Title: Assessment and prioritization of cultural ecosystem services in the Sahara-Sahelian region

Abstract

Desert environments remain largely neglected by the society and their potential to provide benefits to people remain understudied. Hotspots of cultural ecosystem services have been identified in some deserts; yet, knowing which countries need to strengthen efforts to satisfy people's demand for those services is timely needed. Here, we show the performance of countries within the Earth's largest warm region – the Sahara-Sahel – in managing cultural ecosystem services. Using the most-advanced decision-support tools and updated databases on biodiversity features and constrains to ecosystem services and on socioeconomic indicators, we identified national priorities for cultural services management. We also identified countries that are missing opportunities for local sustainable development. About 34% of Sahara-Sahel is prioritized for cultural ecosystem services, particularly in the main mountains and waterbodies of the region and along the Western and Eastern coastal limits. Algeria, Egypt, Libya, Morocco, Senegal, and Tunisia are performing better in managing their cultural services given the availability of such services in their territories. Burkina Faso, Cameroon, Chad, Egypt, Libya, Mali, Niger, Nigeria, Sudan, and South Sudan need to urgently improve their ease of mobility, governance, safety, socioeconomic and health systems to foster ecosystem services demand. Cameroon, Eritrea, and Senegal are receiving far less tourists than what their ecosystems can handle and need to improve their local conditions for better marketing international tourists able to economically contribute to sustainable development through ecotourism programs. The approach developed here serves as a framework for conserving the last world wild ecosystems

and is replicable to other contexts where regional planning for ecosystem management is compulsory.

Keywords: Sahara-Sahelian Region; Cultural Ecosystem Services; Maximum Likelihood Classification; sustainable development; Principal Component Analysis; socio-economic analyses

1. Introduction

Global ecosystems are imperiled by unsustainable human development and conflict (Cardinale et al., 2012; Díaz et al., 2019; Levin et al., 2019; Maron et al., 2019; Newbold et al., 2015; Tilman et al., 2017). The largest warm region of the world (≈11,200,000 km^2), which includes the African ecoregions of the Sahara Desert and its contiguous Sahel arid area (Fig. S1; Dinerstein et al., 2017), are no exception and several human factors are dismantling the region's ecosystems. Armed conflicts threaten biodiversity and local people (Brito et al., 2018; Daskin & Pringle, 2018; Dioko & Harrill, 2019; Walther, 2017), and the unsustainable use of natural resources severely depletes natural ecosystems (Brito et al., 2014, 2018; OECD/SWAC, 2014; Santarém et al., 2020b). Furthermore, while many countries within Sahara-Sahel will see a large proportion of their biodiversity to be up-listed in conservation status (Durant et al., 2014; Powers & Jetz, 2019) they are among the least studied (Brito et al., 2014; Durant et al., 2012, 2014) and among the most underfunded for conservation worldwide (Waldron et al., 2013). The region is among the last natural places on earth (Di Marco et al., 2019; Watson et al., 2018) partially managed by indigenous people (Garnett et al., 2018). This offers chances to tourists seeking 'last-chance-to-see' wild places (Saarinen, 2019) to benefit from the many cultural ecosystem services (CES) that the region supplies (Santarém et al., 2020b) (CES refer to non-material benefits that people obtain from nature through experiences, recreation and tourism, for example; Díaz et al., 2019). Most Sahara-Sahel countries remain among the poorest (UNDP, 2019) and least visited worldwide (UNWTO, 2019), fostering a continuing regional ecosystem crisis (Brito et al., 2018), and yet the region remains neglected by the global society (Durant et al., 2012).

To counteract the degradation of ecosystems and to improve human wellbeing worldwide, CES have received an increasing importance in research and policy making (Díaz et al., 2018; Kosanic & Petzold, 2020; Wood et al., 2018). Among the many CES that desert environments can provide (see Safriel et al., 2005 and Teff-Seker & Orenstein, 2019), ecotourism and related recreational activities have been proposed as key to combat poverty and stimulate environmental protection (Santarém et al., 2020a; Santarém & Paiva, 2015; UNEP, 2006b; Winkler & Brooks, 2020). To achieve sustainability in deserts (or elsewhere), it is crucial that decision-makers contemplate the spatial characteristics of CES supply and management (Burkhard et al., 2012), but analyzing CES is challenged by their intangibility (Cheng et al., 2019; Ogada et al., 2012; Satz et al., 2013; Small et al., 2017; Teoh et al., 2019). Even considering this challenge, there is a growing body of research concerned with mapping CES worldwide (Bachi et al., 2020; Casado-Arzuaga et al., 2014; He et al., 2019; Nahuelhual et al., 2013; Peña et al., 2015; Scholte et al., 2018), with several methods being developed to date, such as ESTIMAP (Zulian et al., 2014), ARIES (Villa et al., 2014), or InVEST (Sharp et al., 2014). Several methodologies for ecosystem services assessments and their limitations have been revised in the ecosystem services literature (Brown & Fagerholm, 2015, Crossman et al., 2013, Kosanic & Petzold, 2020, Martnez-Harms & Balvaner,a 2012, Milcu et al., 2013 and Wolff et al., 2015). In this regard, desert CES have been recently assessed and mapped (Santarém et al., 2020b; Taylor et al., 2017; Teff-Seker & Orenstein, 2019; Winkler & Brooks, 2020), but very few studies are concerned with the management of ecosystem services in North African deserts (Hosni, 2000; Santarém et al., 2020a, 2020b; UNESCO, 2003b, 2003a; Vale et al., 2015).

Previous studies identified many CES hotspots within Sahara-Sahel (particularly ecotourism and recreation; Santarém et al., 2020b) but neglected the broad-scale socio-economic conditions that underly ecosystem management in the region. These CES-rich regions remain poorly protected (Brito et al., 2016) and are suggested to face increased environmental degradation from growing human population and wealth (OECD/SWAC, 2014). Given these facts, knowing which Sahara-Sahel countries are doing better than their peers in managing CES (particularly ecotourism and recreation) is timely needed. Solving all these issues is of paramount importance for regional policymakers to manage the various elements of human wellbeing in one of the Earth's most threatened regions and to provide the elements for sustainability (Blicharska et al., 2019; Wood et al., 2018).

