# MAPPING AND ANALYSING CULTURAL ECOSYSTEM SERVICES IN CONFLICT AREAS

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**Abstract**
Human-mediated global environmental change threatens ecosystem services worldwide. Detailed cultural ecosystem services mapping is crucial to counteract ecosystem degradation, but such mapping exercises have been confined to small-scale analyses in developed countries. Additionally, land disturbances constraining the supply of cultural ecosystem services transboundary have never been mapped, which hampers the accurate management of ecosystems, particularly in underdeveloped countries affected by human conflicts. The Sahara-Sahel ecoregions of Africa represent an excellent model to map the distribution of transboundary attractions and constraints to cultural ecosystem services due to the many conflicts affecting its drylands. We mapped and analysed the supply of cultural ecosystem services in the Sahara-Sahel, using a multicriteria approach that includes transboundary attractions and constraints playing at broader scales. We wanted to understand where are located the hotspots of cultural ecosystem services and which regions displaying the highest levels of attractions may be simultaneously threatened by constraint features. Overall, 35.4% of the study area displays high (27.9%) to very high (7.5%) levels of attractions to cultural ecosystem services supply, while 8.6% of the area displays high (7.5%) to very high (1.1%) levels of constraints that limit the usufruct of these services in the region. Our findings showed that the main mountains and wetlands are supplying high levels of cultural ecosystem services but are threatened in some parts of their range by transboundary constraints. Some country-borders displayed a high concentration of constraints impacting desert biodiversity and human communities. This highlights the urgency of policymakers to reinforce transboundary strategic actions to halt the ongoing destruction of natural resources in the region. The developed approach is scalable and replicable in any ecosystem, including in those located in data-scarce regions. Including constraints to ecosystem services supply is paramount to achieve the United Nations Sustainable Development Goals.

**Keywords**
Mapping ecosystem services; deserts; drylands; Sahara; Sahel; ecotourism; constraints; ecotourism attractions; impacts

## 1. Introduction

Global environmental change and unsustainable human activities affect ecosystems worldwide and decision-makers struggle to create policies that halt biodiversity loss and related human impoverishment (Díaz et al., 2019). The idea of ecosystem services has been increasingly adopted to manage and counteract the degradation of ecosystems worldwide, to safeguard the natural capital for future generations, to provide new opportunities for local economies, and to highlight the direct and indirect contributions of ecosystems to human wellbeing (Costanza et al., 2014; Martinez-Harms et al., 2015; Kubiszewski et al., 2017). Recently, within the overall ecosystem service thinking, cultural ecosystem services (CES) have received an increasing importance in research and policy making (TEEB, 2010; Ståhhammar & Pedersen, 2017). The Millennium Ecosystem Assessment defines cultural ecosystem services as the non-material benefits people obtain from ecosystems through spiritual enrichment, cognitive development, reflection, recreation and aesthetic experience, and which include aesthetic, spiritual, educational and recreational services (Daniel et al., 2012; Milcu et al., 2013; Stålhammar & Pedersen, 2017). CES have been recognised as crucial to human wellbeing (Safriel & Adeel, 2005) and, despite recent critics on their operationalisation and value to land-management (see Kirchhoff, 2019), are now part of the strategies to achieve many of the targets under the United Nations Sustainable Development Goals (UN-SDGs), such as SDG1 – no poverty, SDG8 – economic growth, and SDG15 – life on land (UNWTO & UNDP, 2017; Wood et al. 2018). Particularly, ecotourism and related recreational activities have been proposed as a key tool to frame programmes aiming to eradicate extreme poverty and to stimulate environmental protection in fragile areas (UNWTO, 2018a).

To achieve the UN-SDGs, it is crucial that decision-makers contemplate the actual spatial characteristics of CES supply (i.e. the capacity of an area to provide ecosystem goods within a given time; Burkhard et al., 2012a; Lu et al., 2018) in land-use planning decisions (Maes et al., 2012; Schulp et al., 2014; Peña et al., 2015). Reviews on ecosystem services mapping (e.g. Martínez-Harms & Balvanera, 2012; Crossman et al., 2013) have revealed that CES are among the least commonly mapped ecosystem services, which highlights the need for additional research. Indeed, mapping and analysing CES are important to identify priority areas ensuring long-term provision of ecosystem services (Martínez-Harms & Balvanera, 2012; Lu et al., 2018), but they may be challenging due to their intangible nature and dependence in social models (Daniel et al., 2012; Milcu et al., 2013; Small et al., 2017). Some studies have attempted to map and analysed CES supply worldwide, with a bias towards developed countries (Milcu et al., 2013). However, most of the studies are limited to local (from 100 to 1,000 km$^2$) and regional (from 1,000 to 100,000 km$^2$) geographical scales (e.g. Kienast et al., 2012; Nahuelhual et al., 2013; Plieninger et al., 2013; Casado-Arzuaga et al., 2014; van Berkel & Verburg, 2014; Peña et al., 2015; Gigović et al., 2016; and Nahuelhual et al., 2017), while very few have tried to cover continental or global scales (>1,000,000km$^2$; Martinez-Harms et al., 2015; but see Paracchini et al., 2014; van Zanten et al., 2016; and Komossa et al., 2018).

Mapping CES supply at continental or sub-continental scales, however, supports decision-making and implementation in multiple ways. First, it helps identifying priorities for ecosystem management and restoration across political borders, which may enhance the preservation of natural assets through the development of transboundary "green" infrastructure networks that benefit neighbouring societies (Naidoo et al., 2008; Schulp et al., 2014). Second, it allows addressing thoroughly the continuum of ecosystem services across multiple scales, as many CES tend to be omni-directional, flowing to beneficiaries in many directions (Rosa et al., 2017). Third, it helps considering and analysing environmental problems that do not fit into the context of small spatial scales, avoiding overlooking ecological and social processes that operate across large scales of management (Martinez-Harms et al., 2015; Rosa et al., 2017). Forth, it allows cross-cultural comparisons of various recreation values that are being transformed by similar processes across the globe. Lastly, it helps understanding the diversity and similarities of continent's cultural-historical backgrounds on desiring the preservation of iconic landscapes (van Zanten et al., 2016).

Mapping CES supply requires extensive information to capture the heterogeneity of recreational attractions and constraints in ecotourism (Egoh et al., 2007; Komossa et al., 2018). As such, CES mapping using multicriteria approaches linked with Geographical Information Systems (GIS) has increased exponentially over the last years (Wolff et al., 2015). However, most analyses use proxy variables (e.g. land-cover) instead of primary CES data (Seppelt et al., 2011; Martínez-Harms & Balvanera, 2012; Crossman et al., 2013), despite the potential biases induced by proxies (Eigenbrod et al., 2010; Cerretelli et al., 2018). Mapping CES supply is usually based in coupling recreation values into integrative maps after weighting criteria via participatory methods (e.g. Kienast et al., 2012; Nahuelhual et al., 2013; Plieninger et al., 2013; van Berkel & Verburg, 2014; Peña et al., 2015; Nahuelhual et al., 2017; Komossa et al., 2018). In this respect, participatory methods are useful to understand how potential ecotourists valorise different landscape attributes (van Berkel & Verburg, 2014), but it can also include several methodological limitations: 1) they can only be performed in moderately to highly visited places; 2) they are subject to biases, for instance on choosing the stakeholders to engage in the study and on stakeholders overvaluing the most well-known places; 3) they cannot assure the complete commitment of interest groups for participation; 4) they are expensive to conduct; and 5) they present spatial and temporal limitations that hamper the systematic comparison of results, especially across large political relevant scales (van Berkel & Verburg 2014; Brown & Fagerholm, 2015; Wolff et al., 2015; Small et al., 2017; Komossa, et al., 2018; Scholte et al., 2018; Wood et al., 2018). In addition, mapping and analysing land disturbances threatening CES supply is considered crucial to conserve the biodiversity underpinning those same services (O'Farrell et al., 2010), yet, most CES studies fall short to include representative constraint factors causing changes in CES delivery at broader geographical scales (Martinez-Harms et al., 2015; Hanaček & Rodríguez-Labajos, 2018). For instance, land-degradation is decreasing the capacity of ecosystems to provide ecosystem services at unprecedented rates, urging the identification of priority areas for intervention (Cerretelli et al., 2018).

Constraints to CES supply, such as regional insecurity caused by conflict acting across country borders (e.g. attacks by extremist groups in several adjacent African countries; Harmon, 2016; Brito et al., 2018) or by mining expansion (Hanaček & Rodríguez-Labajos, 2018), emphasise the need to address CES mapping at transboundary scales. Mapping transboundary constraints to CES is of paramount importance for policymakers to identify areas where changes are impacting ecosystems, classify avoidance-areas for ecotourists (Lanouar & Goaied, 2019), and allocate recreation resources thoroughly (Lu et al., 2018). In remote and poorly visited regions, alternative approaches independent from participatory methods are needed to assess the attractions and the constraints to CES supply at continental scales.

