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Influence of nature values on environmental assessments in the ESGAP framework

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Abstract

Environmental metrics are used to describe the state of the environment in order to help actors responsible for implementing public policies for development and environmental protection to evaluate the effectiveness of their actions. To describe the state of the environment in Senegal, we use the ESGAP method, which consists of evaluating each dimension of the environment in biophysical units, in order to estimate at the national level, the capacity of natural capital to perform its environmental functions. The strong environmental sustainability (SES) index informs the gap between the current state of the environment and the environmental sustainability objectives. Four functions (the renewal of natural resources, the capacity of ecosystems to absorb pollution up to their critical load, the maintenance of biodiversity, and the impact of the environment on health and well-being) are measured by 33 indicators.

The main challenge in Senegal is to understand the respective influences of the data quality supporting indicators, the choice of one indicator instead of another to inform one dimension of the environment and the weight of each environmental dimension on the aggregated SES index. For that, we performed a global sensitivity analysis (GSA). We found that the weights of dimensions with low uncertainty and extreme score ('UNESCO sites', 'Terrestrial ecosystems' and 'Soil resources') are highly influencing the aggregated SES index. They are responsible of 66 % of the SES index variability in the GSA. Then the choice between indicators with very different scores to inform one dimension of the environment was the second group of influential variables. For example, the choice between the 'biodiversity intactness index', the 'red list index' or the 'mean species abundance' to inform the 'terrestrial ecosystem' dimension is highly influencing the aggregated SES index because they give different scores (respectively 89, 94 and 51). Finally, the choices between databases given different results for the same indicators are the third influential group of variables. For example, the choice between two data sources to inform the soil resource in Senegal is responsible of significant part of the SES index variability in the GSA. We concluded that participatory approaches to introduce negotiated values in the evaluation of the state of the environment through weights between the dimensions of the environment was highly important, but only for well-informed indicators. Thus, the participatory process and the data gathering are complementary to evaluate a robust and relevant state of the environment.

Introduction

Senegal's socio-economic development and population growth are having a major impact on the country's environment, in a context of increasingly tangible climate change impacts. Senegal is already facing many environmental problems, including resource management (degradation of forest cover, overexploitation of fisheries resources, coastal erosion, water stress), pollution (freshwater and coastal water pollution), biodiversity erosion, and health and well-being issues (poor condition of UNESCO heritage sites, air pollution). The coastal zone is one of the main areas affected by these environmental problems. By 2050, Senegal could experience a sea level rise of 0.6m (Croitoru et al., 2019), which will aggravate flooding: more than half of the city of Saint Louis, already affected, will be flooded by 2030 (World Bank, 2022). On the "Petite-Côte", a crucial region for tourism and the economic activity of the country, coastal erosion is generalized and can reach 1 to 2m per year. But other ecosystems are also affected by these environmental problems. Advanced land degradation concerns 6% of the country's total land area (CSE, 2020). The loss of forest cover (FAOSTAT, 2015), as well as the destruction and fragmentation of ecosystems mainly due to anthropogenic factors (agriculture, urbanization, artisanal and industrial mining) result in a loss of biodiversity throughout the country (CSE, 2015).

In order to face these problems, Senegal commits itself through international agreements, takes part in regional actions and implements national policies and sectoral action plans. Senegal has demonstrated its commitment to environmental protection by joining conventions such as the United Nations Framework Convention on Climate Change and the Convention on Biological Diversity. The country is already part of a World Bank regional program with other West African countries for coastal environment management, the West Africa Coastal Areas Management Program (WACA) (Croitoru et al., 2019). Several infrastructures are built, under construction or at the project stage, such as beach nourishment, or the construction of protective dikes. However, some developments have had or are likely to have impacts on the marine and coastal environment, particularly in topographically sensitive areas (CSE, 2020). The country takes part in the Great Green Wall initiative led by the African Union since 2007, which aims to combat the effects of climate change and desertification by planting a wall of trees stretching across the entire Sahel. In Senegal, over 12 million trees have been planted as part of this project, but the project is struggling to achieve its goals (UNCCD, 2020). The overall objective of Senegal's environmental and sustainable development policy is announced in the "Lettre de Politique du Secteur de l'Environnement et du Développement Durable" (LPSED), defined for the period 2016-2020, which takes over from the previous letter for 2009-2015. It consists in "creating a national dynamic for the improvement of the management of the environment and natural resources, the integration of the principles of sustainable development in policies and the strengthening of the resilience of populations to climate change". Senegal has successively developed several important strategic planning documents such as the National Action Plan for the Environment (PNAE), the National Action Plan to Combat Desertification (PAN/LCD), and the "Plan Sénégal Vert" ("PSE vert") which is currently being finalized.

These numerous efforts in terms of development and environmental protection policies are not sufficient to stop environmental degradation at the moment. A first step to support a policy process is the valuation of nature, understood here as "the intentional process to make explicit the values individuals or communities hold about nature, nature's contributions to people, and human-nature relationships" (IPBES, 2022). Recognizing the diversity of nature's values through undertaking relevant and robust valuation and "making visible otherwise neglected, intangible contributions and detriments from nature" are the first leverage points identified by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) to help create the necessary conditions for achieving the vision established by the 2030 agenda for sustainable development and the 2050 vision for biodiversity. Valuation of nature can support policy making across the different stages of the policy cycle undertaken to perform the changes necessary to stop environmental degradation: it can help set agendas and support commitment to agreed goals, help with policy formulation, aid policy adoption, design monitoring to support in-course adjustments and undertake retrospective policy evaluation (IPBES, 2022).

Incorporating diverse values in decision is challenging because the choice of the valuation process has to deal with the relevance (salience in terms of the values that can be used in decisions), robustness (reliable, consistent, and socially representative) and resource (time, financial, technical, human resources) requirement trade-off (IPBES, 2022). Multi-criteria participative assessments are able to address some of these challenges. In particular, the relevance of valuation is enabled by the consideration of a large number of environmental dimensions, leaving the decision maker free to decide, and allowing stakeholders to introduce their own restrictive assumptions in order to allow different values to be assessed (Martinez-Alier et al., 1998; Saarikoski et al., 2019). But participatory multi-criteria assessments raise implementation issues: (i) assessing multiple dimensions of the environment, (ii) with transparency on the quality of data and methodology to make the assessment reliable and robust, and (iii) with a participatory process that is not too resource consuming to not constrain the assessment (IPBES, 2022).

We anchor our study in the Environmental Sustainability Gap (ESGAP) framework to assess the state of the environment in Senegal (Ekins et al., 2003; Usubiaga-Liaño & Ekins, 2021b). The ESGAP is a dashboard of indicators to assess environmental sustainability (Usubiaga-Liaño & Ekins, 2021b). The dashboard of environmental indicators in the ESGAP assesses the maintenance of critical natural capital and its ability to perform its functions over time. Critical natural capital is a set of environmental conditions that have to be maintained through time for functional and ethical reasons (Ekins et al., 2003). It is rooted in strong sustainability, stipulating non-substitutability between natural capital and other forms of capital (Ekins, 2014). The ESGAP framework evaluates for a list of biophysical indicators a measure of absolute deviation from a value of "good environmental status" and a measure of the progress to be made to reach the objective. While it has been applied in a few countries in Australasia (Comte et al., 2021; Nguyen et al., 2022), Europe (Usubiaga-Liaño & Ekins, 2021a), and Kenya (Otieno et al., 2022), it is the first study conducted in West-Africa.

These studies using the ESGAP framework have produced estimates of the state of the environment based on a pre-defined conceptual framework. For these results to be used in a decision-making process, a participatory approach is particularly important to include diverse nature value (IPBES, 2022). In contrast to other studies using ESGAP, we seek to understand the importance of a participatory process and the influence of different stakeholders' values of nature in a decision-making process on the assessment of the state of the environment in Senegal.

Materials and methods

Senegalese context

Senegal is a Sahelian country located in the extreme west of the African continent. Its geographical position leads to climatic differences between the coastal zone and the interior regions, and between the North and the South, which gives it a rich potential in biological diversity. Its population of 16.74 million inhabitants is concentrated in the capital Dakar (23,03% in 2019) (ANSD, 2018), in the West of the country. It is crossed by two major rivers, the Senegal River, which concentrates the agricultural and agro-industrial activities, and the Gambia River. The agricultural sector is considered to be the lever of the national economy, with agriculture employing more than 70% of the working population and the agribusiness dominating Senegal's industry (ANSD, 2018).