Globally, developed countries are associated with higher visitation levels (UNWTO, 2019). In a relative sense, countries within Sahara-Sahel show similar patterns, with the most economically developed ones being more visited than the less developed states (Fig. S2). Countries with biodiversity hotspots tend to have higher annual growth of tourism investments than places without ecosystem-based attractions (Blicharska et al., 2019) and, in Africa, especially in eastern and southern regions, ecotourism is commonly promoted as a tool for both conservation and socioeconomic development (World Tourism Organization, 2014). However, we lack information about which Sahara-Sahel countries are potentially missing opportunities to attract ecotourists interested in supporting nature conservation and improving local economies in deserts. Knowing this is needed to improve countries commitment to CES management, as local governments can be further pressed to maintain pristine ecosystems so international tourists are attracted and contribute financially to the sustainable development of the region.

Here, we address all these knowledge gaps and provide the first estimate of countries' performance in managing CES (particularly ecotourism and recreation) in the largest warm region in the world, the Sahara-Sahel. Furthermore, we identify which countries are missing opportunities to use and promote desert CES for sustainable development by using ecotourism, given the availability of areas supplying CES that are priorities for conservation within their territories. Our analyses are indicative at the regional and national scales and form a usable framework for conserving the last wild ecosystems in the world (Di Marco et al., 2019), including the Sahara-Sahel region.

We addressed four questions that are fundamental for improving our understanding of the importance of desert CES and for effectively implementing strategies to both promote and preserve desert ecosystems under threat: (1) among the lands supplying the highest levels of CES, which ones are priority for conservation and management?; (2) which socioeconomic variables are constraining national conditions for better CES management?; (3) given the prioritized lands of CES availability and the socioeconomic conditions within each Sahara-Sahel country, what is their performance in managing CES?; and (4) which countries display substantial availability of CES and yet are missing opportunities for socioeconomic development based on ecotourism? There are some data and methodological limitations in answering fully to all these research questions, which are discussed in detail later.

2. Methods

We conducted an interdisciplinary analysis with several steps, from spatial data collection to spatial prioritization, and from socioeconomic data assortment to evaluation of the performance of countries in managing CES in the Sahara-Sahel (Fig. S3). We constructed environmental performance indicators specific to Sahara-Sahel nations by making use of the most updated and high-resolution data available and advanced decision-support tools developed to date (Moilanen et al., 2014). These tools allowed us to perform a prioritization ranking of the Sahara-Sahel landscapes for CES management among different countries. We gathered revised spatially-explicit and fine-scale data related to CES in deserts (Table 1; Santarém et al., 2020a), followed by related prioritization results with the most updated socioeconomic indicators (Table 3) to evaluate the performance of Sahara-Sahel countries in managing their CES. We also identified countries missing opportunities for socioeconomic development through operational ecotourism by relating inbound tourist data with the number of prioritized landscape units for CES conservation.

2.1. Spatial Component

2.1.1. Spatial data collection

To perform a spatial prioritization of the landscape for CES management, one needs to first gather relevant attraction and constraint features to conservation (Moilanen et al., 2014). We collected a set of 148 spatially-explicit data layers representative of 24 variables influencing CES in deserts (Santarém et al., 2020b, 2020a; UNEP, 2006b, 2006a) from multiple sources (Table 1). In all layers, input data were converted to the geographic coordinate system WGS84 and rasterized to a 0.5º spatial resolution (n = 4120 pixels of 50km^2), using the geographic information system ArcGIS 10.1 (ESRI, 2012). The layers consisted of positive features: species (2 variables: large- and small-flagships), other biodiversity (3 variables: forest reserves, protected areas and UNESCO World Heritage Sites), landscape (8 variables: major landscape features, gorges and mountain passes, peculiar rock formations, caves, major wetlands, mountain rock pools, desert ecosystem intactness, and areas of extreme remoteness), and cultural (7 variables: Sahara-Sahel ethnographic groups, oases, monuments, caravan villages, fortifications from the colonial period, sites of historical occupation and rock art), and of cost features: conflict (2 variables: landmines and attacks and violence against civilians) and exploitation of natural resources (2 variables: oil, gas, mining facilities, and high Human Footprint) on Sahara and Sahel ecoregions (see Santarém et al., 2020a for methodological details on spatial data acquisition and processing). A detailed explanation on the spatial data acquisition and processing is available in Supplementary Material (Text S1).

2.1.2. Spatial prioritization process

We used the most recent publicly available decision-support tool, Zonation v4.0 (Lehtomäki & Moilanen, 2013; Moilanen et al., 2014) to produce ranking maps for CES in Sahara-Sahel (n = 4120 pixels of 0.5º spatial resolution). This software is capable of processing problems of four or more orders of magnitude bigger than previously possible (Kremen et al., 2008; Lehtomäki et al., 2009; Lehtomäki & Moilanen, 2013; Pouzols et al., 2014). Zonation uses a maximum-coverage approach, aiming to maximize the conservation benefits for a fixed cost (Moilanen et al., 2011). It prioritizes maps by ranking landscape elements (as pixels) iteratively from the lowest to the highest priority for conservation (Lehtomäki & Moilanen, 2013). The removal order thus reflects the rank order of importance of planning units to the systematic planning issue, with the most important units remining until last (Moilanen, 2007; Moilanen et al., 2005, 2014). Zonation produces a balanced ranking, meaning that for any given rank level areas are complementary, and jointly achieve a well-balanced representation across all biodiversity features (Moilanen et al., 2014; Pouzols et al., 2014), a key objective in systematic planning (Kukkala & Moilanen, 2013).