The Sahara-Sahel ecoregions of Africa represent an excellent model to test alternative methodologies to map and analyse transboundary CES attractions and constraints. On the one hand, the Sahara-Sahel is mostly dominated by deserts and arid landscapes (Dinerstein et al., 2017), which constitute one of the last wild biomes on Earth (Watson et al., 2018) and offers prospects for ecotourists seeking ‘last-chance-to-see’ wild places (see Lemelin et al., 2012; Saarinen, 2018). In the current context of global environmental change, this kind of last chance tourism (LCT) refers to tourism motivated by a need to experience a place or certain environmental condition before they may disappear (Hall & Saarinen, 2010; Piggott-McKellar & McNamara, 2016). In this respect, Sahara-Sahel is still rich (although under threat) in unique biodiversity adapted to aridity that can be found nowhere else in the world (Brito et al., 2014; Durant et al., 2014; Brito & Pleguezuelos, 2019) and provide important ecosystem services for local people. Examples of these services include water-supply (crucial for settling people near water-rich regions) and food- and medicines-supply of desert-adapted plants (e.g. *Nitraria retusa* and *Herniaria hirsuta*, respectively), as well as regulating services like pollination by local wildlife, and supporting services such like sand fixation by particular desert-adapted plants (Safriel & Adeel, 2005; Davies et al., 2012; Bidak et al., 2015; Ghazi et al., 2018). In particular, mountains are rich in endemic and flagship species (Brito et al., 2016; Santarém et al., 2019a) inhabiting small and relict wetlands of global importance (Vale et al., 2015) and in geological, cultural and historical features that help understanding how human communities adapted to arid environments throughout time (Santarém et al., 2019b). These desert attractions have been partially explored in CES mapping at local scales (e.g. in Mauritanian wetlands; Santarém et al., 2018), but standardised CES mapping at transboundary level is lacking.

On the other hand, the Sahara-Sahel spreads across 18 countries, most of them ranked among the least human developed (UNDP, 2018) and least visited in the world (UNWTO, 2018b), which hampers the development of participatory methods to weight recreation values. For instance, Mali and Chad are among the poorest countries in the world and among the 30 least visited countries by international tourists. Some of these countries also account for the largest reported tourist deaths associated to conflicts and terrorism (Dioko & Harrill, 2019). Regional insecurity, such as transboundary attacks, kidnapping and smuggling routes, has contributed to the impoverishment of local people and the depletion of natural resources that international ecotourists would enjoy if they were preserved in first place (Lanouar & Goaied, 2019). For instance, Sudan, Libya and Mali have recorded an increased number of conflict events since 2011 and some borders (e.g. Mali-Algeria, Mali-Niger) are now under control by armed groups or terrorists (Brito et al., 2018). Constraints to CES supply have been partially mapped in the Sahara-Sahel (Brito et al., 2018), but others, such as pipelines of natural resources exploitation or landmines, remain unmapped. In addition, some countries (e.g. Morocco and Libya) may face the strongest species' habitat-suitability losses that will force a large proportion of species to be up-listed in conservation status (Powers & Jetz, 2019), but remain mostly neglected for biological conservation (Durant et al., 2012; Waldron et al., 2013; Brito et al., 2014; Durant et al., 2014; Brito & Pleguezuelos, 2019) and CES mapping exercises (Seppelt et al., 2011; Hanaček & Rodríguez-Labajos, 2018). Consequently, our understanding of which Sahara-Sahel regions concentrate the largest environmental and cultural attractions and which transboundary features constraint CES supply at larger scales is very deficient. Mapping and analysing attractions and constraints to the supply of CES in the Sahara-Sahel is needed to help decision-makers developing strategies that improve the benefits of these services to human well-being, while avoiding conflict-areas (Hanaček & Rodríguez-Labajos, 2018).

The main objective of this work is to identify, map and analyse the supply of CES, specifically for recreation and ecotourism, in the Sahara-Sahel. The study utilises a multicriteria approach that considers primary and secondary data, including constraints playing at broader scales, and that is independent from participatory methods (see Fig. 1 for details on the workflow). In particular, we want to understand: 1) which is the distribution of individual attraction and constraint features?; 2) which regions within the Sahara-Sahel concentrate the largest number of attractions and constraints for CES supply?; 3) given the spatial variability in attractions and constraints, which regions concentrate the highest levels of attractions and simultaneously display or not constraint features? Given the inherent characteristics of the Sahara-Sahel, we hypothesise that most of the attractions for CES supply will be located in the main mountains and wetlands of the region, and that most of the constraints will tend to cluster in the same regions where constraints have been estimated to locate in previous studies (see Brito et al., 2014, 2018).

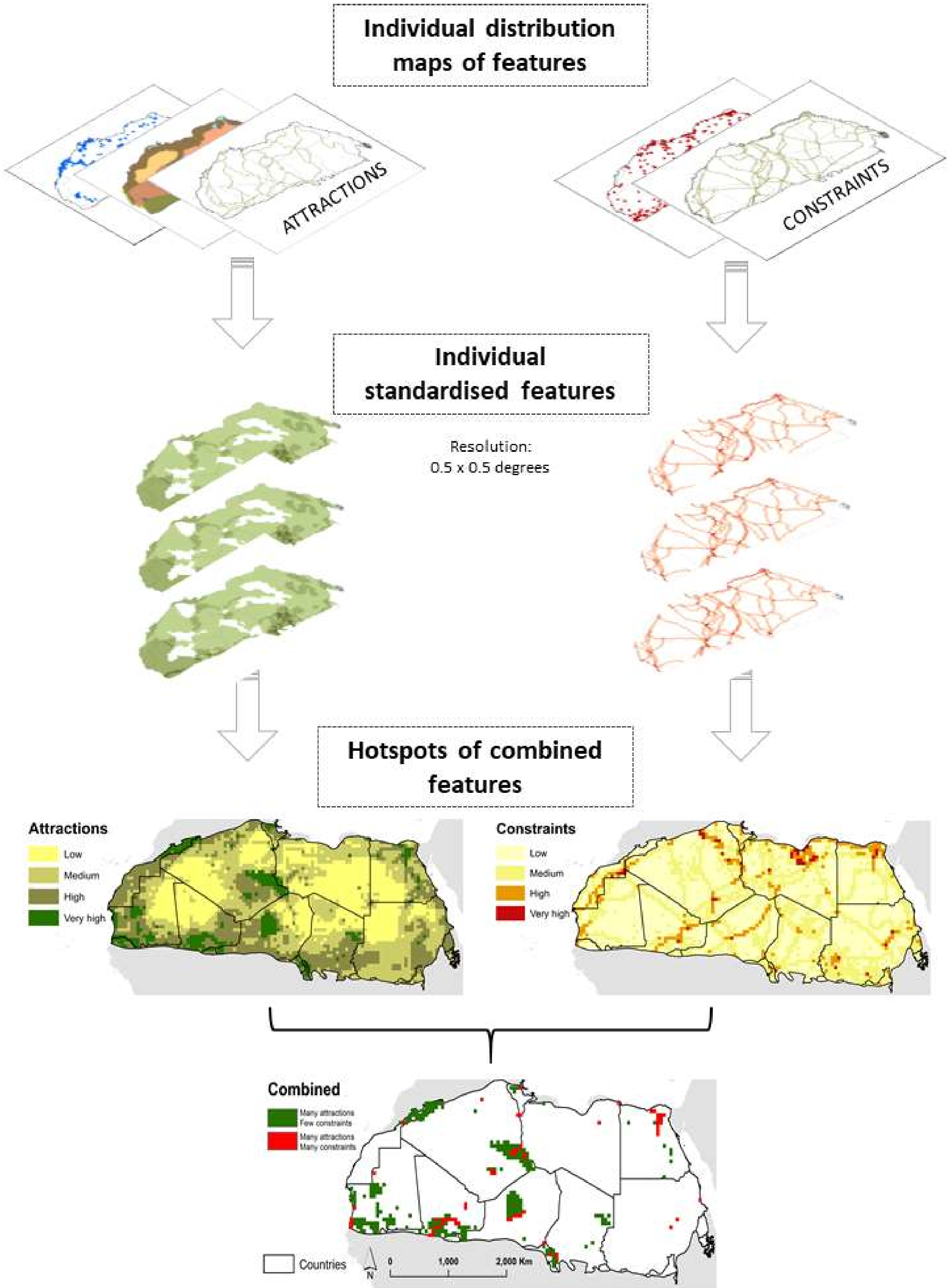


Fig. 1. Flowchart detailing the steps taken to map and analyse cultural ecosystem services supply in the Sahara-Sahel.

# 2. Methods

## 2.1. Study area

The study area (Fig. 2a; Fig. A1) comprises the Sahara, the largest warm desert in the world, and the contiguous arid Sahel (≈11,200,000 km$^2$). To map and analyse CES supply, we used as baseline the ecoregion limits (Dinerstein et al., 2017) and divided it in 4120 pixels of 0.5 degree resolution (WGS84 coordinate reference system).

## 2.2. Distribution of attraction and constraint features

A multicriteria approach was applied to map and analyse CES supply, based on variables that are known to condition the decision of potential ecotourists to visit regions (see below). A total of 26 variables were considered, including primary and secondary data organised in two categories: 21 attraction and five constraint features (see Tables 1, A1 and A2 for data sources and details on variables).