In a context characterized by the increasingly tangible effects of climate change, Senegal is now facing a number of environmental issues. The galloping urbanization and industrial concentration in the Dakar region contribute to problems of flooding, sanitation, access to drinking water and waste management (CSE, 2020). The overexploitation of groundwater, combined with the decrease in rainfall, favors the entry of a saltwater wedge and leads to soil degradation while increasing the risk of the country being under water stress, especially the Guiers Lake which provides 75% of Dakar's drinking water consumption (CSE, 2015). Groundwater is suffering from fluoride and iron pollution (CSE, 2015). Biodiversity faces threats such as the continued degradation of vegetation cover due to bush fires, overexploitation of forest resources and the persistence of poaching. The marine and coastal environment is affected by overexploitation of species as well as the adverse effects of climate change, coastal erosion, and industrial pollution (CSE, 2020).

Environmental management in Senegal is shared among different ministerial departments that are also responsible for collecting data at the national level. For example, the Department of Water and Forests, Hunting and Soil Conservation is responsible for the management of wildlife and forest ecosystems as well as the monitoring and evaluation of forest resources. The state of the environment is presented by the Centre de Suivi Ecologique (CSE) in the State of the Environment Report published every 5 years for the Ministry of Environment and Sustainable Development in Senegal (CSE, 2015, 2020). The ESGAP completes this exhaustive description of the environment by its synthetic aspect, the definition of environmental standards, and the quantification of numerous indicators, which allows them to be compared with each other to prioritize environmental protection.

General overview of the ESGAP methodology

The Environmental Sustainability GAP (ESGAP) framework proposes a dashboard of indicators for monitoring the state of critical natural capital (Usubiaga-Liaño & Ekins, 2021b). This framework focuses on monitoring the gap between the current environmental condition and the level of environmental functions necessary to have a good ecological state of the biosphere (Ekins et al., 2003). In this study, we focus on a composite indicator for measuring sustainability against environmental standards or targets, named Strong Environmental Sustainability Index (SESI). The small number of time series providing information on environmental indicators for more than 5 years prevented us from calculating a trajectory for the indicators (called Strong Environmental Sustainability Progress Index in the ESGAP framework). Four environmental functions support the ESGAP frameworks: source, sink, life-support, and human health and welfare. 22 environmental dimensions have been listed in the theoretical ESGAP paper (Usubiaga-Liaño & Ekins, 2021a).

We conducted a 10-step assessment of the SESI (Fig.1): (1) review of the environmental dimensions present in the territory, (2) review of the possible indicators to inform each of these dimensions, (3) calculation of each indicator, (4) choice of the sustainability objectives, (5) calculation of the SES value for each indicator, (6) evaluation of the quality of the databases used to calculate the indicators, (7) choice of the indicators used to inform each dimension, (8) calculation of the SES value for each dimension, (9) choice of the weights of the dimensions in the aggregate indicator and (10) calculation of the aggregate SESI.

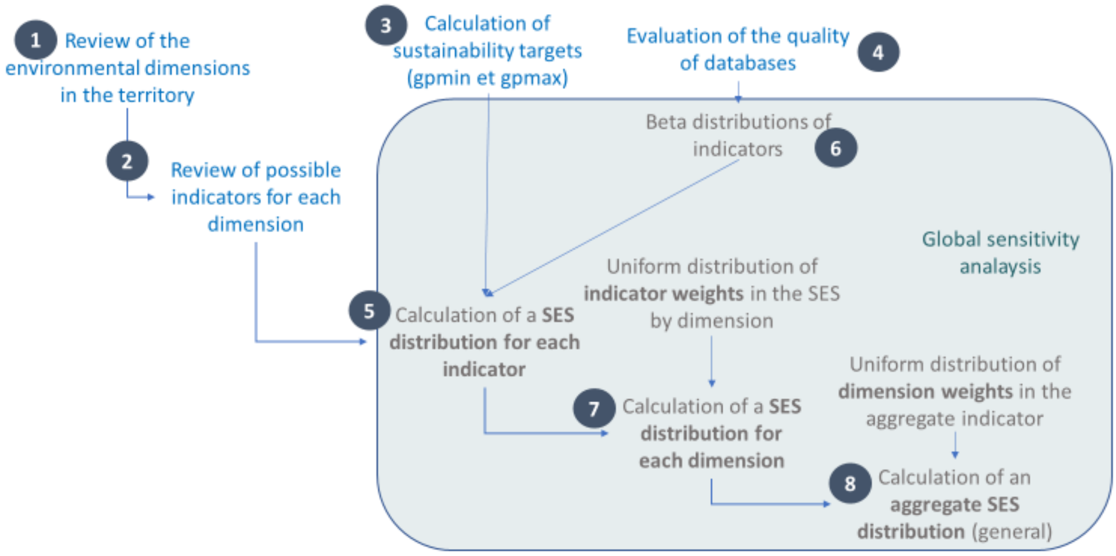

Figure 1: General method used in this study to calculate the ESGAP. The brown steps are parts of the global sensitivity analysis.

Most of these steps have been used in previous studies using ESGAP (refs). The original aspects of our method are (i) the explicitness of the uncertainty associated with the data used and (ii) the explicitness of the evaluator's choices through weightings between the different indicators in the calculation of a dimension or between the different dimensions in the choice of the aggregate indicator (environmental functions or global levels). To assess the influence of the steps involving assessor choice on the uncertainty associated with the data used in the assessment, we perform an overall sensitivity analysis and variance decomposition by calculating Sobol's indices.

The details of each of these steps are detailed in the next sections.

Data collection (steps 1,2,3 and 4)

As the ESGAP framework relies on a quantitative method, the quality of the data is highly influencing the scientific robustness of results. A special focus on this step has been carried out. The data collection was carried out both through an exploration of international and national databases and through a series of 16 interviews with Senegalese actors working in environmental protection and management in Senegal (research centers and ministerial departments) (Table S1).

In particular, step 1 consisted of listing the environmental dimensions addressed in the National Report on the State of the Environment in Senegal (CSE, 2020) and comparing this list to the environmental dimensions listed by Usubiaga et al (Table 1). This dimension was then validated in discussions with stakeholders. Only one dimension was added, namely the herbaceous resource. As part of Senegal is in the Sahelian zone, the natural vegetation found there is savannah or steppe.

Step 2 benefited from previous deployments of the ESGAP method for other countries has enabled an inventory of existing databases. We conducted (i) an inventory of global databases of interest for Senegal to calculate an initial ESGAP, building on previous work (Comte et al., 2021; Fairbrass & Ekins, 2020) and (ii) completed this list of indicators with Senegalese data gathered during the interviews (Table S1). A particularity of our method compared to other studies using the ESGAP is the use of several indicators to inform a dimension of the environment, whereas previous studies only use a single indicator for each dimension. For example, we included salinity in the indicators on land resource management, because soil salinization is a growing phenomenon that affects nearly one million hectares in Senegal (Fall & Diagne, 2008), and fertility losses in agricultural land (CSE, 2020). All data used in this study were publicly available.

Step 3 consisted of taking the sustainability objectives for each of the indicators from the scientific literature, the grey literature including policy documents. For most of the indicators available to inform the ESGAP in Senegal, it is however not possible to set sustainability objectives in the absence of local public policy documents. In that cases, the sustainability objectives are set according to the authors' judgements (See Table 2). This step is the only step in which not all sustainability objectives for each indicator were systematically studied. The way in which the differences between the political, scientific objectives are addressed raises questions about the legitimacy of these objectives, which is not the subject of this paper. Very few locally defined regulatory or scientific objectives are available for the ESGAP functions in Senegal. Only groundwater and surface water pollution are subject to a numerical threshold not to be exceeded. These objectives are based on the methodology proposed by UN Water and set by the Senegalese Normalisation Agency (ASN) and the Water Resources Management and Planning Directorate (DGPRE). Some of the environmental objectives used come from public policy documents (See Table 2). For the Ozone-depletion substances dimension, Senegal by ratifying the Montreal Protocol, the Vienna Convention and the Kigali Amendment has committed to completely eliminate its consumption of hydrochlorofluorocarbons (HCFCs) by 2030 (Contribution Déterminée Nationale 2020).