We used the additive benefit function (ABF) analysis variant of Zonation, which can be interpreted as the "minimization of aggregate extinction rates via feature-specific species-area curves" (Moilanen et al., 2014). This means that ABF favors grid cells containing large numbers of localized features, summing values across features in each cell (Arponen et al., 2005; Moilanen, 2007). The ABF variant has been extensively used in large spatial analyses (Pouzols et al., 2014) as it produces high return-on-investment solutions (Laitila & Moilanen, 2012; Pouzols et al., 2014), by retaining higher fractions of features' distributions without requiring arbitrary targets (Di Minin & Moilanen, 2012). Additionally, the ABF allows to use cost layers without compromising efficiency and interpretation of prioritization results (Moilanen et al., 2014).

2.1.3. Variables weighting

During the ranking process, Zonation uses feature-specific numerical priority weights that influence the relative balance that emerges between features in the final solution (Arponen et al., 2005; Leathwick et al., 2008; Lehtomäki & Moilanen, 2013). To avoid unequal sub-category weights based on the different number of variables within each sub-category (e.g. an aggregate weight of 271 for biodiversity and 37 for landscape), which would potentially lead to the sub-category with the largest number of variables and data layers having the greatest influence on the analyses outcomes, we set the same combined weight to each sub-category and rescaled the weights of each individual data layer to sum up to the aggregate sub-category group weight (see categories and weight values in Table 1). This process ensured a flexible and balanced weighting, while guaranteeing that the software would treat all features and costs equally during the ranking process (Di Minin et al., 2017; Lehtomäki & Moilanen, 2013).

The success of an informed prioritization exercise depends on the thoroughly consideration of constraints to CES as representative costs to conservation actions (Arponen et al., 2010; Naidoo et al., 2006; Whitehead et al., 2014). Applying negative weights to cost features ensures that areas hosting those features are removed early in the prioritization, while positive features are retained to the top ranks of the landscape (Moilanen et al., 2014). Thus, negative weights were given to the cost features constraining CES (Di Minin et al., 2017; Kujala et al., 2018; Moilanen et al., 2011, 2014; Whitehead et al., 2014). We performed a cost sensitivity analysis, by testing three cost weightings (see Fig. S4): costs were weighted one time (1x), one-hundred times (100x), and one-thousand times (1000x). Because costs tend to dominate the solution when higher multiplying factors are applied (Moilanen et al., 2014), we conducted further analyses using the simplest approach (1x cost). By weighting the aggregated set of costs equally to the aggregated weights of features (i.e., making sure costs in aggregate would sum one), we ensured a balanced solution between features and costs (Di Minin et al., 2017). Still, the integration of costs requires careful consideration, as other factors may influence the effectiveness of spatial prioritizations, such as dynamic social and economic factors (Arponen et al., 2010; Pouzols et al., 2014; Waldron et al., 2013), especially in African countries subjected to weak governance (Bradshaw & Di Minin, 2019).

2.1.4. Ensemble prioritization framework

Despite ecosystem services are supplied along the continuum of landscape and do not recognize artificial human-imposed borders, priorities for ecosystem management can vary between regions (Moilanen & Arponen, 2011). In systematic planning exercises, global prioritizations retrieve different, and sometimes conflicting, outputs in comparison to national ones (Kukkala et al., 2016; Moilanen et al., 2013; Moilanen & Arponen, 2011; Pouzols et al., 2014). Strong evidence suggests an efficiency loss on prioritizations from global to national or local solutions (Kukkala et al., 2016; Moilanen & Arponen, 2011; Pouzols et al., 2014). Yet, alternative prioritization scenarios present distinct methodological details that need to be thoroughly considered. For example, some variant analyses may highlight country-specific priorities (using the *strong administrative priorities* analysis option), others may emphasize global solutions (see Moilanen et al. (2014) and Moilanen and Arponen (2011) for details), and others may produce "edge effects" when administrative boundaries artificially cut the distribution of features, affecting the outcome of prioritization solutions (Moilanen et al., 2013). Combining continental and national analyses has the potential to increase decision-making efficiency, by enabling country-level decision-making to occur in the context of international priorities (Moilanen et al., 2013; Pouzols et al., 2014). Thus, to account for uncertainties in the prioritization ranking, we conducted 10 prioritizations with varying settings (Whitehead et al., 2014) (see the different scenarios in Fig. S4 and Table 2). When needed, the area of countries was used as input *region-specific weights* (Moilanen et al., 2014; Moilanen & Arponen, 2011) (Table S2). Country areas were calculated with the function *Calculate geometry* in ArcMap 10.1 (WGS 1984 World Mercator) (ESRI, 2012), and were normalized to aggregately sum to one (Moilanen et al., 2013). Administrative country boundaries were based in the Global Administrative Areas spatial database (GADM, 2018), adjusted for their limits within Sahara-Sahel ecoregions (Dinerstein et al., 2017).

The 10 prioritization scenarios were scaled onto a 3 classes score scale according to the prioritization ranking for CES availability. We ensembled the 10 prioritization outputs into an averaged priority rank (Meller et al., 2014) and scaled it onto a 1-3 score scale, which was used in the following analyses (Fig. 1).

2.1.5. Further prioritization considerations

We performed ranking of CES priorities without generating aggregation across landscape elements (Arponen et al., 2012; Lehtomäki et al., 2009; Moilanen et al., 2005; Moilanen & Wintle, 2007), as it was recently showed that small isolated habitat patches are key for ecological conservation (Wintle et al., 2019) and because some of the features are naturally fragmented across the landscape (e.g. rock formations, rock pools and oases; Santarém et al., 2020a).

The berm between south-eastern Morocco and north-western Mauritania is heavily mined and militarized (United Nations, 2019). It is impossible to safely visit the region (Santarém et al., 2020b) and most of its biodiversity and ecosystems have been extirpated (Brito et al., 2014). All scenarios were performed excluding it from the analysis, by masking out all the grid cells that intersected with the 2700km-long berm polyline (Kremen et al., 2008; Moilanen, 2013). This procedure ensured that Zonation excluded those pixels since the beginning of the iteration removal process (Moilanen et al., 2014).