Table 1. Categories and subcategories of the variables assessed to map and analyse cultural ecosystem services in the Sahara-Sahel, their code, original data types and data sources. * See Table A1 for details.

| Categories | Code | Variable | Original data type | Data sources |
|---|---|---|---|---|
| *Attractions* | | | | |
| Biodiversity | Speci | Total species | Polygon | Brito et al. (2016); IUCN (2018) |
| | Endem | Endemic richness | Polygon | Brito et al. (2016); IUCN (2018) |
| | Flags | Flagship richness | Polygon | IUCN (2018); Santarém et al. (2019) |
| | Ecore | Terrestrial ecoregions | Polygon | Dinerstein et al. (2017) |
| Conservation | Fores | Forest reserves | Point | NGA (2016) |
| | ProtA | Protected Areas | Polygon | IUCN & UNEP-WCMC (2017) |
| | Herit | UNESCO World Heritage Sites | Polygon | UNESCO (2018) |
| Landscape | LandF | Major landscape features* | Polygon | GeoCover (2018), updated from PSSC (2018) |
| | GorMt | Gorges and mountain passes | Point | Updated from NGA (2016) |
| | RockF | Peculiar rock formations | Point | Updated from NGA (2016) |
| | Caves | Caves | Point | NGA (2016) |
| | Wetla | Major wetlands* | Polygon | GeoCover (2018) |
| | Guelt | Rock pools (known as *guelta*) | Point | Updated from Brito et al. (2014) |
| Cultural | EthnG | Major ethnographic groups* | Polygon | Updated from OECD-SWAC (2014) |
| | Oases | Oases | Point | Updated from NGA (2016) |
| | Monum | Monuments | Point | Updated from NGA (2016) |
| Historical | CarVi | Caravan villages | Point | Updated from OECD-SWAC (2014) |
| | CarRo | Caravan routes* | Polyline | Updated from OECD-SWAC (2014) |
| | Forti | Fortifications from colonial period | Point | Updated from NGA (2016) |
| | Ruins | Ruins, tombs, sites of empires historical land occupation | Point | Updated from NGA (2016) |

| | | | | |
|---|---|---|---|---|
| | RockA | Rock art | Point | Updated from Lluch & Philip (2003); Gauthier & Gauthier (2006); Jesse et al. (2007); Gauthier & Gauthier (2008); Le Quellec (2009); Riemer (2009); Gauthier & Gauthier (2011); Noguera & Zboray (2011); Biagetti et al. (2013); Gallinaro (2013); Le Quellec (2013); Barnett & Gaugnin (2014); Brémont (2018) |
| *Constraints* | | | | |
| Conflict | Landm | Landmines | Point | DesertInfo (2006) |
| | Attac | Attacks/battles and violence against civilians (2011-2016) | Point | de Hass (2007); Ewi (2010), Raleigh et al. (2010); Beauchamp (2014a,b); Grossman (2015); START (2015); Weiss (2016); Brito et al. (2018) |
| | Migra | Smuggling and human migration routes | Polyline | Brachet et al. (2011); Rekacewicz (2012); OECD-SWAC (2014); Brito et al. (2018) |
| Exploitation of natural resources | ExtraF | Oil, gas, mining extractive facilities | Point | NIMA (1997); Duncan et al. (2014) |
| | Pipel | Pipelines | Polyline | NIMA (1997) |

*Attraction features*

Animal species are one of the main attraction elements to a given site and localities exhibiting high species richness are linked with increased recreational value (Chung et al., 2018). Importantly, endemic and flagship species are key factors to attract ecotourists (Santarém et al., 2019a) and have been used in mapping CES supply (e.g. Scholte et al., 2018). Thus, we considered the total number of amphibian, reptile, bird and mammal species occurring in the Sahara-Sahel (Fig. 2b), and the number of endemic (Fig. 2c) and flagship species (Fig. 2d) of these groups. We quantified species richness of these three groups per pixel based on polygons depicting individual species ranges. The species richness of endemics by pixel was weighted over the total species found in each pixel.

Ecoregions, i.e. ecological regionalisations that delineate areas of similar environmental conditions, ecological processes and biotic communities (Dinerstein et al., 2017), help distinguishing different landscape determinants of CES supply (Weyland & Laterra, 2014). Forest Reserves and other protected areas are crucial for biodiversity preservation and nature recreation worldwide (Balmford et al., 2015; Chung et al., 2018) and they have been assessed in other CES studies (Scholte et al., 2018). UNESCO World Heritage Sites help preserve the cultural and natural heritage of universal importance and provide an additional value to ecotourists seeking places of outstanding value (Levin et al., 2019). Based on this we quantified the number of ecoregions (Fig. 2e), forest reserves, protected areas and UNESCO sites (Fig. 2f) per pixel.

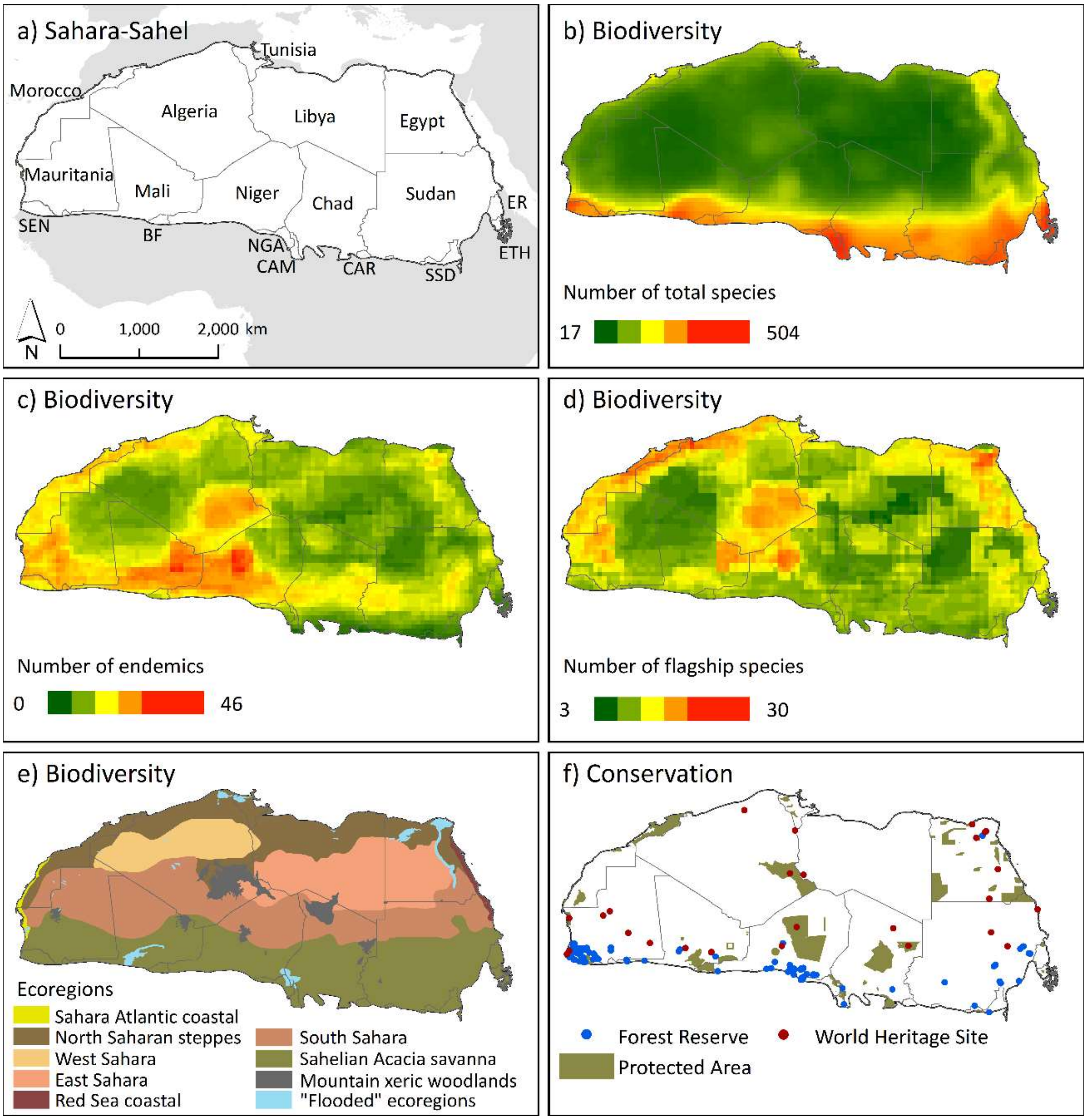


Fig. 2. Map of the Sahara-Sahel (a) and distribution of the biodiversity (b-e) and conservation features (f) in the region. BF – Burkina Faso; CAM – Cameroon; CAR – Central African Republic; ER – Eritrea; ETH – Ethiopia; NGA – Nigeria; SEN – Senegal; SSD – South Sudan;.

In deserts, specific landscape features provide multiple opportunities for recreation. For instance, sand dunes and flat plains provide scenic settings that trigger deep emotional connections to nature and provide solitude and tranquillity from stressful urbanised cores (Cooper et al., 2006; Santarém et al., 2018, 2019b). Continental and coastal cliffs, as well as gorges and mountain passes create wonder to landscape aficionados. Rock canyons, valleys, inselbergs, escarpments, and rock formations (such as rock arches, desert potholes, aeolian landforms, and saltpans) and caves are also prominent desert landscape attractions to recreationists and ecotourists. High altitude areas and associated plateaus, volcanic cones and meteor impact craters are also geological features of potential interest to desert ecotourists (UNEP, 2006a,b; Santarém et al., 2019b), thus, we calculated the number of these landscape features per pixel (Figs. 3a-e).
Wetlands are crucial for species and humans in deserts and tend to concentrate large species diversity and traditional human activities (Brito et al., 2014; UNEP,

2016a) and have been assessed in other CES studies (Plieninger et al., 2013; Peña et al., 2015; Scholte et al., 2018). Particularly, mountain rock-pools constitute local biodiversity hotspots (Vale et al., 2015) and are fundamental to ecotourism activities in deserts (UNEP, 2016b; Santarém et al., 2018). We quantified the number of wetlands and mountain rock-pools per pixel (Fig. 3f).