The evaluation of the quality of the databases carried out in step 4 followed the method of Fairbrass et al. (2020) by adding three evaluation criteria. The Faibrass method consists of evaluating the frequency of updating, the date of the last update, the spatial coverage and the spatial resolution of each database over 3 points. The 3 criteria that have been added are the accuracy of (i) the data source, (ii) the method used to calculate the indicator in the case of secondary data and (iii) the use of a method based either on the data or on the opinion of several experts, or on the opinion of a limited number of experts. This last criterion is assessed out of 6 points in order to counterbalance the scores obtained for the two previous criteria. Thus, a database built on the opinion of a single expert who has specified his source and method (expression of his opinion) has the same score as a database built with data without specifying either the source or the method. The evaluation criteria are specified in supplementary information.

Table 1:Description of indicators used in the SES index

Fonction	Theme	Indicator	GPmin	GPmax	Unit	Source
Source	Forest resources	Fellings/net anual increment	1	0	-	(CSE, 2020)
		Deforestation/reforestation	70	0	-	(FAO, 2020)
		Percentage of non-exploited forest	0	100	%	(FAO, 2020)
		Percentage of naturally forested area actually forested	0	100	%	(Laestadius et al., 2011)
	Fish resources	Fish stock within safe biological limits	0	100	%	FAO-FISHSTAT
		Proportion of under and moderately exploited stocks	0	1	-	(Coll et al., 2016)
	Freshwater	Inland renewable water resources/capita	1700	5000	m3/cap	(World Bank, 2022)
		Inland renewable water resources/capita	1700	5000	m3/cap	LPSD 2015-2025
		Inland renewable water resources/capita	1700	5000	m3/cap	AQUASTAT
		Inland renewable water resources/capita	1700	5000	m3/cap	DGPRE 2017-2018
		Freshwater withdrawal as % of available freshwater resources	25	0	%	(World Bank, 2022)
		Freshwater withdrawal as % of available freshwater resources	25	0	%	DGPRE 2017-2018
		Water Debt Repayment Time	1	0	-	(Tuninetti et al., 2019)
	Groundwater	Groundwater bodies in good quantitative status	-	-	-	No data
	Soil Resources	Surface with tolerable soil erosion	0	100	%	(Panagos et al., 2022)
		Wind erosion: area of land highly susceptible to wind erosion	0	100	%	(CSE, 2020)
		Water erosion: area of land degraded by water erosion	0	100	%	(CSE, 2020)
		Surfaces not affected by soil degradation	0	100	%	(CSE, 2020)
		Surfaces not affected by salinity	0	100	%	(CSE, 2020)
Sink	GHG	Per-capita CO2 emissions	2.5	0.5	t CO2/cap	(European Commission. Joint Research Centre., 2022; Huppmann et al., 2019)
		Per-capita GHG emissions	7.9	5.9	t CO2eq/cap	
	ODS	Consumption of ozone depleting substances			t ODS	(UNEP, 2022)
	Ozone pollution	Cropland and forest area exposed to safe ozone levels	-	-	-	No data

	Pollution by heavy metals	Ecosystems not exceeding the crititcal loads of cadmium/lead/mercury	-	-	-	No data
	Eutrophication	Ecosystems not exceeding the critical loads of eutrophication	-	-	-	No data
	Acidification	Ecosystems not exceeding the crititcal loads of acidification	-	-	-	No data
		Percent of country area not exceeding the critical load of acidification	0	100	%	(Dentener et al., 2006)
		Deposition of inorganic nitrogen / sulphur dioxide and sulphate	-	-	-	No data
	Surface water pollution	Surface water bodies in good chemical status	-	-	-	No data
		Surface water bodies in good chemical status	-	-	-	No data
		Proportion of bodies of surface water with good ambient water quality	0	100	%	Suivi ODD 6.3.2 Surface water
	Groundwater pollution	Groundwater bodies in good chemical status			No data	No data
		Proportion of groundwater with good ambient water quality	0	100	%	Suivi ODD 6.3.2 Groundwater
	Marine pollution	Coastal water bodies in good chemical status	-	-	-	No data
	Terrestrial ecosystems	BII			-	(Hudson et al., 2017)
		RLI			-	(IBAT, 2022)
		MSA			-	(Schipper et al., 2020)
	Marine ecosystems	Coastal water bodies in good ecological status	-	-	-	No data
		Proportion of marine protected areas				(CSE, 2020)
		Proportion of marine protected areas				(IUCN & UNEP-WCMC, 2020)
		Proportion of marine protected areas				(Deme et al., 2021)
	Freshwater ecosystems	Surface water bodies in good ecological status	-	-	-	No data
Human health and welfare	Outdoor air pollution	Population exposed to safe levels of PM2.5	-	-	-	No data
	Indoor air pollution	Population using clean fuels and technologies for cooking	0	100	%	(World Health Organization, 2016)
	Drinking water pollution	Samples that meet the drinking water criteria	-	-	-	No data
	Bathing waters	Recreational water bodies in excellent status	-	-	-	No data
	Natural and mixed world heritage sites	Natural and mixed world heritage sites in good conservation outlook.	0	100	%	(Osipova, 2020)

Constructing the SES indicator (steps 5)

In step 5, the method used to calculate the Strong Environmental Sustainability (SES) index is derived from the recommendations provided by Usubiaga-Liaño & Ekins (2021b). The SES is calculated as the difference at one point between the current value of the indicator and sustainability targets. The upper bound of sustainability targets is the gpmax, which is the level above which improvement of the indicator does not change the environmental function associated and the lower bound is the gpmin which is the most degraded level acceptable for the indicator. States of the environment with higher levels than the target are cap to gpmax and ones with lower levels than the most degraded level acceptable are cap to gmin. (See Table S3 for a complete description of the gmin and gmax of each indicator).

The indicator ($value$) is then normalized (norm) between 5 ($norm_{min}$) (not zero because the 0 score of an indicator would influence to much the geometric average computed in the aggregation process) and 100 ($norm_{max}$) as follows:

$$SES = norm_{min} + (norm_{max} - norm_{min})\frac{value - gp_{min}}{gp_{max} - gp_{min}}$$

The Global sensitivity analysis (steps 6, 7 and 8)

After informing the SES index in the previous steps, we perform in steps 6 to 8 a global sensitivity analysis (GSA) with the python package OpenTurns (Baudin et al., 2017) to determine the influence of the ESGAP users' choices in the calculation of the aggregate SES indicator in a context of high data uncertainty. The GSA consists of varying the set of parameters subject to uncertainty throughout the range of values that the parameters can take. This allows us to capture the effects of interactions and explore the influence of extreme values taken by variables. Usually, the choice of the indicator used to inform the ESGAP thesis (or the average of the indicators) and the choice of the importance of each dimension in the aggregated index is up to the evaluator. Here we start with no preconceptions about these choices and use the most neutral probability distributions possible to study the impact of these choices on the final ESGAP SES.

The aggregation of the indicators ($SES_{i,t}$) is done by a weighted geometric mean at the different levels of dimensions (step 7), functions and then at the final index level (step 8). Unlike the arithmetic mean, the geometric mean is less sensitive to the highest values.

$$SES = \prod_t \prod_i (SES_{i,t})^{w_i \times w_t}$$

With w_i which is the weight of the indicator in the dimension t, $\sum_i w_i = 1$, w_t which is the weight of the dimension t in the aggregated level and $\sum_t w_t = 1$. Dans le cas où il y a qu'un seul indicateur par dimension, on a $w_i = 1$.

The overall sensitivity analysis includes the uncertainty on (i) the indicators reported in the ESGAP $SES_{i,t}$, (ii) the weight of each indicator in the calculation of the theme (w_i) and (iii) the weight of each theme (w_t) in the aggregate SES indicator.

In step 6, uncertainty associated with each indicator is represented here by beta distributions whose parameters are estimated according to the quality of the database used to calculate the indicator according to the method proposed by (Kennedy et al., 1997). Based on this method, the α, the β and the range endpoints of each beta distribution are defined based on the score obtained during the quality assessment of each database in step 6 (See Table S…). The scores are rescaled between 1 and 5 to match the data quality indicator defined in Kennedy et al. (1997).

Step 7 consists of calculating the average SES per ESGAP dimension by averaging across the possible indicators to represent that dimension. The indicators may be different because they represent different aspects of the same dimension, or because the databases that support them are different. In the first case, it is the uncertainty associated with a choice made by the evaluator, whereas in the second case, it is uncertainty associated with the data. This second case is therefore included in the uncertainty associated with the data and will be aggregated in this category with the uncertainty associated with the quality of the database. We distribute the weights according to a uniform law between 0 and 1 which we scale back to have a sum equal to 1 to have a weighted average. The same method is used for the weights assigned to each theme in the calculation of the aggregated SES indicator.