Our spatial prioritization approach utilized two kinds of data: distribution data of biodiversity features and costs, and structural data elements. The first class of data included high resolution data digitized at the Sahara-Sahel scale, which avoided introducing additional biases in early analysis stages. The second class included mask layers (country borders and the berm boundaries), which are typically known or digitized as polygons with high precision (Pouzols et al., 2014). Additionally, the chosen spatial resolution may had a noteworthy effect on the outcomes of the spatial prioritization (Arponen et al., 2012). However, these potential constraints were likely diluted when using a coarser spatial resolution (pixel size of 0.5º; Brito et al., 2016; Moilanen et al., 2013; Santarém et al., 2020a, 2019; Weyland and Laterra, 2014). Spatial data limitations were, to our best knowledge, halted with all the steps we have taken.

2.1.6. Spatial data analysis: clustering and Maximum Likelihood Classification

To account for the spatial variance of the 10 prioritization scenarios for CES availability in Sahara-Sahel, we performed a principal component analysis (PCA) (Brito et al., 2016) (Fig. S5), using the function *Principal* Components within the *Spatial Analyst* tool in ArcMap 10.1 (ESRI, 2012). The two PCs were then used to determine the natural grouping (clustering) of the cells in the multidimensional space, using the function *Iso Cluster*. Following the three classes used in the spatial prioritization outputs (see above) 500 iterations were performed on three classes of the clustering. Given the heteroscedasticity of spatial results, we then estimated the maximum likelihood among the spatial data using the function *Maximum Likelihood Classification* (MLC).

We obtained a raster output that was used to count the number of 0.5° pixels with high availability of CES within each country. We first counted the raw number of 0.5x0.5-degree resolution planning units (PUs(N) hereafter) prioritized for CES and then weighted them by the country-area that falls within the Sahara-Sahel ecoregions (0.5x0.5-degree resolution; PUs(N/country), which will be considered as an index of CES availability hereafter). This procedure ensured that we would account for methodological commission errors related to the spatial prioritization when country borders were considered. For instance, small countries tend to be fully prioritized when compared to large countries because it is relatively easier to protect a large proportion of a small area than of a large area (a full explanation of possible prioritization outcomes from different country sizes can be found in Kukkala et al., 2016; Moilanen et al., 2013; and Pouzols et al., 2014).

2.2. Socioeconomic analyses

2.2.1. Indicators of country performance in CES management

To be useful for policy decisions, conservation frameworks need to have broad general applicability at global and national levels, and indicators of individualized country-performance in achieving management objectives need to be available, applicable, and representative of the general socioeconomic paradigm of each country (Waldron et al., 2017). We selected a set of the most updated and publicly available variables to represent country performance scores in preserving CES at a national level (Table 3): tourism (2 variables: international tourist arrivals - TOU - and ease of movement - VIS); economic (2 variables: gross national income per capita corrected for purchasing-power parity - GNI - and multidimensional poverty - MPI); governance (government effectiveness - GOV - and country' regulatory environment to conduct business operations - GEF); environment (3 variables: conservation investment levels - CON, biocapacity of each country to regenerate its ecosystems - BIO, and number of threatened species - THR); health (3 variables: tuberculosis - TUB, unsafe water - WAS, human immunodeficiency virus - HIV); social (percentage of population with access to electricity - ELE - and to the internet - INT); and security data (3 variables: peace - GPI, terrorism - GTI, traffic mortalities - ROA). When data were not available for a given year, we took the mean value of that variable from previous available yearly data, which allowed calculating meaningful statistics (Bradshaw & Di Minin, 2019; Daskin & Pringle, 2018). Variables are explained in details in the Supplementary

Material (Text S2).

2.2.2. Statistical analysis

The selected indicators are here considered as proxies of the performance of Sahara-Sahel countries in terms of CES management. All indicators were normalized (*n-1*) before statistical analyses to place effect sizes on a common scale. We performed a PCA (using Pearson's correlation) of the indicators to identify which variables contribute the most to explain the variability of Sahara-Sahel countries in managing CES. This allowed to empirically quantify the influence of socioeconomic variables in the performance of Sahara-Sahel countries in managing CES (Santarém et al., 2018). To avoid interpretation errors due to projection effects common in PCA, and to produce meaningful interpretations for principal components, it is important to identify which variables are associated with the components in question (Peres-Neto et al., 2003). Thus, we used the squared cosines of the socioeconomic normalized variables (Table S1), which reflect the representation quality of a variable on a PC axis and are useful to compare multiple independent variables. Because PC1 explains most of the variance (and the eigenvalue for PC1 was three to four times larger than for PC2 and PC3, respectively), this principal component was used to further evaluate country-performance in managing CES. PC1 was further utilized as an index of country-performance in managing desert CES. Descriptive statistics were summarized prior to performing the PCA (Table S1). All statistical analyses were performed with the statistical software tool XLSTAT (Addinsoft, 2020).

2.2.3. Measuring countries performance in preserving CES

We related the conditions of visiting (i.e., the conditions that each country offers for the usufruct of CES) with the availability of CES (i.e., the PUs(N/country) highly ranked for conservation during the prioritization process) in each country. We also compared these conditions to the number of raw planning units with high availability of CES (PUs(N)), the 2017 national visit rates (UNWTO, 2019) (see under "*Identification of missing tourism opportunities"*), and the 2019 national peacefulness index (Institute for Economics & Peace, 2019). The peace levels of a country are a major concern to tourists visiting regions under conflict (Santarém et al., 2020b).

Integration of uncertainty in ecological-economic research has been underlined in recent ecosystem reviews, as it is crucial to inform ecosystem management decisions (e.g. Paul et al., 2020). Thus, we performed a sensitivity test and related the availability of CES with the Human Development Index (HDI), a composite of indicators related to education, life expectancy, wealth and standard of living (UNDP, 2019) that could had been similar to the indicators we collated. We performed additional sensitivity analysis of the potential effect of spatial heterogeneity and prioritization methodological issues, by relating the availability of CES with the PC1 of the PCA (Figs. S8-9) and with the HDI (Figs. S10-11) considering the prioritization ranking results (i.e., with the results obtained before calculating the MLC of the spatial data heteroscedasticity.

2.2.4. Identification of missing tourism opportunities

To identify countries that may be missing opportunities to develop tourism activities, we related inbound tourist data (UNWTO, 2019) with the number of PUs (N/Country) with high availability of CES. This allowed to understand which countries are explored to the limit and which ones deserve further exploration, given the number of PUs highly prioritized for CES.