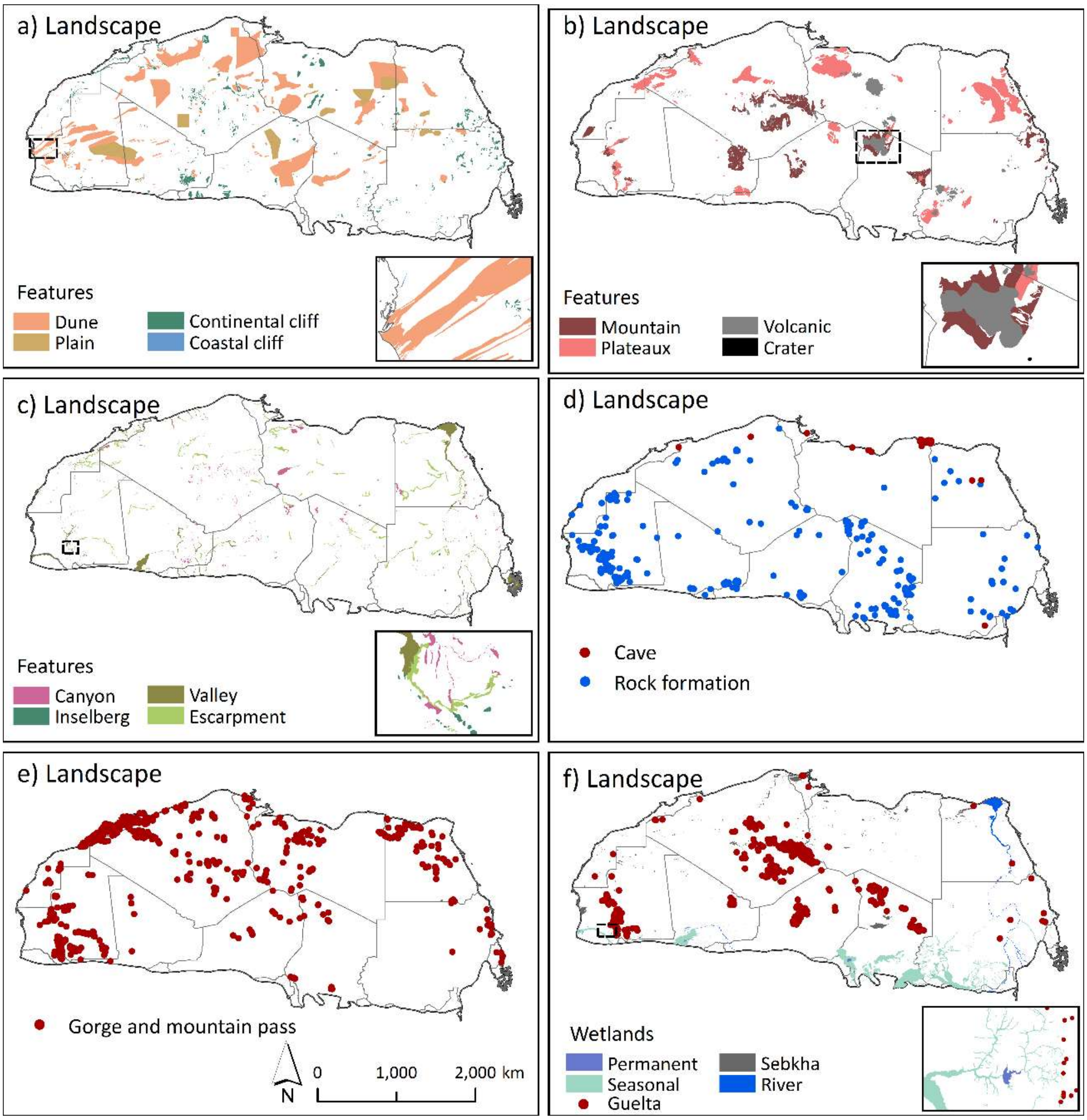

Fig. 3. Distribution of major landscape features (a-c), caves and rock formations (d), gorges and mountain passes (e) and wetlands and gueltas (f) in the Sahara-Sahel.

Historical and cultural features associated with human presence in deserts add value to the general recreational experience. Indigenous people have long adapted to the harsh arid environment by using desert elements to counter extreme temperatures and winds and a generalised paucity of water (UNEP, 2006b; Santarém et al., 2019b). The presence and diversity of ethnic groups has been linked with ecotourism potential (Zeppel, 2006; Fennell, 2015; Saarinen et al., 2014; Saarinen 2016). We counted the number of ethnic groups per pixel (Fig. 4a).
Oases represent an example of cultural adaptation to arid environments. They were created and managed by local communities for agriculture purposes

(mostly for production of date palms, *Phoenix dactylifera*) that benefit from the unpredictability of rain. They are now a vital asset to CES supply that benefit local people living in their surroundings (Davies et al., 2012), mostly because of their ecological and cultural importance (UNEP, 2006a,b; Santarém et al., 2018, 2019b). Grounded on this, we quantified the number of oases per pixel (Fig. 4b).

The historical occupation of deserts is noticeable in cultural monuments, which comprise large structures erected to commemorate notable persons or events and are valued among many recreationists (van Berkel & Verburg 2014; Peña et al., 2015). We counted the number of monuments per pixel (Fig. 4b).

Commercial villages and caravan routes have long been established in deserts for trading exchange and religious-cultural enrichment. They offer extensive depositories of desert knowledge and are highly appreciated by ecotourists (UNEP, 2006a; Santarém et al., 2019b). Thus, we quantified the number of caravan villages and routes per pixel (Fig. 4c). Furthermore, many historical sites have been identified for desert CES (UNEP, 2006a,b; Santarém et al., 2019b). In Sahara-Sahel, fortifications from colonial periods and ruins, tombs and sites of historical empire land occupation (e.g. Roman and Ancient Egypt) abound (UNEP, 2006a). Therefore, we quantified the number of fortifications and ruins per pixel (Fig. 4d).

Finally, rock paintings and engravings illustrate past livelihoods and past climatic shifts in the regions where they are depicted. In particular, the Sahara Desert is considered an open book of Human history (Gallinaro, 2013). Here, desert rock art is highly recognizable among international recreationists and ecotourists because it is easily found in large concentrations (Santarém et al., 2019b). We quantified the number of rock art sites per pixel (Fig. 4e).

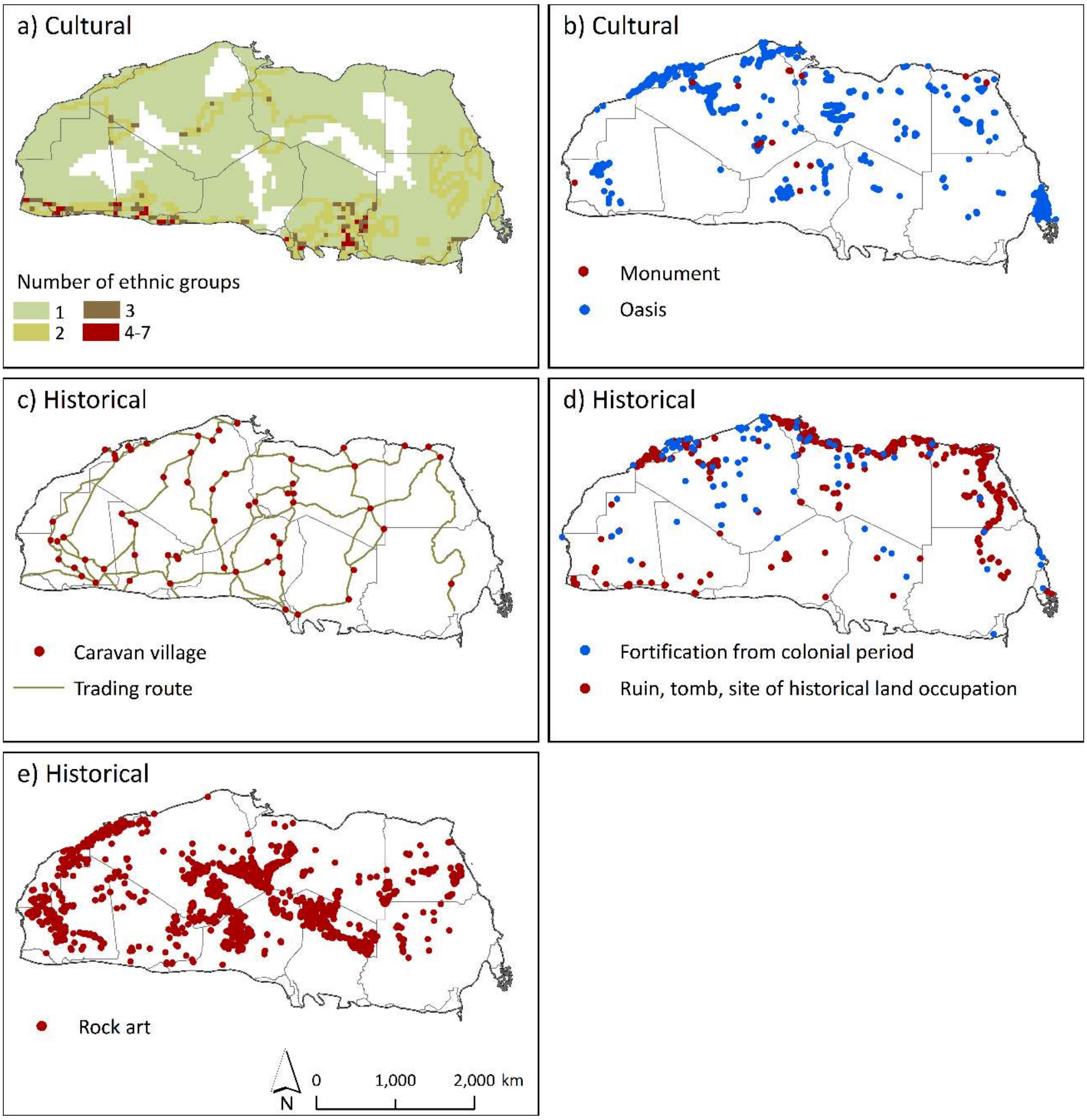


Fig. 4. Distribution of cultural (a-b) and historical features (c-e) in the Sahara-Sahel.