In step 8, the calculation of the aggregate indicator with different weights assigned to each dimension may seem contradictory to the notion of critical natural capital initially used in previous theoretical papers on ESGAP (Usubiaga-Liaño & Ekins, 2021a). In these studies, each dimension of the environment should be considered equally because each dimension is necessary for the maintenance of the environmental services provided by nature. In this study, we place ourselves in a framework where human and financial resources to maintain this natural capital are limited, as is the case in developing countries like Senegal. The application of ESGAP in an environmental management framework and in a context with limited financial and human resources has led us to propose this non-uniform weighting between the different dimensions of the environment.

Results

Data collection

Resulting from the step 1 and 2, 13 dimensions out of 23 could be calculated, 5 with one indicator and 8 with multiple indicators (Fig.2). This means that for 8 ESGAP dimensions, the evaluator has to choose either between similar indicators but constructed from different databases (e.g. freshwater abstraction versus renewable water quantity is different in the World Bank database compared to the database constructed by the "Direction de la Gestion et de la Planification des Ressources en Eau" (DGPRE) of the Senegalese administration) or different indicators informing different aspects of the same dimension (e.g. percentage of unexploited forest or the ratio between fellings and increment of forest in volume of wood). While the first choice may be based on database quality criteria, the second is largely arbitrary. The proportion of missing indicator is more important for the "Health" function.

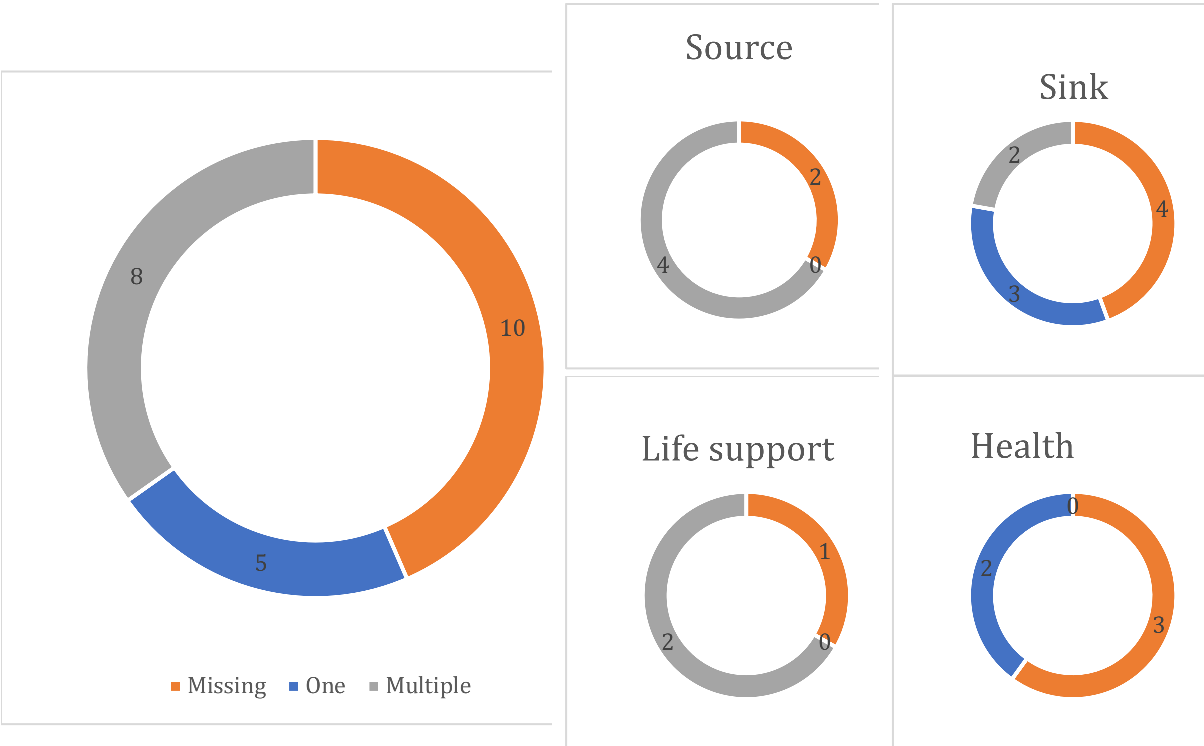

Figure 2: Dimensions of the ESGAP informed by one (orange), multiple (grey) or no indicator (blue) for the total SESI, or per functions

Resulting from the step 3, we get the sustainability objectives (gpmin and gpmax) for the 33 indicators computed in this ESGAP. A detailed description of these objectives is provided in Table 2. Ten targets (gpmin and gpmax) out of the 33 indicators have been found from the scientific literature, while 23 targets were proposed by the authors.

Resulting from the step 4, the databases used to inform the SES index of the ESGAP mostly moderate quality (15) with quality scores between 8 and 16 out of 24. The remaining databases have high quality scores (10) or low-quality score (8). The "source" function is the function with all the bad quality databases.

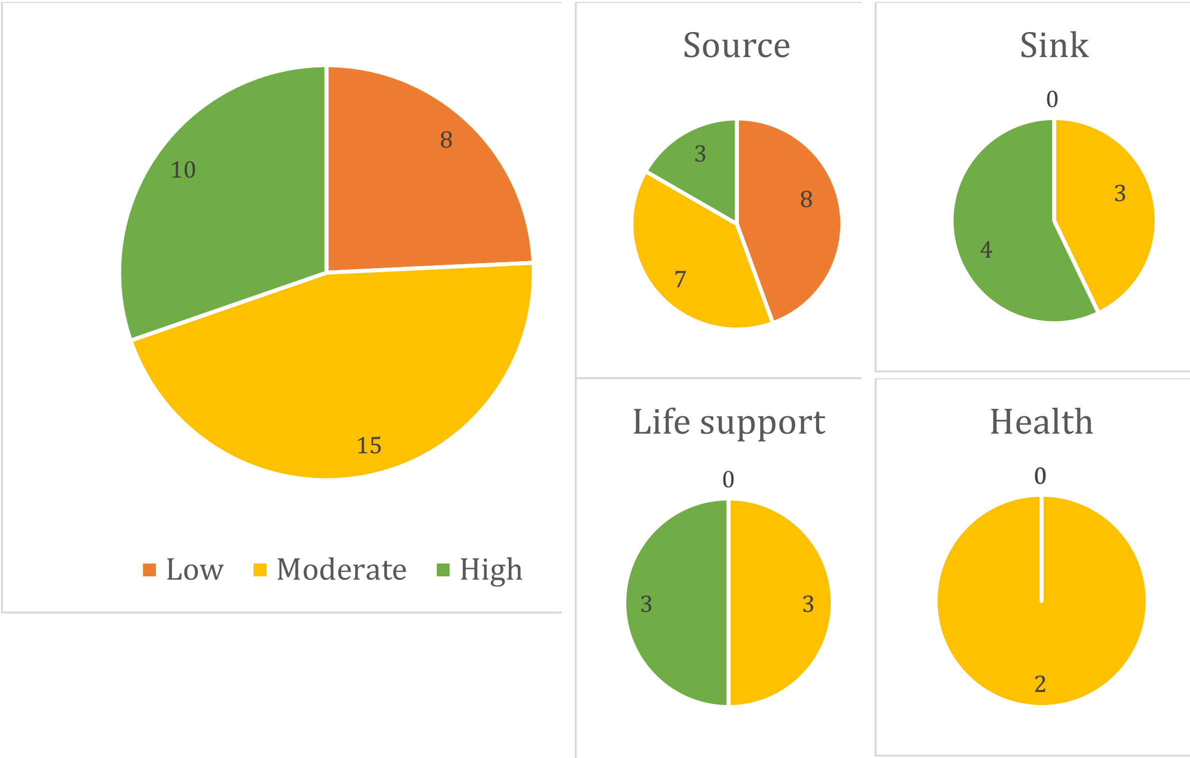

Figure 3: Data quality classification of databases used to compute the SES

SES index

Most SES indicators indicate intermediate level of the environment, 9 of them indicate degraded level (Freshwater water/cap SDG3.1, Water debt, Water stress SDG 3.1, Defor./Refor. Area, Fellings/Increment, Soil degradation, Water quality SDG 6.3.2, surface water pollution SDG) and 9 of them indicate a good level (Freshwater/cap LPSD, % of non-exploited forest, Soil non-eroded by water, Soil not affected by salinity, Soil erosion of ESDA, CO2 emissions/cap, GHG emissions/cap, RLI, BII) (Fig. 4).