3. Results

3.1. Priorities for cultural services in deserts

Our results show that 33.8% of the Sahara-Sahel landscapes display high availability of CES (Fig. 2a). Algeria, Chad, Egypt, Libya, Mauritania, Morocco, Niger, and Sudan account for most of the highly ranked areas (i.e., high availability of CES). Yet, when weighting planning units by the area of the country within Sahara-Sahel limits, Burkina Faso, Cameroon, Egypt, Eritrea, Morocco, Senegal, and Tunisia stood out, showing more than half of their country-areas with high availability of CES (Fig. 2b). Conducted sensitivity analyses on spatial prioritizations found minor differences according to the methods used (Fig. 1) that, nevertheless, do not invalidate the main pattern found. The main mountains and waterbodies of the region were prioritized in both analyses (Figs. 1b and 2a), although with differences in the number of planning units prioritized within each country (Figs. 1c and 2b). The Atlantic and Indian coasts also display high availability of CES (Fig. 2a). In contrast, the lowest availability of CES is generally located in the largest remote plains of the region (Figs. 1a and 2a).

3.2. Factors conditioning ecosystem services management in Sahara-Sahel

The variables with the highest influence in the first axis of the PCA (PC1) were: access to electricity (ELE) and Internet (INT) and tourist arrivals (TOU) with a direct relationship;

multidimensional poverty (MPI), governance effectiveness (GEF), ease of doing business (BUS), HIV prevalence (HIV), deaths attributable to unsafe water, sanitation, and hygiene (WAS), and mortality caused by road traffic (ROA) with a inverse relationship. In the second axis of the PCA (PC2) they were: gross national income (GNI), conservation spending (CON), and terrorism (GTI), all with a positive relationship. Variables do not cluster in the PCA, but they are meaningful for this study: nine of them have strong links with the corresponding principal component (see squared cosines in Table S2) and contribute substantially to the first principal component, which account for the highest variance (see eigenvalues and cumulative variance in Table 4). Cumulatively, the two first principal components accumulated 61.89% of the variance (PC1: 47.2% and PC2: 14.7%) (Fig. 3; Table 4) but note that only the PC1 was used as an index to assess country performance in managing CES it explains most of the variance.

3.3. Countries performance in managing cultural ecosystem services

Our results show that Algeria, Egypt, Morocco, Senegal, and Tunisia are performing better than all other countries in relation to their capacity to manage CES (Fig. 4). In this study, they display better conditions for CES management (PC1 positive values in Fig. 4), while also supplying the largest CES in their territories (measured by the widespread availability of CES; Y axis in Fig. 4). Among them, Senegal showed higher peacefulness levels than the other countries during the studied period (see symbols in Fig. 4) and it stood out as the one with more conditions for visitation and widespread availability of CES. Uncertainty analysis to development conditions revealed that Senegal displays distinct conditions according to the indexes used: whereas the index based in our multivariate analysis of socioeconomic indicators revealed that the country provides more conditions for the usufruct of CES (Fig. 4), the Human Development Index (HDI) positioned the country to the group providing worse conditions (Figs. 5 and S7).

3.4. Countries missing opportunities for local development

We showed that Cameroon, Eritrea, and Senegal are missing opportunities to develop their social and economic conditions based on sustainable ecotourism (red symbols in Figs. 4 and 6), whereas Egypt, Morocco, and Tunisia have already explored their CES resources to the limit or even beyond (yellow symbols in Figs. 4 and 6). Most of the other analyzed countries display low availability of CES and less favorable conditions for ecotourism visitation (black dots in Figs. 4 and 6).

4. Discussion

We have made use of several sources of spatial and socioeconomic data, including high-resolution indicators of constraints to CES management. This is the most complete existing spatial and analytical study ever conducted in desert ecosystems. To meet our study objectives, it was crucial to account for several spatial-explicit species, landscape, and cultural data, as well as constraints to CES (Table 1), and three simulations with 10 different scenarios (Table 2).

4.1. Prioritization of CES in Sahara-Sahel landscapes

The main mountains and wetlands of the Sahara-Sahel, and the Atlantic and Indian coasts display high availability of CES, such as ecotourism and recreation (Figs. 1b and 2a). These regions have been previously identified as hotspots of CES (Santarém et al., 2020b) and of flagship-species for conservation and ecotourism promotion (Santarém et al., 2019), highlighting their importance for ecosystem-based conservation (Mengist et al., 2020). Yet, these regions have attracted very little scientific attention (Durant et al., 2014). In contrast, the lowest availability of CES were generally located in the largest remote plains of the region (Figs. 1a and 2a), where armed conflicts and overexploitation of ecosystems are widespread, with substantial impacts on people and on the services they could had benefited from if geopolitical tensions were ameliorated (Brito et al., 2014, 2018; Santarém et al., 2020b).

Priorities for CES management were found to be high in Burkina Faso, Cameroon, Egypt, Eritrea, Morocco, Senegal, and Eritrea. Yet, Algeria, Chad, Egypt, Mauritania, Mali, Niger, and Morocco showed a higher number of raw planning units (PUs(N)) highly ranked for CES management. These differences are related to countries' surface areas: while the latter group of countries are the largest in Sahara-Sahel, the former group of countries have limited areas within the Sahara-Sahel ecoregions. Thus, for example, Algeria has larger numbers of areas providing CES, but its substantial size diminishes its overall CES availability at the regional level, which may condition results interpretation (Moilanen et al., 2013, 2014). These size effects and corresponding prioritization performance are discussed in the literature (see, for instance, Kukkala et al., 2016; Moilanen et al., 2013; Moilanen & Arponen, 2011). Yet, by accounting for both the number of raw planning units (PUs(N)) and the planning units weighted by the country-area that falls within the Sahara-Sahel ecoregions (PUs(N/country) we have balanced priorities with regional to global preferences in the spatial prioritization process (Moilanen & Arponen, 2011).