### *Constraint features*

Accelerated land-use changes and unsustainable development programmes are striking deserts. Preliminary constraining elements to desert recreation have been identified in the Sahara-Sahel, such as armed conflicts, military-defensive structures (e.g. landmines) and violence against civilians (Brito et al., 2018; Santarém et al., 2019b). Smuggling and human migration are now a common issue in many parts of the region (OECD-SWAC, 2014; Harmon, 2016). Natural resources exploitation, via oil, gas and mining facilities, is increasing in the Sahara-Sahel, threatening local biodiversity (Brito et al., 2014; Duncan et al., 2014; Brito et al., 2018) and CES supply (Hanaček & Rodríguez-Labajos, 2018). These constraints deplete the desert from natural and cultural features (Brito et al., 2014; Levin et al., 2019), and impact the recreation potential of the region. We quantified the number of these constraining features per pixel (Figs. 5a-d).

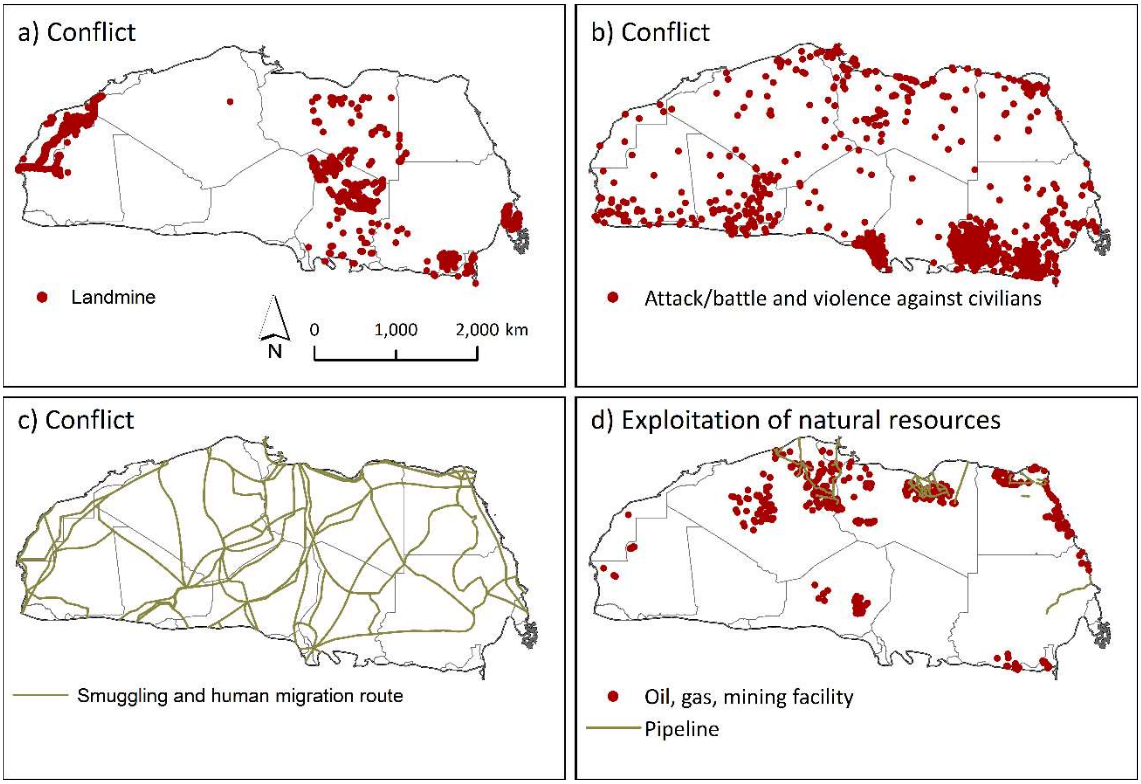


Fig. 5. Distribution of conflict (a-c) and exploitation of natural resources features (d) in the Sahara-Sahel.

### 2.3. Identifying hotspots of attractions and constraints to cultural ecosystem services supply

To map and analyse the locations of CES hotspots in the Sahara-Sahel we first standardised each of the 26 variables, dividing each entry value in the database by its maximum value, to obtain re-scaled variables varying between 0 and 1 (as in Peña et al., 2015). Then, the 26 standardised variables were mapped in ArcMap 10.1 (ESRI, 2012) to obtain the individual distribution of standardised attractions and constraints to CES supply in the study area. After, regions remarkably supplying higher levels of CES were identified by combining the 21 standardised attraction features to produce a map of CES attractions hotspots, and the same procedure was employed to map the location of constraints hotspots threatening CES supply, using the five standardised constraining features. All features were considered equally important, covering complementary aspects of CES supply, and were equally weighted. The resulting hotspots of CES attractions and constraints were classified into four main classes – low, medium, high and very high – using the Jenks Natural Breaks in ArcMap 10.1 (ESRI, 2012). This approach provides natural groupings inherent in the data, by identifying groups of similar attractions and constraints and maximising differences between classes (Casado-Arzuaga et al., 2014; Peña et al., 2015).

To identify the areas where many attractions are threatened or not by many constraints, the distributions of classified attraction and constraint hotspots were overlapped to generate the combined attraction-constraint hotspots (as in Santarém et al., 2019a). The hotspots combining many attractions with few constraints overlapped the class very high attractions with the class low constraints, while the hotspots combining both many attractions and many constraints overlapped the class very high attractions with the classes high and very high constraints.

## 3. Results

### 3.1. Distribution of attraction and constraint features

*Attraction features*

The Sahara-Sahel displays substantial spatial heterogeneity in the distribution of attraction features related with CES supply (Fig. 6). Species richness is higher in the Sahel in comparison to the Sahara, a pattern that contrasts with the higher number of endemics and flagships found in the Sahara along the Western and Eastern corridors, mountains, and wetlands. Ecoregions are heterogeneously distributed along the region, but parts of Mauritania, Algeria and Egypt display contact zones between multiple ecoregions. Forest reserves are dense along the Senegal River and in southern Niger. Protected areas are generally widespread, but some regions display denser levels, such as along the Morocco-Algeria, Mauritania-Senegal and Algeria-Libya borders, in central Tunisia, and Lake Chad surroundings. Some countries (e.g. Egypt) protect much more parcels of land than others (e.g. Libya). World Heritage Sites are heterogeneously spread across the region, but denser levels can be found along the Algeria-Libya border. There is no clear geographic structure in the distribution of all landscape features, but some regions tend to concentrate higher levels, such as central Mauritania, southern Algeria, and along the Egypt-Libya-Sudan borders. Gorges and mountain passes are well distributed in Sahara-Sahel, but higher concentrations can be found mainly along Morocco-Algeria border. Rock formations are numerous in Mauritania and Chad, but the highest density can be found in only one pixel in southern Niger. High density of caves can be found in north-eastern Libya. Wetlands are denser in the wettest parts of the Sahel, along the Niger and Senegal rivers, and Lake Chad. Rock-pools (gueltas) are concentrated in the Saharan mountains. Ethnic groups richness is higher along Sahel parts of Mauritania, Mali and Chad. Oases concentrate particularly in central Niger, and along the Algeria-Tunisia and Eritrea-Ethiopia-Sudan borders. Monuments are overall rare in Sahara-Sahel and can be found mostly in Egypt and Algeria. Caravan villages are spread across the study area, as well as caravan routes. Fortifications concentrate mostly in Algeria and Morocco. Ruins and sites of historical occupation are mostly found in northern Sahara (Morocco, Tunisia, and northern Libya) and along the Nile River. Rock art is denser in southern Algeria and Libya, along the Libya-Egypt-Sudan borders, and in Egypt.