The confidence interval is in average around 10% indicating a medium quality of the database. Some indicators have much higher interval confidence as BII, "% fish sust. exploit. FAO", "Water stress SDG6.4.2", "Soil erosion ESDAC" or "'Freshwater/cap LPSD" indicating high uncertainty on these indicators.

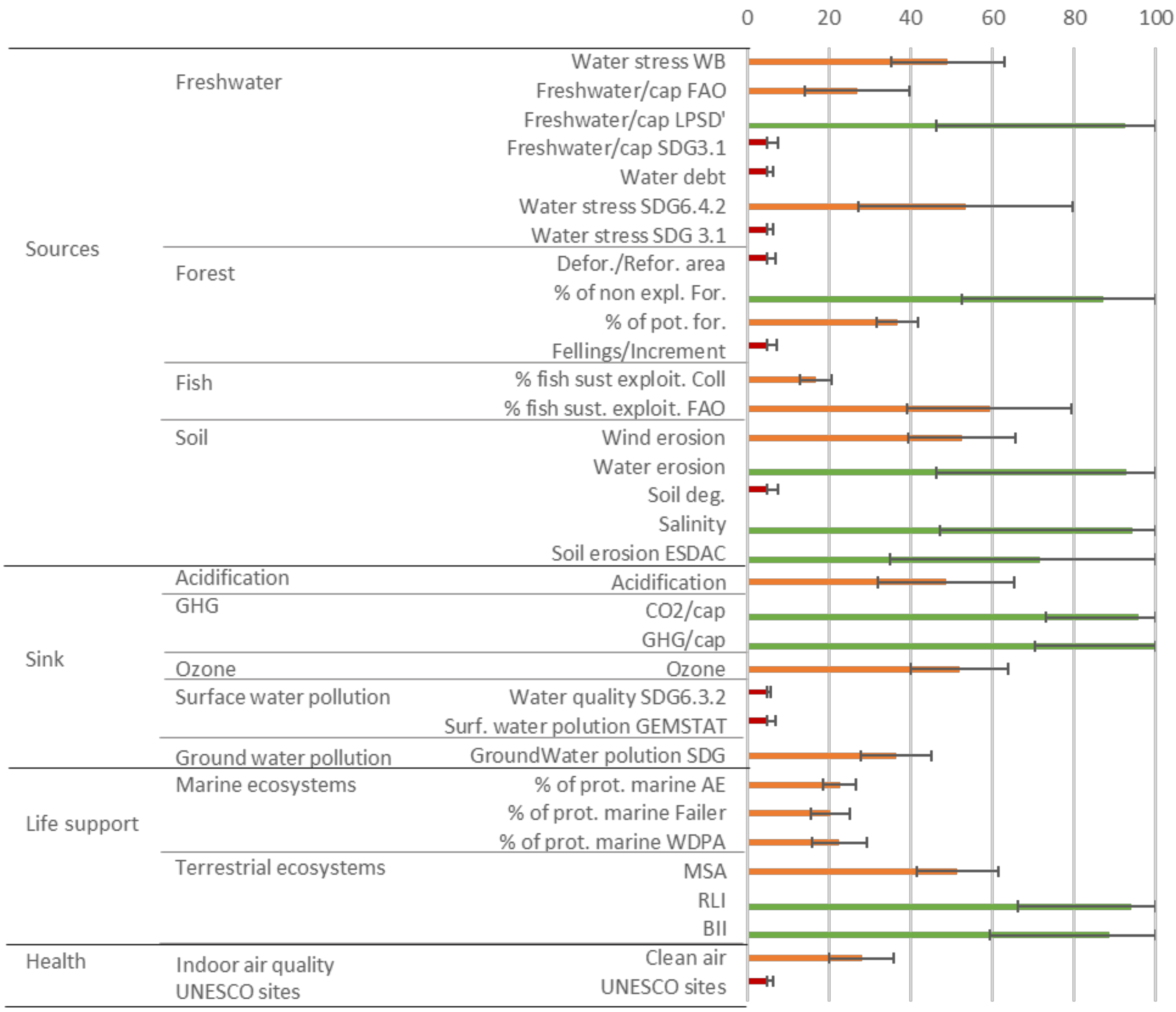

Figure 4: SES index for each indicator grouped by dimensions and resources. A green bar indicates an average SES above 70%, an orange bar an average SES between 10 and 70% and a red bar a SES below 10%. Error bar indicate the confidence intervals of 95%.

Global sensitivity analysis

The SESI aggregated score of Senegal is 40.9 out of a maximum score of 100 (Fig…). The health and welfare function have the lowest score of 11, while the life support function has the highest score of 50. The source and sinks functions have intermediate scores of 30.1 and 29.8 respectively (Fig…). The distribution of the aggregated SES is quite compact, but the distribution of functions is already more spread especially for the life support function.

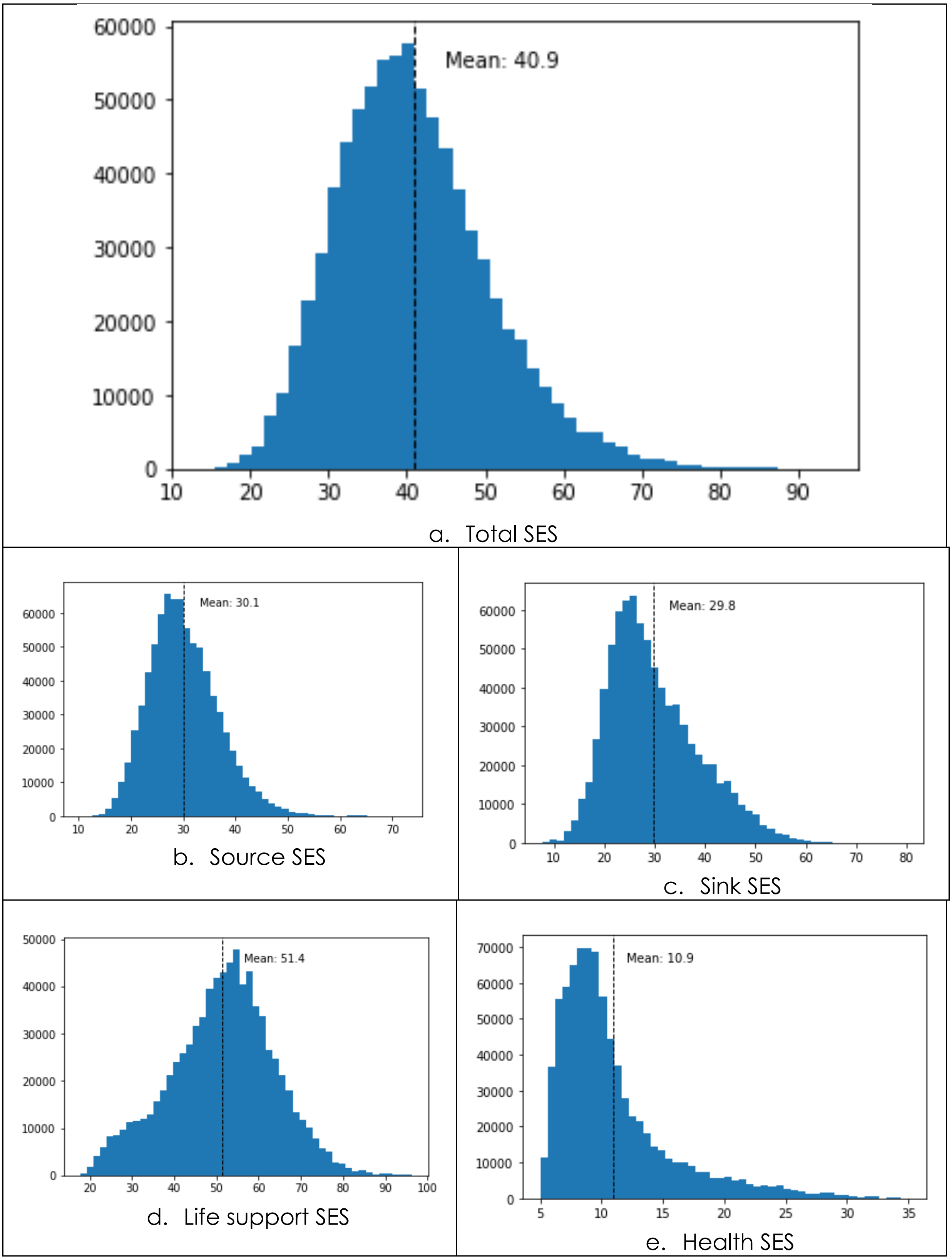

Figure 5: Distribution of the total (a), source (b), sink (c), life support (d) and health (e) aggregated SES index in Senegal.