4.2. Countries performance in managing Cultural Ecosystem Services

Algeria, Egypt, Morocco, Senegal, and Tunisia are performing better than all other countries in relation to their capacity to manage CES. They not only showed higher availability of CES (except Algeria; PUs (N/country) = 0.3), but also more conditions for visitation. Among these countries, Senegal showed higher peacefulness levels than the other countries during the studied period. Sensitivity analysis to development conditions revealed that Senegal displays distinct conditions according to the indexes used. Note that HDI includes indicators such as "Life expectancy at birth", "Expected years of schooling", "Mean years of schooling", and "Gross national income per capita" whereas our index goes further and includes many more components of different areas (see Table 3). Rather than Senegal, all other Sahara-Sahel countries need to improve safety conditions to attract international tourism, or else the consequences of long-term conflict will be nefarious for local communities seeking sustainability (Ospina, 2006). Cameroon, Chad, Mali, Niger and Nigeria are particularly vulnerable to terrorism and conflicts, and security in Burkina Faso, Egypt, Libya, Sudan and South Sudan needs to be reinforced (OECD/SWAC, 2014; Walther, 2017). Ameliorating conflicts and improving hospitality conditions in these countries will enable the attraction of ecotourists, which potentially can contribute to the sustainable development of local societies (Santarém et al., 2020a).

Biodiversity losses related to weak governance and socioeconomic factors may accelerate losses in ecosystem functioning (Cardinale et al., 2012), threatening nature services to people (Blicharska et al., 2019; Santarém et al., 2020b). Looking forward, the picture for low-income countries is much more uncertain than for high-income countries, in general, as bad governance and poor socioeconomic conditions may limit plans for ecosystem services conservation. Globally, countries with weak governance and high political corruption are associated with poor conservation performance (Bradshaw & Di Minin, 2019) and lower visitation levels (Hausmann, Toivonen, Heikinheimo, et al., 2017), and the same pattern is found along Sahara-Sahel countries (Brito et al., 2018). For instance, a large proportion of Niger's and Chad's natural ecosystems remain intact (Di Marco et al., 2019) and offer prospects for CES, yet they need to improve levels of social organization, stability and good governance to achieve the goals of conserving CES (Maron et al., 2019). Niger has committed to conservation programs targeting key biodiversity (Durant et al., 2014), but recently the Government decided to declassify part of the Termit and Tin-Toumma National Nature Reserve (RNNTT) in favor of oil exploitation activities, threatening whole ecosystems that could supply CES to people if remained protected (IUCN SSC Antelope Specialist Group, 2020). Obviously, also health and safety issues need to be improved if countries want to increase ecotourism based on their CES. Severe health issues keep untreated along Sahelian countries (Beasley et al., 2002; Yakum et al., 2017), furthering a human crisis that fail to cease. New opportunities for tourism can be developed if basic needs are met in the short/medium term.

Our analyses showed that access to electricity and Internet are the most important factors in conditioning the performance of Sahara-Sahel countries in managing CES, as it is the case across all Africa (Hausmann, Toivonen, Heikinheimo, et al., 2017). Combined with the other strongest indicators of countries performance in managing CES, our analyses revealed that CES in Sahara-Sahel are conditioned by many contextual human and political factors that deserve thoroughly consideration when developing national and especially supra-national conservation plans that are much needed in the Sahara-Sahel region (Brito et al., 2016). We contend the fact that we used indicators from many different fields: tourism, socioeconomic, governance, environmental, health, and security (Table 3). Individual countries, however, can be analyzed based on a smaller group of indicators when performing national level identification of optimum or near-optimum sites for CES provision and demand.

4.3. Missing opportunities for sustainable development

Countries such as Cameroon, Eritrea, and Senegal are missing opportunities for sustainable development. They need to improve their socioeconomic conditions to attract more international ecotourists to benefit from desert CES and economically contribute to the sustainable development of the region. Particularly, Eritrea is among the poorest and least visited countries in the world (UNWTO, 2019), but showed a considerable availability of CES in this study. In contrast, Egypt, Morocco, and Tunisia are receiving far more tourists to benefit from their CES than what their ecosystems possess (CES availability between 0.52 and 0.63). Until 2017, these countries received 235 to 378 times more tourists than the poorest and least visited countries in Sahara-Sahel (e.g., Chad; Fig. S2). This disparity between country' tourism arrivals calls for urgent balancing at the regional level, as otherwise there is a serious risk of overexploiting some types of ecosystems while others remain underexplored (OECD/SWAC, 2014). Although most of the other countries are not missing nor overexploiting opportunities, they could develop strategies that will enable them to attract more international ecotourists and improve their socioeconomic conditions. For instance, some of the rarest charismatic desert species (e.g. *Nanger dama* and *Addax nasomaculatus*) still persist within their territories and could be used for synergic ecotourism and conservation promotion (Durant et al., 2014; Santarém et al., 2019).

4.4. Potential data limitations and methodological constraints

Our work is based on the availability of big datasets containing georeferenced data on features and costs for the prioritization of natural resources in the Sahara-Sahelian region integrated with country-level socio-economic data to understand countries-performance in managing their CES. While using big datasets presents advantages related with data availability, it also presents limitations related with data quality and local-scale processes, which may have conditioned the analyses performed (Cerretelli et al., 2018). The lack of high-resolution data for some regions in the Sahara-Sahel has been identified in previous research (Brito et al., 2014, 2016), and the use of a coarse spatial resolution may have compromise, for instance, the efficiency of prioritization rankings. Still, a large spatial resolution is needed given the large extent of Sahara-Sahel and the computational power to perform the spatial prioritization demands these compromises (Brito et al., 2016). Even if this approach may limit local-scale interpretations in some parts of the region, the research here developed offers hints to develop CES planning at the regional level that, nevertheless, can be adapted to finer-scale levels once future detailed data is available.