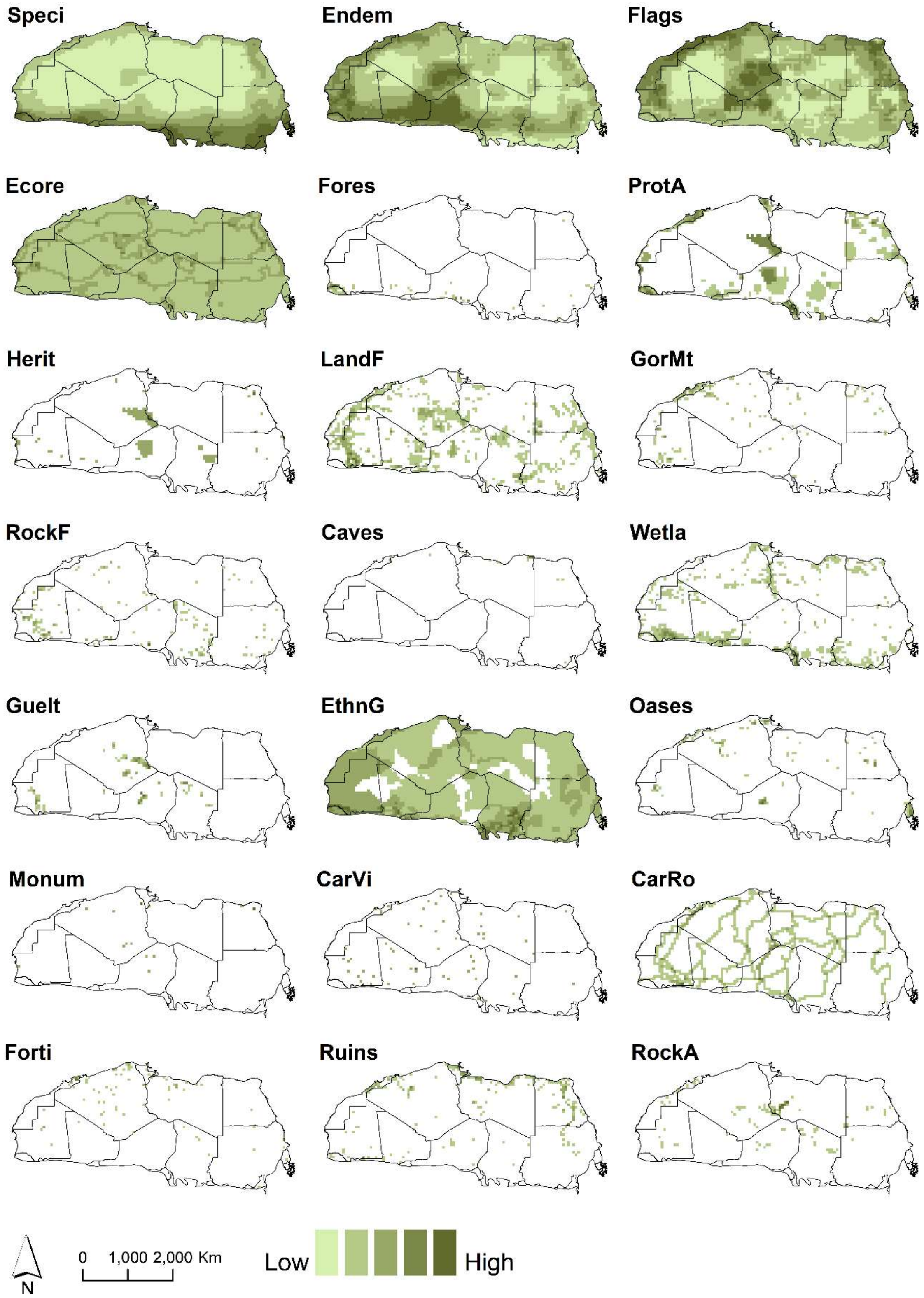


Fig. 6. Distribution of standardised attractions to cultural ecosystem services supply in the Sahara-Sahel at 0.5-degree resolution. See Table 1 for codes of variable.

*Constraint features*

Considerable spatial heterogeneity in the distribution of constraint features related with CES supply was found (Fig. 7). Landmines are denser along the Morocco-Mauritania border, in northern Chad, and along the Libya-Chad and Eritrea-Sudan borders. Attacks and violence are denser in northern Egypt and

Sudan. Smuggling and human migration routes are spread in Sahara-Sahel but tend to concentrate along borders between countries. Exploitation of natural resources is highly concentrated in north-eastern Algeria and northern Libya.

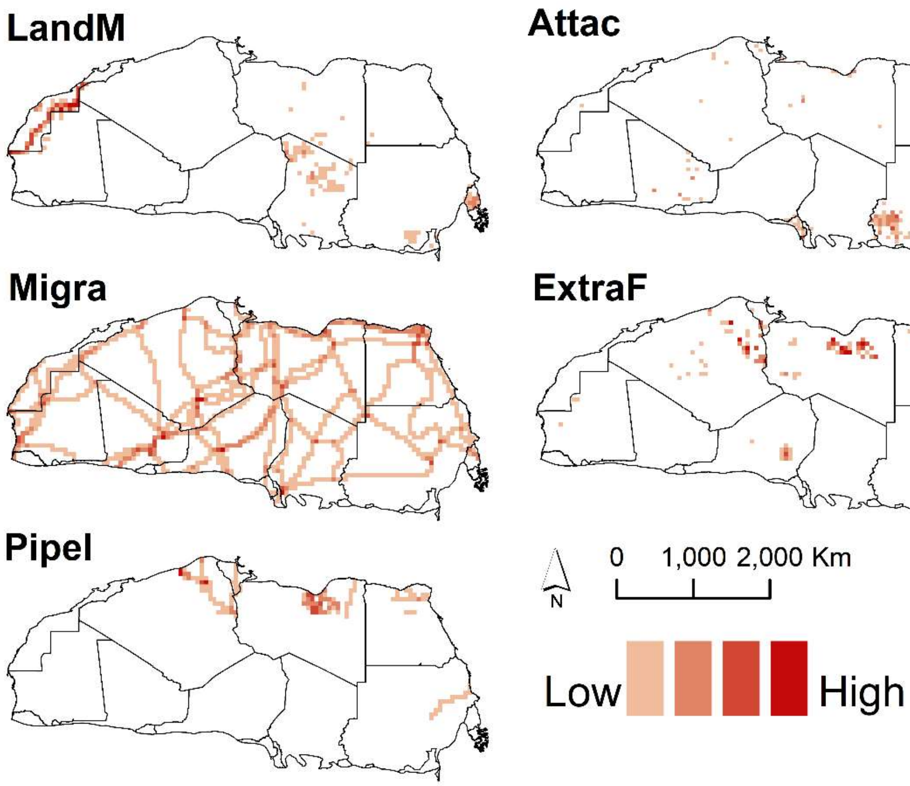


Fig. 7. Distribution of standardised constraints to cultural ecosystem services supply in the Sahara-Sahel at 0.5-degree resolution. See Table 1 for codes of variable.

### 3.2. Hotspots of cultural ecosystem services attractions and constraints

The spatial distribution of hotspots of attractions and constraints for CES supply in Sahara-Sahel varied substantially (Fig. 8). Large areas concentrate the highest level of attractions, especially in most of the main Sahara-Sahel mountains, along hydrographic networks (Senegal, Niger and Nile rivers, Lake Chad, and Chott El Jerid), and in south-eastern Morocco. Isolated attraction hotspots are also found, for instance in Egypt, Algeria, Chad or coastal Mauritania. Large flat areas tend to concentrate fewer attractions. Overall, 35.4% of the study area displays high (27.9%) to very high (7.5%) levels of attractions to CES supply. High to very high levels of constraints can be found along the Morocco-Mauritania and Algeria-Libya borders, north-eastern Algeria, Mali, Libya, northern Egypt, and western and eastern Sudan. Areas exhibiting low levels of constraints are mostly coincident with the areas displaying low levels of attractions. Overall, 8.6% of the study area displays high (7.5%) to very high (1.1%) levels of constraints impacting CES supply.

The combined distributions of attractions and constraints to CES supply also varied substantially (Fig. 8). Contiguous pixels displaying very high levels of attractions and very few constraints are found along central and southwestern Mauritania, Nile and Senegal rivers, Chad (Ennedi mountain), and southeast

Morocco, while isolated pixels can be found in south-eastern Egypt and Mauritania, and central Chad. Furthermore, contiguous pixels displaying both very high levels of attractions and constraints are found in Algeria (Tassili-n'Ajjer and Hoggar mountains), Niger (Aïr mountains), Lake Chad, Niger River, and lower Nile River in north-eastern Egypt, while isolated pixels are found in eastern Sudan, north-eastern Libya and Mali, and in the Algeria-Tunisia-Libya border.