The decomposition of variance with aggregated Sobol's indices informs us that the majority of the variance in the aggregate indicator comes from the weighting between the environmental dimensions (66% of the variance), followed by the choice of indicator (22%), while the uncertainty associated with the data accounts for only 12% of the variance (Table ...).

Table 1: Sobol's indices and percent of the variability of the aggregated score explained by the uncertainty in the data, the choice of the indicator to represent the theme, the choice of the weight of the theme in the final aggregated indicator

	First order		Total order	
	Sobol's Indices	% of variability	Sobol's Indices	% of variability
Data uncertainty	0.05	7%	0.15	12%
Choice of the indicator	0.08	11%	0.27	22%
Choice of weight	0.60	82%	0.82	66%
Total	0.73	100%	1.24	100%

The variables with the greatest influence on the overall SESI are the weights attributed to terrestrial biodiversity, soil, surface water pollution and the UNESCO site, which account for 9%, 12%, 6% and 7% of the overall first order variability respectively (Fig …). After these highly influential variables, we find the weight in the dimension average of specific indicators with different score than the other variables corresponding to the same dimension. For example, the RLI (94) and BII (88) which have a much higher score than the MSA (51), or the salinity and the water erosion which concern in our data much less land (respectively 6% and 7) than the wind erosion (47%). Finally, the choice of the data source to compute a same indicator can highly influence the general SES variability. For example, the choice of the ESDAC database instead of TrendsEarth or the choice of FishStat data instead of Coll and coauthors data are responsible for 3% of the variability each.

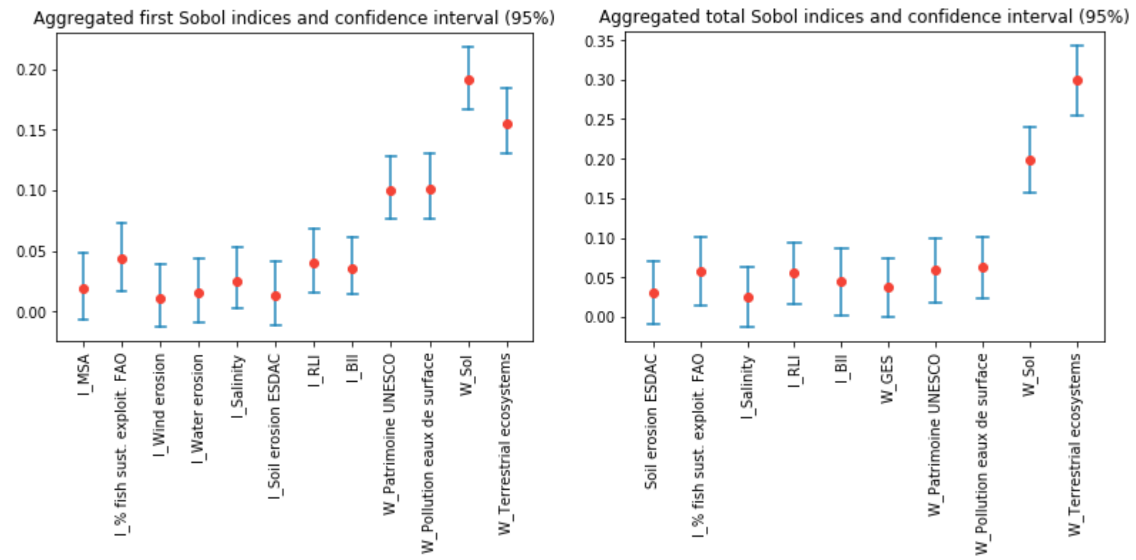

Figure 6: Sobol indices describing the influence of the 10 most influencial variable on the aggregated SES in the global sensitivity analysis. The confidence intervall is obtained by bootstraping (n=1000).

Discussion

Data availability and quality

While environmental data for Europe are in sufficient quantity and quality to inform 22 themes (Usubiaga-Liaño & Ekins, 2021a), this is not the case for Senegal with 13 themes informed. The link between policy and management information systems at the national level has strengthened since the Second World War, particularly in European countries (Umbach, 2020). This desire on the part of Europeans to transplant good governance systems to developing countries has been widely criticized (Malito et al., 2021). It therefore appears necessary to dissociate the development of information systems from the scientific process and to keep the development of information systems under the control of decision-makers. ESGAP allows for the interaction between environmental policy and information systems to be supported, leaving space for policy to appropriate environmental data. In particular, the global sensitivity analysis used in this study highlights the importance of the choice of weights attributed to certain indicators (66% of the variance), the importance of the choice of indicator to inform a specific ESGAP theme (22%) (Table ...) as well as the importance of the choice of certain databases rather than another (6% of the variance due to the choice of database for the state of the soil and fishing stocks). In contrast, the uncertainty contained in certain databases, particularly global ones, with a low level of precision have little influence on the overall SES. This distinction between the sources of uncertainty makes it possible to (i) highlight the importance of the political choices to be made in constructing this type of indicator and (ii) make the indicator more transparent and credible for decision-makers.

In the case of a political choice for the development of the information system, the harmonization of the information system common to several countries can lead to comparisons and competitions between countries on their performance (Cooley & Snyder, 2015). In the case of environmental indicators, this can create a dynamic for environmental protection in the countries that do not perform well. Data can also be used by non-state actors to highlight state failures. The link between policy and data thus directly influences the impact of data on the public policies implemented. In its current version, the ESGAP was constructed by the authors of the study in partnership with the institutions involved in the drafting of the annual environmental report (CSE, 2015, 2020). The development of an interactive ESGAP dashboard would democratise its use and take it out of the hands of the group of experts appointed to produce these annual environmental reports. In its current form, ESGAP thus supports a centralised governance of environmental data.

The assessment of data quality undertaken in this study allowed a qualification of the robustness and accuracy of existing datasets supporting the ESGAP, but it does not inform the challenges associated with institutionalising the use of data in the decision-making process: (i) the politicisation of data and its use, (ii) the transparency and diversity of data and (iii) the objectivity and contestability of data (Umbach, 2020).

The construction of data within an institutional framework can lead to strong political influence on the data producer. Transparency of data is necessary for the assessment of its quality and for the trust that politicians place in the data. Finally, the objectivity of the data can be lost when the politician considers the data purely as a standard without any link to reality, as the so-called neutrality of the numbers crowds out the political aspect of the numbers. An assessment of these challenges could be included in future data quality assessments. It would be particularly relevant in the context of Senegal, where data production is often centralised in institutions dependent on politicians for their resources.

The ESGAP as a tool to confront competing values

We tested the influence of different weight between themes in the overall SES average. From an ecological point of view, each function is necessary to maintain the good ecological status of Senegal. But from a management point in view, resource constraints require decision-makers to make choices between different dimensions of environmental protection. In line with the literature, we show in this study that the weighting greatly influences the results of the aggregated indicator (Gan et al., 2017). Despite the aggregated indicators are not the central indicators of the ESGAP because the aim of this multi-criteria tool is precisely to have a multi-dimensional vision of the environment, we know that policy-makers could use this kind of tool to have an overview of the environment in Senegal and make choices with constraint resources that must balance the environment with other dimensions of sustainable development such as access to food, energy, etc.

In previous ESGAP study, authors made the apparent neutral assumption of equal weight between the dimension of the environment to compute the aggregated average SES index (Usubiaga-Liaño & Ekins, 2021a). In fact, equal weighting between indicators gives more weight to extreme indicators (with low scores for the geometric mean) and to dimensions with few other dimensions reported within the same function. The apparent neutrality is therefore difficult to defend in countries such as Senegal where (i) not all dimensions are filled in and (ii) the dimensions are filled in by uncertain indicators and give varying scores even for the same dimension. This different context led us to study the influence of non-equal weights to reflect different nature values, although this may seem to contradict the notion of critical capital that supports the ESGAP framework.

