatial indicators. The mapping of ES-hotspots and identification of ES-bundles have been put forward as promising methods for spatial prioritisation and the assessment of multifunctionality. While "hotspot mapping" and "ES-bundles" speak to the imagination of many, it is open to many different interpretations. In addition, there is a risk that the commonly applied hotspot mapping of single services and subsequent overlay analysis does not capture true hotspots of multifunctionality, where we expect multiple services to co-occur, but at lower intensities. Therefore, hotspot mapping should be applied on ES-bundles, rather than single ES. Yet, there are few methods to objectively identify and map such bundles of co-occurring services. In this research we propose dimension reduction principal component analysis (PCA), as a solution to identify and map bundles of ES. This technique is an established technique in remote sensing, where it is used to reduce unnecessary clutter in a data set. This research shows that if the methods for quantification and mapping of ES are sufficiently independent and biophysically sound, the PCA method can reveal multifunctionality between services and lead to (new) insights that can be used for better informed decisions on management and planning. The PCA graphs, ES-bundle maps and the integrated RGB-visualisation are objective and factual outputs of a statistical analysis that can be used for communication and discussion with stakeholders. It gives insight in co-occurrence of services and challenges to look for answers to why things are the way they are. Although scale effects did not play an important role in the results of this study, we advise to use this method on relatively small scales and repeat analysis rather than generalizing large scale results to the local scale or transfer findings between study sites as land-use patterns (and its interplay with abiotic conditions) are the result of many different socio-ecological developments throughout history, which can obviously differ from region to region.

1. Introduction

Landscape multifunctionality is an important objective in modern spatial planning. The concept of ecosystem services has increasingly been adopted as narrative to point-out that the societal relevance of many "clustered" services outweighs the market value of few, mostly provisioning services (Jones et al., 2013; Plieninger et al., 2014; Termorshuizen and Opdam, 2009; Vallés-Planells et al., 2014). But translating this narrative to spatial explicit assessments remains a challenge. So far, there have been only a few studies that encompass a broad range of services in a comprehensive, quantitative and spatially explicit manner (Boerema et al., 2016). But with an increasing availability of tools and methods, we can expect a trend towards integrated, high resolution assessments that address many ecosystem services.

Such studies generate a vast amount of spatial explicit data and there is a need to filter this information to insightful spatial indicators. The identification and mapping of ES-hotspots and ES-bundles have been put forward as promising methods forspatial prioritisation and the assessment of multifunctionality. While "hotspot mapping" and "ES-bundles" speak to the imagination of many, it is open to many different interpretations. Since a multitude of definitions and interpretations exist, the concepts are prone to misuse (Schröter and Remme, 2015).

The most common definition of single ecosystem services hotspots is the definition of Egoh et al. (2008), which identifies hotspots as "*areas which provide large proportions of a particular service*". The existing techniques for mapping this type of hotspot are well established and relatively easy to implement and areas which signify high delivery (Bai et al., 2011; Beverly et al., 2008; Crossman and Bryan, 2009; Egoh et al., 2009, 2008; Forouzangohar et al., 2014; Gos and Lavorel, 2012; Locatelli et al., 2014; O'Farrell et al., 2010; Onaindia et al., 2013; Plieninger et al., 2013; Schulp et al., 2014; Timilsina et al., 2013; Willaarts et al., 2012; Willemen et al., 2010). These types of hotspots

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mapping techniques are suitable when single or few ecosystem services are used for the identification and prioritisation of sites for conservation (Schröter and Remme, 2015). The methods to identify and map multi-service hotspots are much less established. There, the aim is to map zones, which are high in delivering a multitude of ecosystem services (Schröter and Remme, 2015).

The methods to identify and map multi-service hotspots are much less established. There, the aim is to map zones, which are high in delivering a multitude of ecosystem services (Schröter and Remme, 2015). The concept of multi-service hotspots is closely related to the idea of ES-bundles. According to Raudsepp-Hearne et al. (2010), ES-bundles are "sets of ecosystem services that repeatedly appear together across space or time for a given area". Multi-service hotspots therefore should signify locations that are high in delivering a certain bundle of services. These multi service areas are not only of great importance for conservation purposes (Egoh et al., 2009), but also on a policy level they commend special attention in larger planning processes.

Although the concept of ecosystem service-bundles (ES-bundles) is relatively well-established (Crouzat et al., 2015; Qiu and Turner, 2013; Raudsepp-Hearne et al., 2010; Van der Biest et al., 2014), its practical application is not straightforward. Identifying ES-bundles encounters several conceptual and technical problems. Currently, the top richest cells method is often applied on individual services and then used as a basis to identify the multiservice hotspots (Eigenbrod et al., 2010; Qiu and Turner, 2013; Rodriguez et al., 2015; Wu et al., 2013). The spatial overlap of single service hotspot maps is used as a criterion to identify multi-service hotspots. But simply adding up single service hotspots ignores the notion that ecosystem services often occur in bundles due to physical (e.g. moisture gradients, slope etc.), anthropogenic (accessibility, population density) and ecological factors and constraints.