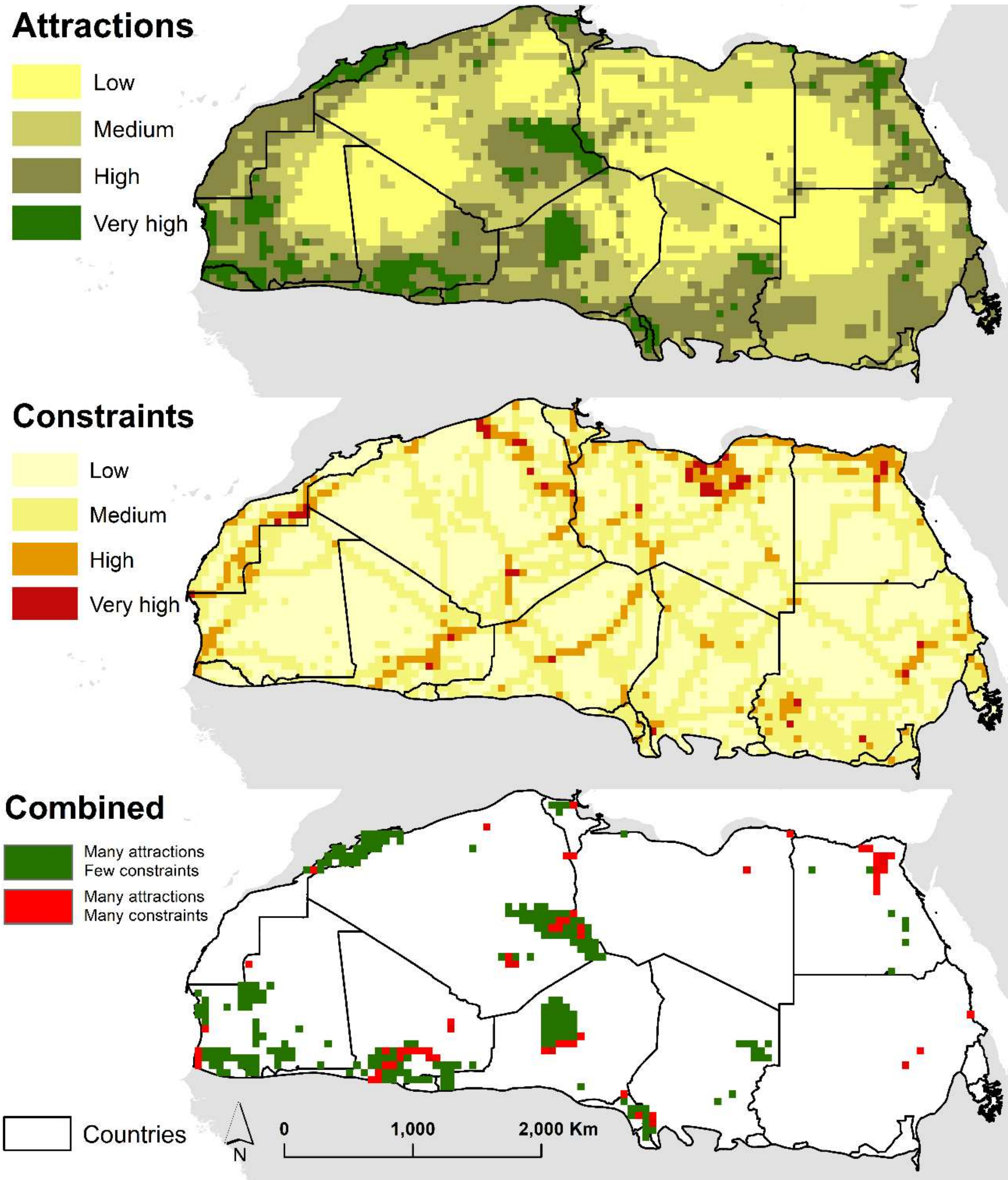


Fig. 8. Distribution of hotspots of attraction and constraint features to cultural ecosystem services supply in the Sahara-Sahel at 0.5-degree resolution (top and middle) and of hotspots combining many attractions with few constraints and simultaneously many attractions and constraints (bottom).

## 4. Discussion

To our best knowledge, this is the first study mapping and analysing transboundary constraints threatening the supply of CES at the sub-continental scale using primary and secondary data. This is one of the first studies mapping and analysing ecosystem services in the Sahara-Sahel region and provides the largest and the most comprehensive database on the natural and historical-cultural heritage of the region to date. Integrating attractions and constraints for mapping and analysing CES supply in the largest warm region of the world, as we did here, provided a tool that allows policymakers to identify priority areas of intervention in order to promote sustainable use of the arid ecosystems. Next, we discuss some spatial patterns found, as well as possible management applications, and limitations of the work that deserve future improvement.

### 4.1. Spatial patterns of CES supply in the Sahara-Sahel

Overall, 35.4% of the Sahara-Sahel area seems to supply high to very high levels of CES, a result similar to what was found in other continental-scale (e.g. 38% in Europe; Parachinni et al., 2014) and local-scales studies (e.g. 44% in Basque Country, Spain; Peña et al., 2015). This finding suggests that despite the generalised lack of research interest in studying desert ecosystem services (Lu et al., 2018), the biome displays high recreational values that need to be further explored. Recent global valuations of ecosystem services demonstrated that deserts are among the biomes providing the highest monetary value per area (Costanza et al., 2014; Kubiszewski et al., 2017). If the monetary value of desert CES remains to be calculated (Davies et al., 2012), our findings suggest that this figure can be high in comparison to other biomes. Additionally, although remoteness and harsh environments characterise deserts, the sparsely distributed vegetation and uncovered large landscapes facilitates the observation of large-bodied species (Safriel & Adeel, 2005; Santarém et al., 2019a,b) and, therefore, these species may supply more CES in deserts than in any other biome where vegetation may limit their sight. Hence, adopting a "Green Economic Growth" strategy in deserts will help protecting natural and cultural assets and maintaining the supply of ecosystem services on which human development and well-being depend on (Safriel & Adeel, 2005; Davies et al., 2012; Bidak et al., 2015; Ghazi et al., 2018).

As initially hypothesised, most of the attraction features mapped tended to concentrate in or around the main mountains and wetlands (Fig. 5; Fig. A1), which linked them with hotspots of CES supply (Fig. 7). Mountains and wetlands have also been identified as hotspots in other continental-scale (Paracchini et al., 2014; van Zanten et al., 2016; Komossa et al., 2018) and local-scale analyses (Plieninger et al., 2013; Peña et al., 2015). As wetlands tend to concentrate higher levels of attraction features, ecotourists probably tend to attribute an increased importance to wetlands availability (Scholte et al., 2018), especially when mountains and wetlands are protected (Paracchini et al., 2014; van Zanten et al., 2016) and where cultural heritage is dense (van Berkel & Verburg, 2014; Komossa et al., 2018). Despite Sahara-Sahel mountains and wetlands remain largely under-sampled, they constitute refugia for local biodiversity (Brito et al., 2014; Brito & Pleguezuelos, 2019) and support key ecosystem services (Davies et al., 2012), and were here revealed as main CES suppliers. Corridors along the Nile River and the Atlantic Sahara also showed a strong CES supply, reinforcing their key role in preserving the desert natural capital (Brito et al., 2014).

The flat and sandy parts of the Sahara-Sahel apparently displayed fewer attractions for CES supply. These areas tend to be highly homogeneous and are thus less demanded by ecotourists for recreation (Peña et al., 2015). Yet, as vast empty-quarters and dune massifs are crucial for the persistence of large flagship Sahara species, such as the Addax (*Addax nasomaculatus*) and the Scimitar-horned oryx (*Oryx dammah*) (Durant et al., 2014; Brito et al., 2018; Santarém et al., 2019a), they may supply moderate to high levels of other ecosystem services at finer scales (e.g. provisioning services; Wei et al., 2018). Future studies could explore the validity of this assumption.

Hotspots of constraint features matched our initial hypothesis that they would tend to occur in areas where human-led threats were preliminarily identified (see Brito et al., 2018). For instance, the current conflict, the high density of natural resources exploration activities, and the smuggling routes converging in northern Libya suggest the region as no-go area for ecotourists. Additionally, in areas where the number of conflicts is high (e.g. southern Sudan or northern Egypt), our study revealed hotspots of constraints that likely alter local ecosystems. For instance, many World Heritage Sites were identified as severely threatened by terrorist group activities. Thus, it is urgent the deliberation of crucial avenues for global transparent and real-time mechanisms to tackle the risks of permanent loss of these sites of outstanding importance to humanity (Levin et al., 2019).

Some of the areas concentrating very high levels of attractions spatially matched with areas displaying very high levels of constraints, such as the cases of the Niger River valley and the Lake Chad surroundings. Despite being among the places displaying more attractions for CES supply, they are downgraded by pixels exhibiting multiple constraints threatening CES supply. Similar cases occur in isolated clusters, for instance in the lower Nile valley, where the number of attacks against civilians and migration routes are likely impacting local CES supply. This overlap between areas of high CES supply and human threats exacerbate the challenges to preserve the natural and cultural heritage of Sahara-Sahel and emphasise the need to carefully consider human-wildlife mitigation measures (Brito et al., 2014, 2016, 2018).

Large clusters displaying very high levels of attractions with very few, if any, constraints were identified, for instance in Morocco, Mauritania, Algeria, Niger and Chad. These areas allow maximising the returns of visiting time, i.e. where ecotourists can observe different attractions in the same region without the need to travel between distant regions, and with minimum jeopardy from constraint features. Still, our results should be interpreted cautiously, as areas currently depicting high levels of attractions or constraints may alter in the future. Yet, this CES mapping exercise provides ecotourists, planners, and companies with a preliminary view, though not optimized (see section 4.2.), on which are the safest areas to visit in the Sahara-Sahel.

### 4.2. Management of CES in Sahara-Sahel

The combined map of attractions and constraints hotspots in Sahara-Sahel revealed considerable areas supplying CES. Yet, recreational use in a form of ecotourism in Sahara-Sahel is currently very asymmetrical and not all the attractions are equally harnessed. For example, UNESCO World Heritage Sites and oases are being explored by local tour companies that offer cultural experiences (Santarém et al., 2019b), but most of these experiences are