The influence of the choice of indicators and objectives on the final sustainability score raises the question of environmental values. The latest IPBES report describes a typology of values, including intrinsic, relational, and instrumental values (IPBES, 2022). It also describes methods for valuation of the environment. The ESGAP framework is mostly concerned with ensuring the good environmental state. But this, in a more fundamental way, raises the question of the choice of value to define what is critical natural capital in a specific context. Critical natural capital is originally defined as scientific thresholds, which is then operationalized in the early applications of the

ESGAP in the form of environmental standards based on the scientific literature, and also found in the planetary boundaries. We argue here that this definition should not be (and is indeed not) left to scientifically assigned thresholds. Stakeholders should be able to discuss and define critical natural capital in their context.

The use of scientific estimates of CNC is a mirage, as all norms are negotiated in some ways. For example, one of the most important environmental standard and planetary boundary, the objective of the Paris Agreement to stay well below 2°C of warming by the end of the century, is a constructed norm that required complex exchanges between science and policy (Cointe et al., 2019; Randalls, 2010). While this target is globally agreed, the group of small-island developing states and least-developed countries of the UNFCCC argued that a lower threshold, 1.5°C, is the safe threshold for them (Cointe & Guillemot, 2023). These backs and forths between science and policy is therefore warranted to build meaningful dashboards of indicators on environmental sustainability, at different scales.

As described above, ESGAP allows for the grouping of environmental indicators with different social values. For example, the exploitation of natural resources refers to instrumental values that are associated with material development objectives such as food sovereignty for fisheries or energy self-sufficiency for wood energy. Conversely, the health function refers much more to cultural values. The comparison of these values is then difficult because of the incommensurability of these values and their incomparability (Martinez-Alier et al., 1998).

The ESGAP allows this discussion on commensurability by requiring the definition of environmental objectives to be maintained. Different groups of actors with different sets of values will not consider sustainability in the same way, that will be reflected in the choice of environmental objectives to be set. The incomparability of different environmental dimensions can also be discussed within the ESGAP framework, with the choice of representation of indicators in the dashboard. Different environmental themes that are not comparable can be shown separately, while themes that can be compared can be aggregated with the possibility to adjust their weight in function of their perceived importance.

This tool can therefore be used in a participatory process to discuss, and make groups of decision makers with different values set sustainability targets. It can also be used in different groups to compare different sets of values. These results could then be used to confront priorities towards environmental sustainability following the method suggested in Fig 7.

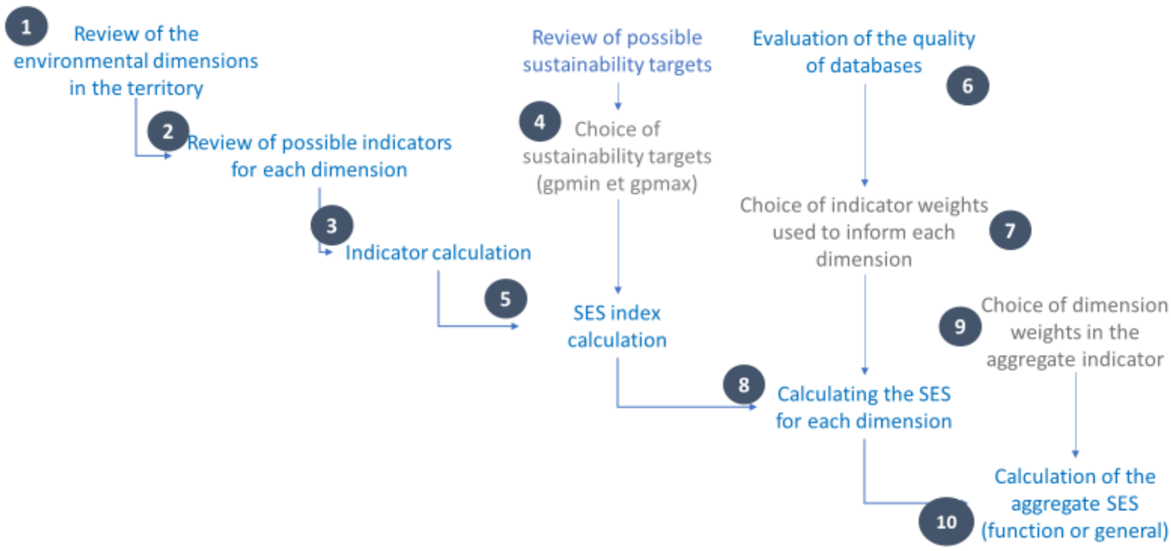

Figure 7: Suggestion of methodology for the use of the ESGAP within a participatory approach

Conclusion

The ESGAP dashboard established in this study confirms that forest management, surface water pollution and the protection of UNESCO sites are three dimensions of the environment in critical condition in Senegal, in line with other studies. In contrast, greenhouse gaz emissions are in good ecological condition. Most environmental dimensions are, however, in a fairly degraded state. These medium degradation state of the environment in Senegal are consistent with what is observed in the countries of the global South and in contrast to the results obtained in the countries of the North where the environment is highly degraded but on an improving trend (Usubiaga-Linao et al., 2021b).

These results can be challenged by (i) the fairly low-quality of data sources (45% and 25% with respectively moderate and low-quality databases), (ii) the lack of consistency between databases to inform a same indicator, (iii) the very different ecological scores of different indicators used to inform the same dimension of the environment and (iv) the application of the ESGAP in a very different context than in Europe where the ESGAP was designed originally with probably different nature values.

Based on a global sensitivity analysis (GSA), we found that the weights of dimensions with low uncertainty and extreme score ('UNESCO sites', 'Terrestrial ecosystems' and 'Soil resources') are highly influencing the aggregated SES index. They are responsible of 66 % of the SES index variability in the GSA. Then the choice between indicators with very different scores to inform one dimension of the environment was the second group of influential variables. For example, the choice between the 'biodiversity intactness index', the 'red list index' or the 'mean species abundance' to inform the 'terrestrial ecosystem' dimension is highly influencing the aggregated SES index because they give different scores (respectively 89, 94 and 51). Finally, the choices between databases given different results for the same indicators are the third influential group of variables. For example, the choice between two data sources to inform the soil resource in Senegal is responsible of significant part of the SES index variability in the GSA. We conclude that participatory approaches to introduce negotiated values in the evaluation of the state of the environment through weights between the dimensions of the environment was highly important, but only for well-informed indicators. Thus, the participatory process and the data gathering are complementary to evaluate a robust and relevant state of the environment.

The deployment of this ESGAP framework in a participatory process has the potential to initiate and foster discussions around the values of the actors involved in environmental management and policy on different dimensions of the environment. This integration of values would make the assessment more robust by adding relevance to the choice of indicator, but above all more legitimate by allowing the people using the ESGAP to take ownership of it, to have confidence in its results and to move beyond predetermined values of the assessors.

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Supplementary Information

1. Experts

Table S1: Experts interviewed to build the ESGAP's indicators

Institution	Expertise
CSE	Environmental data
CRODT	Fisheries
DGPRE	Water quantity and quality
DAMPC	Biodiversity
DPM	Fisheries
Centre de gestion de la qualité de l'air	Air quality
ISE	Biodiversity, Forest management
INP	Soils
ex ANSD	National statistics
ISE	Water quality
DGPRE	Water quality
DPN	Biodiversity
DEEC	
Programme WACA (érosion côtière)	Coastal protection

2. Computation of indicators specific to this ESGAP

Annual GHG emissions

To calculate the greenhouse gas emissions indicator, we used data from 78 1.5C scenarios provided by the Integrated Assessment Modelling Consortium (IAMC). We linearly interpolated between the years 2015 and 2020 where possible (or between the years 2010 and 2020 in the other case) to obtain the 2018 global greenhouse gas emissions (CO2, N2O and CH4) in tons of CO2 equivalent per capita for each scenario. For the SES score, we took as goal post max (gpmax) the minimum of greenhouse gas emissions per capita and as goal post min (gpmin) the maximum of greenhouse gas emissions per capita among the different scenarios. Finally, we used the EDGAR database to obtain per capita greenhouse gas emissions for Senegal, the most recent being 2018.

For the SESP score, we calculated the per capita greenhouse gas emissions for the year 2015 using the same MCAI scenarios (we filled in the gaps for 2015 by taking the 2010 data). We averaged the per capita greenhouse gas emissions across all scenarios and obtained the x0. For the xtr, we used the maximum per capita greenhouse gas emissions among all scenarios for the year 2030.