Ecosystem services supply and demand interactions rely on many interacting biotic and abiotic drivers. Depending on spatial context and configuration, identical land use may deliver different services. A patch of forest in an urban environment will provide many other services (e.g. air quality regulation, recreation, noise attenuation, health effects) then an identical patch of forest in a rural environment (e.g. carbon sequestration, timber production, pollination). This makes that some ecosystem services will unlikely occur at the same locations and they will cancel each other out when simply adding up maps (Assessment, 2005; Bennett et al., 2009; Daily et al., 2009; Raudsepp-Hearne et al., 2010; Setala et al., 2014; Turner et al., 2014; Zhang et al., 2007). Therefore, the convergence of e.g. 3 ES in a specific type of ES-bundle can be as important as the convergence of 6 other ES in another type of bundle. When used for multiservice hotspots, this technique encounters these problems with positive and negative correlations making it less reliable and more difficult to interpret the results.

More advanced methods, such as Self-Organizing Maps (SOM) (Crouzat et al., 2015; Kohonen, 2001; Mouchet et al., 2017; van der Zanden et al., 2016) give promising results, but its application in the domain of ES-research remains limited. Its practical application may be hampered by the complexity of the method and high sensitivity to data quality and issues with the occurrence of no-data zones in input maps (Rustum and Adebayo, 2007). Some types of ecosystem services typically have large areas of no-data or zero values when they are mapped. Other techniques like Bayesian Belief Networks (BBN) require a weighing of the different ecosystem services (Van der Biest et al., 2014), which is not only very difficult to do but it relies heavily on expert judgment which introduces extra subjectivity in the analysis (Gos and Lavorel, 2012). The correlations between ecosystem services can be difficult to interpret with an increasing number of ecosystem services, especially for large study sites (Carpenter et al., 2009; Pataki et al., 2011; Raudsepp-Hearne et al., 2010; Setala et al., 2014).

Therefor there is need for an objective procedure to identify and map ecosystem service bundles, especially for studies that encompass many services.

This paper applies the principle of dimension reduction on an extensive dataset of ecosystem service maps. To reduce the dataset this technique statistically groups highly correlated variables, in our case ecosystem services maps, on principal component (PC) axes. These PC axes provide two main results. First, each axis provides a statistical grouping of correlated ecosystem services. Secondly, these axes can be presented as maps which signify the multi-service hotspots for that bundle of ecosystem services.

In this paper we apply this method on a study site and discus the applicability and differences with the existing method. Further, we hypothesise that composition and robustness of ES-bundles depends on the scale and context of the study site and illustrate the scale effects by applying the developed methodology on different spatial extends with the same resolution. Finally we suggest guidelines for application and interpretation.

2. Materials and methods

2.1. Study area

2.1.1. Small scale

The small-scale study area is a 12 km by 12 km square near the city of Turnhout, Belgium (Fig. 1). The area is characterised by two main focal points: a mid-sized city (Turnhout, 43.460 inhabitants) and the E34 highway which crosses trough the study area. Nature reserves are located north, south and easth of the city. Woodland and agriculture are also common in the area. A full description of the land use in the study area can be found in Table 1.

2.1.2. Larger scale

As the larger scale study area we opted for the province of Antwerp in which the small scale study area is situated. The province has 1.8 million inhabitants on an area of 2867 km^2. It includes both rural areas as well as one of the most urbanized areas of Belgium. A description of the land use in the area can be found in Table 1.

2.2. Input data

All 15 maps used, were developed within the ECOPLAN project, which mapped and modelled ecosystem services for the Flemish Region (part of Belgium), using input data of high thematic and spatial resolution (5m) (Ecoplan, 2016). The ecosystem service maps used in the analysis are presented in Table 2. A full description of the ECOPLAN project and the used ecosystem services can be found in the supplementary materials. These quantitative maps result from biophysical and statistical models, using a large set of biophysical variables. The use of quantitative maps has the advantage to be less subjective than maps based on qualitative indicators.

2.3. Dimension reduction PCA

We applied techniques for dimension reduction on a set of ecosystem services maps. Due to the spatially explicit nature of remote sensing techniques it can provide solutions for the spatial related issues involved in ecosystem services mapping such as extent and specific locations (Feng et al., 2010). Because remote sensing imagery often results in large datasets consisting of many different bands, dimension reduction is often used in remote sensing as a pre-processing step before classification (Li et al., 2012). A dimension reduction technique reduces these large datasets into more manageable datasets by removing redundant information and reducing the variability between the bands to a limited number of components (Plaza et al., 2005).

A PCA was used for dimension reduction. PCA was developed by Pearson in 1901 and developed independently by Hotelling, 1933; Jolliffe, 1986. Abson et al. (2012) already stated the potential of PCA to aggregate spatially explicit variables. PCA is a well-known technique and, in remote sensing, one of the most commonly used dimension