located for instance in Morocco and Algeria, while Mauritania and Chad remain poorly visited (UNWTO, 2018b). Here, we identified other areas and values that could be also explored and that could improve local economies where well-known international cultural attractions are lacking. For example, southern Mauritania displays one of the largest populations of the West-African crocodile (*Crocodylus suchus*) inhabiting the desert biome, a flagship species whose observation through detailed flagship-based ecotourism programmes could generate additional income sources to local people (Brito et al., 2014). Direct and indirect jobs in the ecotourism sector and the improvement of physical infrastructures for education (schools) and aid assistance (hospitals, clinics) can generate an extra incentive to protect local biodiversity. Additionally, diverting from cultural-only tourism to ecotourism can also contribute to the long-term preservation of deserts biomes, as environmental awareness among ecotourists and locals improves, and sustainable strategies for local development start to be a priority in policymaking (UNEP, 2006b; Santarém et al., 2019b). Still, there are several aspects that need improvement, such as the limiting entry requirements (VISA politics) of several countries or the "negative" impression given by past conflicts that detracts international ecotourists from travelling to North-Africa. Bureaucracy needs to be facilitated to improve confidence and specialised ecotourism requests need to be further explored.
Our study identified many transboundary CES hotspots, which helped understanding the diversity and similarity of continent's cultural-historical backgrounds and emphasised the need to map and analyse CES across borders (van Zanten et al., 2016). For instance, while the utilization of CES along the Algeria-Niger border is facilitated, it is impossible along the Morocco-Mauritania border due to the heavily mined 2,700km military berm dividing these countries, which detracts any form of travelling. Additionally, mapping and analysing CES transboundary helped to identify priorities for ecosystem management and restoration across borders (Naidoo et al., 2008; Schulp et al., 2014). For instance, the populations of the African savannah elephant (*Loxodonta africana*) can be observed in Mali during the dry season, but during the dry season ecotourists need to travel to Burkina Faso in order to follow their movements (Wall et al., 2013). Similarly, a deep understanding of how past societies have lived in the region is only possible if ecotourists visit both the mountains of Tassili-n'Ajjer in Algeria and Tadrart Acacus in Libya, which are considered a "cultural province" (Gallinaro, 2013).
In this paper we have stressed the importance of considering the preservation of natural and cultural assets through the development of transboundary "green" infrastructure networks that benefit neighbouring societies (Naidoo et al., 2008; Schulp et al., 2014) and of including indigenous communities in regional plans aiming to maximise CES supply. By mapping ecosystem services transboundary, decision-makers may identify areas where changes could impact ecosystems, classify avoidance-areas for ecotourists and allocate recreation resources thoroughly (Lanouar & Goaied, 2019).
Despite the high concentration of constraints in some regions, a differentiation between their intrinsic characteristics and consequences for wildlife and ecotourists should be done. On the one hand, there are constraints that impact mostly biodiversity features, such as oil and mining facilities that promote the extirpation of charismatic megafauna (Duncan et al., 2014; Brito et al., 2018). These constraints diminish the possibilities of ecotourists to observe Sahara-

Sahel charismatic species. On the other hand, there are constraints that may be capital to people's life, such as landmines (Brito et al., 2018; Dioko & Harrill, 2019), and that may clearly detract ecotourists from visiting certain areas of the Sahara-Sahel. Measuring the time length of each constraint would be pertinent for policymakers prevent socio-economic costs related to the loss of desert CES and, consequently, from ecotourists to visit certain areas. Doing so will help determining which type of policies should be implemented to recover and enhance ecosystems (Lanouar & Goaied, 2019). Still, local and international decision-makers should reinforce transboundary strategic actions to manage biodiversity and the ecosystem services derived by it to halt the ongoing destruction of natural resources. Overall, ensuring Sahara-Sahel CES supply will rely on: 1) detailed mapping of conflict hotspots; 2) increasing the levels of international and regional investment in human development, nature preservation, and technology transfer; 3) reinforcing policies to curb ecosystem degradation and to revert prejudiced effects of war, landmines and kidnapping on local ecotourism; 4) developing community-based natural resources management policies; and 5) capitalising local traditional knowledge (Safriel & Adeel, 2005; Egoh et al., 2007; Brito et al., 2014, 2018; Santarém et al., 2019b). We found that many of the regions responsible for high levels of CES supply are insufficiently covered by the current network of protected areas (Fig. 5). For instance, Mauritania displays many attraction hotspots (Fig. 7) but landscapes, species and ecosystems are poorly protected (IUCN & UNEP-WCMC, 2017). We sound the urgency to develop protecting schemes towards this unique desert biodiversity that deliver key ecosystem services (Brito et al., 2016; Santarém et al., 2019a). Ecological corridors and transboundary mega conservation areas should be prioritised to preserve these services (Davies et al., 2012; Egoh et al., 2012; Brito et al., 2016).

### 4.3. Limitations and further research

This work displays some limitations that may have locally biased our results. For instance, species distributions were based in IUCN polygons depicting extents of occurrence, which are often criticised because they may overestimate species' ranges (Graham & Hijmans, 2006; Chung et al., 2018), or in the case of Sahara-Sahel, they may underestimate distributions due to scarce sampling efforts (Brito et al., 2014, 2016). This may have probably impacted the accuracy of the species richness maps. Similar issues may arise from other world databases used to derive variables useful for assessing ecosystem services (Pandeya et al., 2016). Additionally, some regions may be supplying high to very high levels of attractions, but the generalised paucity of data dictated a different scenario in our study. For instance, the Tibesti Mountain (Chad) is the highest Saharan mountain and displays several landscape features of outstanding value (e.g. volcanic cones and meteor craters; Santarém et al., 2019b); yet, it is among the regions with the least available high-resolution maps of natural features (Brito et al., 2014). Although these constraints may bias the identified CES hotspots, their effects were likely diluted using a coarse spatial resolution of 0.5 degrees (Weyland & Laterra, 2014). Future studies should make use of accurate distribution data to overcome this issue whenever possible, for example by deriving species ranges from ecological niche-based models, as suggested by Santarém et al. (2019a). Using a coarse spatial resolution may compromise the efficiency in identifying areas supplying CES. Yet, such resolution is required when the large extent of the study area and the computational power needed to perform the analysis demands such compromise (Brito et al., 2016). Even if the spatial resolution here used constrained the real CES measures at local scales, this study offered hints to framework regional CES planning that can be applied at finer-scale resolutions. Social media opens new avenues for data mining to locate CES in the space and time. Social networks containing geo-tagged data allow collecting information about CES at the fastest pace ever (Oteros-Rozas et al., 2018; Vaz et al., 2019). This new trend to gather CES data will be useful only if, and when, ecotourism increases in Sahara-Sahel to levels that will allow assembly such data.

The spatial and temporal dynamics of attractions and constraints in Sahara-Sahel were not here specifically considered. For example, the salt-caravans crossing the Ténéré (Niger) are only observable in certain periods of the year, some wetlands are seasonal and only available during the rainy season, and wintering birds or reptiles in northern latitudes are only observable during specific periods of the year. Constraints to CES supply may also be highly dynamic. For instance, long-term regional conflict and lack of formal land access points virtually closed Mauritania to international travelling until the early 2000's, which changed afterwards with the amelioration of security conditions and the opening of an official border post, and again changed after 2008 following localised terrorist attacks throughout the country, to change again around 2018 with increasing of security conditions. The dynamics of these processes are very fast and thus hard to include in general assessments of CES supply. Still, researchers are requesting to contemplate interlinked spatial-temporal dynamics of CES (e.g. Rieb et al., 2017; Small et al., 2017) because they may impact patterns and processes of CES and drive better long-term outcomes if considered. But, in regions like Sahara-Sahel, where scientific data is scarce and spatially fragmented (see Brito et al., 2014), mapping biophysical provision of CES will be constrained until accurate data is available (Small et al., 2017).

The maps here produced only provide possible paths for sustainable desert ecotourism development. Scholars are requesting that studies contemplate not only the supply side, but also the demand side of CES (Wolff et al., 2015). This may also partially challenge some of the supply side results or their implementation as individual ecotourists can experience and value attractions and CES differently, i.e., "there is no consensus regarding what constitutes 'value' of nature for individuals" (Stålhammar & Pedersen, 2017, p. 2). Still, optimized solutions could be derived for cultural tourism, landscape tourism and ecotourism, for example, tailored according to the preferences of distinct visiting groups. Additionally, the different impacts of constraints on CES supply can be explored in future studies by attributing different weights to the constraints that are capital to human life (e.g. landmines) or that diminish local attractions (e.g. gas pipelines). Spatial decision-support tools present an excellent tool to further explore this, as researchers can attribute different weights to variables according to the objective of the work (Moilanen et al., 2014). They have been used to study how multiple ecosystem services are integrated into conservation planning at regional geographical scales (Chan et al., 2006; Hermoso et al., 2018) but conservation planning exercises applied to CES supply at continental scales remain to be done. The usefulness of using these tools at continental scales has been proved, for instance, in identifying priority conservation areas in Sahara-Sahel (Brito et al., 2016), but future studies could use them also to establish spatial priorities for developing recreation and ecotourism for different society segments while accounting for factors constraining CES supply.

## 5. Conclusions

Evaluating hotspots of attractions and constraints to CES supply in conflict regions is an important step to counteract ecosystem degradation and develop tools to improve their provision. The approach developed here is scalable and replicable worldwide and the criteria used could set the guidelines to identify the regions supplying the highest levels of CES in data-scarce regions. We highlight the significance of using raw data to robustly identify the areas supplying CES that are vulnerable to human-mediated constraints. Including conflicts on ecosystem services research as we did here is important to develop the field of research even further. We also note the importance of considering the human, social and natural capital (people, cultural societies and the environment, respectively) to map the benefits that ecosystems provide to people. This brings additional importance in the case of low-income countries and poor peripheral regions where conservation and ecotourism efforts need to be reinforced in order to protect the environment and the local people depending on it for sustainable development.

Ecosystem services planning should also involve multidisciplinary and transdisciplinary teams of scholars and practitioners to fully integrate theoretical and empirical expertise from diverse fields of knowledge – biology, geosciences, geography, economics, and social sciences – and to guide conservation management efforts efficiently (Chan et al., 2006; Naidoo et al., 2008; Rosa et al., 2017). It is by integrating multidisciplinary teams that scholars can maximise the benefits of CES, critical to poverty alleviation (UN-SDGs 1 and 8) and to biodiversity conservation (UN-SDG 15), even in regions under geopolitical conflicts that press nature preservation. In future, integrating science and policy will be critical to sustain ecosystem services and the natural capital (Burkhard et al., 2012b), and policy makers can use the provided framework to help achieve regional targets for UN-SDGs.

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