Percent of the area with deposition above the critical load of natural ecosystem

Total nitrogen deposition is computed for 1996 per grid cell in Senegal (4 grid cell overlay the Senegalese administrative boundaries) based on (Dentener et al., 2006). The gpmin is the product of the critical load of nitrogen in soil (3 mgN.L^{-1} of soil) (Vries & Schulte-Uebbing, 2020) per the volume of soil taken in global soil maps of (FAO & ISRIC, 2012). The gmax is 0 nitrogen deposition.

3. Evaluation of the quality of databases

Table 2: Score of the each dimension of the evaluation process of the databases used in the ESGAP

Fonction	Thème	Base de donnée	Type	Update Frequency	Score	Most recent update	Score	Spatial Coverage	Score	Spatial Resolution	Score	Score total	Qualité
Ressources	Pêche	FAO Fish Stats (SDG)	Mondial	every 2 years	2	2017	2	Région	3	Région (plusieurs pays)	0	7	Moderate
Ressources	Eau Douce	FAO AQUASTAT	Mondial	Same since 2002	0	2002	0	Pays	3	Pays	1	4	Low
Ressources	Sol	ESDAC	Mondial	2001 et 2012	1	2012	1	Pays	3	25km	2	7	Moderate
Ressources	Forêts	FAO FRA 2020	National	Every 10 years	0	2010	0	Pays	3	Pays	1	4	Low
Ressources	Eau Douce	Suivi ODD	National	no update	0	2018	2	Pays	3	Pays	1	6	Moderate
Pollution	GES	EDGAR	Mondial	every year	3	2018	2	Pays	3	Pays	1	9	High
Pollution	SACO	OZONE UNEP	Mondial	every year	3	2020	3	Pays	3	Pays	1	10	High
Pollution	Pollution eaux souterraines	SDG 6.3.2 suivi officiel	National	no update	0	2018	2	Pays	3	Pays	1	6	Moderate
Biodiversité	MSA	GLOBIO	Mondial	every 5 years	2	2020	3	Pays	3	300m	3	11	High
Bien-être	Air intérieur	WHO Stats	Mondial	every year	3	2019	3	Pays	3	Pays	1	10	High
Bien-être	Patrimoine UNESCO	UNESCO	Mondial	tous les 3 ans	2	2020	3	Pays	3	Parc (km)	2	10	High
Pollution	GES	Banque Mondiale	Mondial	every year	3	2018	2	Pays	3	Pays	1	9	High
Pollution	GES	IEA	Mondial	every year	3	2019	3	Pays	3	Pays	1	10	High
Bien-être	Eau potable	UNICEF JMP	Mondial	every 5 years	2	2020	3	Pays	3	Pays	1	9	High
Ressources	Eau Douce	Banque Mondiale	National	no update	0	2019	3	Pays	3	Pays	1	7	Moderate
Ressources	Eau Douce	LPSD	National									0	

Ressources	Sol	Annuaire dégradation des sols : INP	National	no update	0	2008	0	Pays	3	km	2	5	Moderate
Ressources	Sol	Annuaire salinisation : INP	National	no update	0	2008	0	Pays	3	km	2	5	Moderate
Ressources	Sol	Annuaire érosion éolienne : Eros Data Center	National	no update	0	1986	0	Pays	3	km	2	5	Moderate
Ressources	Sol	Anuaire érosion hydrique : CSE	National	no update	0	2005	0	Pays	3	km	2	5	Moderate
Pollution	Pollution eaux de surface	SDG 6.3.2 suivi officiel	National	no update	0	2018	2	Pays	3	Pays	1	6	Moderate
Biodiversité												0	
Biodiversité												0	
Biodiversité												0	
Pollution	Eau potable	Revue nationale volontaire ODD	National	every year	3	2017	2	Pays	3	Pays	1	9	High

Table 2: Uncertainty distribution parameters per SES indicator

Fonctio n	Thème	Base de donnée	Indicator	Score total	Score Kennedy	Alp ha	Be ta	Lowe bound	Upper boun d

Ressources	Eau Douce	FAO AQUASTAT	Inland renewable water resources/capita	7	1,4	1,0	1,0	14,0	39,7
		LPSD 2015-2025	Inland renewable water resources/capita	5	1,0	1,0	1,0	46,2	100,0
		SDG3.1	Inland renewable water resources/capita	6	1,2	1,0	1,0	5,0	7,4
		World Bank ODD 3.1	Inland renewable water resources/capita	16	3,3	1,3	1,3	5,0	6,4
		World Bank ODD 6.4.2	Freshwater withdrawal as a proportion of available freshwater resources	16	3,3	1,3	1,3	35,1	63,0
		SDG6.4.2	Freshwater withdrawal as a proportion of available freshwater resources	6	1,2	1,0	1,0	27,3	79,7
		Tuninetti et al	Water Debt Repayment Time	15	3,1	1,1	1,1	5,0	6,5
	Forêts	FAO FRA 2020 Def./Ref.	Deforestation/reforestation	10	2,1	1,0	1,0	5,0	7,0
		Rapport sur l'état de l'environnement 2020	Fellings/net anual increment	9	1,8	1,0	1,0	5,0	7,2
		Global forest watch	Forested area as a proportion of potential forest area	23	4,8	4,3	4,3	31,8	41,8
		FAO FRA 2020	Percentage of non-exploited forest	10	2,1	1,0	1,0	52,6	100,0
	Pêche	FAO Fish Stats	Fish stock within safe biological limits	13	2,7	1,0	1,0	39,1	79,5
		Coll et al. 2016	Proportion of under and moderately exploited stocks	19	3,9	2,4	2,4	13,0	20,7

	Sol	ESDAC	Surface with tolerable soil erosion	4	0,8	1,0	1, 0	35,1	100,0
		Annuaire sur l'état de l'environnement 2018	Surfaces not affected by salinity	5	1,0	1,0	1, 0	47,1	100,0
		Annuaire sur l'état de l'environnement 2018	Surfaces not affected by soil degradation	5	1,0	1,0	1, 0	5,0	7,5
		Annuaire sur l'état de l'environnement 2018	Area of land degraded by water erosion	5	1,0	1,0	1, 0	46,4	100,0
		Annuaire sur l'état de l'environnement 2018	Area of land highly susceptible to wind erosion	17	3,5	2,0	2, 0	39,4	65,6

Pollution	Acidification	Dentener et al. 2006	Area of the country not exceeding the critical load of acidification	13	2,7	1,0	1,0	32,1	65,3
	GES	EDGAR	Per-capita CO2 emissions consistent with global climate targets	18	3,7	2,2	2,2	72,9	100,0
		EDGAR and IAMC1.5explorer	Per-capita GHG emissions	15	3,1	1,1	1,1	70,5	100,0
	Ozone	Ozone Secrétariat (UNEP)	Consumption of ozone depleting substances	19	3,9	2,4	2,4	40,1	63,8
	Pollution eaux de surface	SDG6.3.2 Surface water	Proportion of bodies of surface water with good ambient water quality	21	4,4	3,4	3,4	5,0	5,9
		GEMStat surface	Surface water bodies in good chemical status	12	2,5	1,0	1,0	5,0	6,9
	Pollution eaux souterraines	SDG6.3.2 Groundwater	Proportion of groundwater with good ambient water quality	18	3,7	2,2	2,2	27,7	45,0
Biodiversité	Marine ecosystems	Annuaire sur l'état de l'environnement 2018	Proportion of marine protected areas AE2018	21	4,4	3,4	3,4	18,5	26,8
		Failler et al 2020	Proportion of marine protected areas Failler	18	3,7	2,2	2,2	15,5	25,1
		WDPA World Database on Protected Areas	Proportion of marine protected areas WDPA	15	3,1	1,1	1,1	15,9	29,2
	Terrestrial ecosystems	PREDICTS database	BII	14	2,9	1,0	1,0	59,4	100,0
		GLOBIOweb explorer	MSA	20	4,2	3,2	3,2	41,6	61,3
		IBAT Database	RLI	15	3,1	1,1	1,1	66,3	100,0

Bien-être	Air intérieur	WHO Stats	Population using clean fuels and technologies for cooking	16	3,3	1,3	1,3	20,0	35,9
	Patrimoine UNESCO	IUCN World Heritage Outlook	Natural and mixed world heritage sites in good conservation outlook.	16	3,3	1,3	1,3	5,0	6,4