Social media data can potentially be used for collecting meaningful ecological and ecotourism data in the future (Hausmann et al., 2019; Hausmann, Toivonen, Heikinheimo, et al., 2017; Hausmann, Toivonen, Slotow, et al., 2017; Toivonen et al., 2019). But such meaningful data will only be possible to collect once localized conflict events are ameliorated (Brito et al., 2018), which can then lead to increased ecotourist visitation levels in Sahara-Sahel that allow assembling these data (Santarém et al., 2020b). Other constraints, such as natural resources extraction facilities or smuggling/trafficking routes that threaten ecosystems and unable people to benefit from natural resources (Brito et al., 2018; Levin et al., 2019; Taylor et al., 2017) can be considered in future studies to highlight the costs related to CES losses. But these elements are highly dynamic in space and time, making them hard to include in CES studies (Santarém et al., 2020a).

Our quantitative approach for evaluating CES is based in a specific index developed for such purpose that uses socio-economic variables as proxies of the performance of Sahara-Sahel countries in terms of CES management. There are other alternative approaches, such as the HDI composite index, which comprises indicators related to education, life expectancy, wealth and standard of living (UNDP, 2019). However, our index goes further in considering additionally tourism, environmental, governance and security indicators, which further details the regional development situation of each Sahara-Sahel country, and thus provides a clearer picture of CES assessment and management.

Our spatial approach is based in the most recent publicly available decision-support tool to produce rankings for the conservation and management of biodiversity (Lehtomäki & Moilanen, 2013; Moilanen et al., 2014), which enables the production of prioritized maps reflecting the rank order of importance of planning units (Moilanen, 2007; Moilanen et al., 2005, 2014). There are numerous alternative methods to evaluate ecosystem services (see Brown & Fagerholm, 2015; Crossman et al., 2013; Kosanic & Petzold, 2020; Martnez-Harms & Balvanera, 2012; Milcu et al., 2013; Wolff et al., 2015 for global reviews on CES methods), including biophysical modelling, simple GIS mapping, or methods focused on participatory methods to evaluate people preferences (Harrison et al., 2018). However, in our case, we opted to use decision-support tools has they have are useful for conservation and management research, despite their application to ecosystem research is just start growing (see for example Di Minin et al., 2017). Furthermore, by applying a novel mixed-method approach, we were able to assess the performance of different states in the conservation of and benefits from CES, something never done before globally.

The PCA developed in this study is unbalanced between the number of countries (18) and the number of socio-economic variables (17) under study. However, the PCA is a statistical approach that assumes that the number of variables should be many times larger than the number of countries to find meaningful patterns ((Björklund, 2019). We addressed this issue by testing the distinctness of the different PCs and used only the most distinct one which displayed the eigenvalue three to four times larger (8.02) than the next two PCs (PC2: 2.5 and PC3 2.1; Table 4). We also presented the squared cosines (Table S2), which reflect the representation quality of the variables on the different PCs and avoided interpretation errors due to projections (Peres-Neto et al., 2003). These steps were taken to minimize possible biases in PCA results.

Future research also needs to refine methods to account for complex and intertwining temporal dynamics of conflicts (Hanaček & Rodríguez-Labajos, 2018), which can rank countries' performance differently along time. For instance, although the peace situation of Burkina Faso was ranked as medium during the studied period, the very recent escalating conflict in the country (in early 2020) most probably influenced the safety perceptions of potential visitors. As such, the changing dynamics of conflicts need to be considered carefully in regional planning, as conditions for visitation can quickly deteriorate or ameliorate.

Lastly, among the many CES deserts supply, the focus of this study was mostly on ecotourism and recreation. We did not address specifically aesthetic values, spiritual and religious values, sense of place, inspiration, or other categories of CES (see, for instance, Milcu et al., 2013 for all categories), which might be of interest to specific segments of the society. Still, many of the components of our spatial dataset can be analyzed in the light of many of these subcategories (for example, UNESCO Heritage Sites tend to display high aesthetic values and inspire people while being used for recreation).

4.5. Recommendations for desert CES management

Globally, ecosystem services derive values to people in the order of USD145trillion/year, a figure that is 4.5 times the value of 2014 Gross World Product (Costanza et al., 2014). Although CES remain poorly understood and neglected (Cheng et al., 2019), their estimated economic contribution to people's mental health alone yields around 2019 USD6 trillion (Buckley et al., 2019), which represents about 8% of the 2017 Global National Product. These are very high figures concerning the services nature provides to people. Deserts' contributions to these figures may be unspotted (Taylor et al., 2017), especially the economic value of desert CES. Studies estimating the value of desert CES are desperately needed to understand their economic and social contribution (Durant et al., 2012; Santarém et al., 2020b), particularly to countries such as Chad, Central African Republic, Eritrea, Ethiopia, Nigeria, Mali, and South Sudan, which display the lowest economic conditions among the studied countries and where the recognized value of CES could significantly improve their economies. For example, the annual value of CES in the Big Bend region of the Chihuahuan Desert was estimated to be around 2015 USD37.82 per hectare, a very high number given the threats that the region is under (Taylor et al., 2017). Nevertheless, we call countries and regional developers to opt for desert ecotourism activities that suit their particular ecological and sociocultural contexts (Santarém et al., 2020a; Santarém & Paiva, 2015; UNESCO, 2003b), in contrast to the forms of mainstream tourism that focus on growth instead of development and that leads to negative impacts on local ecosystems and communities (Buckley, 2011).

We call the regional and international community to jointly consider setting the following initiatives, which, although being quite ambitious, will be essential to deal with nature losses while developing local economies: 1) perform valuations of the natural capital to highlight the economic importance of desert ecosystems to people (Buckley et al., 2019; Costanza et al., 2014; de Groot et al., 2012; Strand et al., 2018; Teoh et al., 2019); 2) split conservation budgets to expand the land under protection (Pouzols et al., 2014), particularly by developing transboundary conservation areas (Brito et al., 2016) across hotspots of biodiversity (Brito et al., 2016; Santarém et al., 2019) and of ecosystem services (Santarém et al., 2020b), and to properly manage existing protected areas (Adams et al., 2019) to ensure the multifunctioning of ecosystems at multiple places and times (Cardinale et al., 2012); 3) strengthen environmental laws (Willemen et al., 2020) through international accepted Arms Trade Treaties to control arms trafficking (Brito et al., 2018) and to diminish armed conflicts in endangered World Heritage Sites of substantial global value (Levin et al., 2019); 4) improve governance, transparency and accountability (Díaz et al., 2019; Maron et al., 2019) to enable local societies to be more open to businesses (Brito et al., 2018); 5) promote community-based management of natural resources (Brito et al., 2018; Garnett et al., 2018) to ensure that their expertise is considered in conservation plans (Tilman et al., 2017; Willemen et al., 2020); and 6) develop community-based and flagship-based ecotourism to improve local social and economic conditions and to preserve threatened biodiversity in the long run (Brito et al., 2018; Santarém et al., 2019; UNEP, 2006b).

At a time when the outlook for nature conservation seems bleak, this study showed that promoting sustainable development practices to conserve CES in deserts will allow the proper functioning of ecosystems and their capacity to provide society with the essential services needed to prosper (Blicharska et al., 2019; Cardinale et al., 2012). The framework developed here presents a constructive opportunity for shaping global policies towards ecosystem management and for highlighting the contributions of cultural services to the SDGs (Wood et al., 2018).

5. Conclusion

Here, an interdisciplinary approach was employed to understand the performance of individual countries in managing their desert CES. The work showed that not only desert ecosystems provide many benefits to people but that there are opportunities for sustainable local development that are not fully explored. The results have implications for regional planners and policymakers that need to manage local ecosystem services to attract more ecotourists able to contribute to the sustainable development of the region. Still, national differences need to be accounted when developing regional plans for ecosystem management. Any approach to manage ecosystems in the Sahara-Sahel needs to be further contextualized and underline country' specificities, as emphasized in this paper. Combining decision support tools with socioeconomic data provided a first step to optimally allocate investments for conservation management. This is especially relevant in a region with big development contrasts, but where most of the countries are still underdeveloped despite displaying large cultural services that can benefit the global society. Policy makers can use the framework provided here to achieve regional targets of the SDGs. The framework is replicable to other areas where regional planning is needed for CES management and where country differences need to be taken in consideration.

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Figure captions

Fig. 1. Frequency of selection of pixels ranked as low (a) and high (b) priorities for CES conservation on the 10 different scenarios, and the absolute number of planning units (PUs(N)) and the planning units weighted by the area of country within the Sahara-Sahel limits (Dinerstein et al., 2017) (PUs (N/country)) selected for CES conservation (c). Pixels (0.5º resolution) are colored according to the number of times they were selected as priorities in the 10 scenarios: less than two times (grey), between two and eight times (yellow), and more than eight times (blue or red). See Fig. S4 and Table 2 for scenarios details, and Fig. S1 for country codes.

Fig. 2. Maximum Likelihood Classification of the two first principal components of the spatial PCA (a), and the absolute number of planning units (PUs(N)) and weighted by the area of country within the Sahara-Sahel limits (PUs (N/country)) highly selected for CES conservation (b). Sahara-Sahel ecoregions (Dinerstein et al., 2017) within Africa are depicted in the small inset. Pixels (0.5º resolution) are colored according to the likelihood of belonging to a given class of CES priority raking: blue – low; yellow – middle; red – high. See Figs. 1 and S5 for the frequency of selection of low and high priorities, and for the spatial PCA, respectively, and Fig. S1 for country codes.

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Fig. 3. Results of the Principal Component Analysis to evaluate the potential performance of countries in managing CES. The components that explain most of the variance (PC1 and PC2)

are depicted. Countries are represented in blue (see Fig. S1 for country codes) and variables are represented in red (see Table 3 for variables codes).

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Fig. 4. Relationship between the conditions for visitation and the availability of CES in each country. Conditions were retrieved from the PC1 loadings of the PCA performed for assessing which socioeconomic indicators are constraining national conditions for CES (Table 4 and Fig. 3). Availability of CES was measured by the number of planning units weighted by the area of the Sahara-Sahel ecoregions (Dinerstein et al., 2017) within each country (PUs (N/country)). Country symbols are colored according to the country-area highly ranked for CES conservation and the 2017 tourism inbounds (UNWTO, 2019): yellow (tourism over-explored); red (tourism under-explored); and black (tourism regularly explored). Symbol shapes represent countries-rankings according to the 2019 index of state of peace (Institute for Economics & Peace, 2019): square – high; circles – medium; diamonds – low; and triangles – very low. Symbol sizes are proportional to the raw number of planning units (PUs(N)) highly ranked for CES (see Fig. S6). See Fig. S1 for country codes.

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Fig. 5. Sensitivity analysis of the relationship between the conditions for visitation and the availability of CES in each country. Conditions for visitation were retrieved from the Human Development Index (HDI) (UNDP, 2019). Availability of CES was measured by the number of planning units weighted by the area of the Sahara-Sahel ecoregions (Dinerstein et al., 2017)

within each country (PUs (N/country). Country symbols are coded according to the country-area (YY axis) highly ranked for CES conservation and the 2017 tourism inbounds (UNWTO, 2019): yellow (tourism over-explored); red (tourism under-explored); and black (tourism regularly explored). Symbol shapes represent countries-rankings according to the 2019 index of state of peace (Institute for Economics & Peace, 2019a): square – high; circles – medium; diamonds – low; and triangles – very low. Symbol sizes represent the raw number of planning units – PUs(N) – highly ranked for CES conservation (see Fig. S7). Thresholds of medium developed countries (0.55) and high developed countries (0.70) are marked with a dashed line. See Fig. S1 for country codes.

This is a 2-column fitting image

Fig. 6. Missing opportunities for local development among Sahara-Sahel countries. Missing opportunities are defined according to the number of planning units weighted by the country-area within the Sahara-Sahel ecoregions (Dinerstein et al., 2017) (PUs (N/country)) prioritized for CES conservation and the inbound tourists in each country. Country symbols are colored as: red (tourism under-explored), yellow (tourism explored to the limit), and black (tourism normally explored when compared to the number of PUs identified with high availability of CES). Tourism data (UNWTO, 2019) are in millions. See Fig. S1 for country codes.

This is a single fitting image