Mapping indicators of food security, human well-being, ecosystem services, and climate solutions in Senegal

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Since its inception nine years ago, Feed the Future Innovation Lab for Collaborative Research on Sustainable Intensification (SIIL) has advanced agricultural practices to improve crop yields and livestock production across 13 countries sustainably. The research and on-the-ground leadership have resulted in data-driven strategies combined with pragmatic recommendations to foster local adaptations and wider adoption. A fundamental assumption underlying these efforts is that increased yield is the most effective lever for decreasing hunger and malnutrition.

Although SIIL takes a systems approach to "integrating socio-economic and biophysical innovations" in agricultural production, a more holistic view of the food system can assure that agricultural interventions are positioned to improve people's lives. Other essential aspects of human well-being that constrain food security include income, access to electricity and clean water, adaptation to climate change, and the benefits of natural capital. The needs are great. For example, the World Bank estimates that in sub-Saharan Africa, 34% of the population lives in poverty, 22% are undernourished, 71% are without access to electricity in rural areas, 66% lack access to basic sanitation, and 187 deaths per 100,000 are attributed to poor household air quality. With a more holistic view of the food system, these challenges can be addressed.

Climate change is a--perhaps the--major constraint to improving human well-being. Droughts and shifts in the rainy season decrease agricultural production and water availability and increase stress on people's physical and mental health. The problem continues to worsen. Guided by national governments, USAID, and many additional partners, countries are developing and implementing plans for low-carbon development to grow their economies and improve lives.

To help fulfill SIIL's mission of "integrating socio-economic and biophysical innovations" of the food system, we developed about 50 data products to help guide funding for which strategies and places will do the most good and meet the greatest needs. These high-resolution spatial data products map indicators of human well-being, climate solutions, and ecosystem services.

Mapping human well-being

Climate change has already adversely impacted the health of populations globally. Climate solutions like clean cooking fuels, community-scale solar, and agroforestry benefit both climate and people. To identify places where climate solutions could do the most good, we used demographic and geospatial data to map indicators of food security, land tenure, income and wealth, and access to electricity, clean cooking fuels, and clean water.

Mapping climate solutions

Clean cooking

Unclean cooking fuels—coal, charcoal, and biomasses— reduce air quality, a leading cause of premature deaths. Clean cooking fuels—electricity, natural gas, biogas, and solar—are a powerful climate solution, reducing household and climate pollutants, and are better for health. However, only about 25% households in Senegal have access to clean fuels. Based on a published model, we found that switching to clean fuels could reduce premature deaths by 7,000 each year, save 0.75 - 1.75 hours spent seeking firewood per household per day, and reduce the climate impact of black carbon from dirty fuels by 5 Mt CO_2-eq emissions (and the associated deforestation and degradation) per year.

Access to electricity

Access to electricity is crucial for improving food security, health, clean water access, income, education, and gender equity. About 57% of people living rural communities in Senegal lack access to electricity. Mini-grid photovoltaic solar and battery systems can be built faster than grid expansion and avoid future greenhouse gas emissions from electricity generated from fossil fuels. Here, we created a simple model to estimate the design requirements for off-grid solar systems for different community sizes in rural Senegal. The modeled systems are designed to generate enough electricity and storage to provide 1.5 kWh/person/day with a reliability target of 95% of hours annually having their load covered by PV and/or battery. (This assumes a low night-time consumption profile.) These systems may be sufficient to provide enough electricity to power medium- and high-intensity appliances, such refrigerators, washing machines, and air circulation systems.

Agroforestry and Silvopasture

Agroforestry and Silvopasture are practices that incorporate trees and shrubs with crop and livestock farming, Agroforestry diversifies income sources and nutrition, reduces heat stress for livestock, provides firewood, and mitigates climate change by storing carbon. Agroforestry is already being implemented in some regions of Senegal where farmers integrate trees alongside crops like millet, sorghum, and maize. Here, we compared published maps of above ground biomass (AGB) to a simple model of AGB associated with these practices to explore potential benefits of their implementation in Senegal.

Mapping ecosystem services

Nature provides a foundation of services critical to maintaining human well-being, particularly for people whose livelihoods depend directly on nature-based activities or who, due to economic insecurity, are more exposed to environmental risks. In order to assess baseline provision of these services, we analyzed the current distribution of six critical functions (pollination, carbon storage, watershed baseflow, sediment retention, nitrogen retention, and phosphorus retention) across Senegal. We then assessed landscape-level impacts of five nature-based climate solutions – three agroforestry practices (agroforestry parkland systems, silvopasture, cashew plantations), habitat restoration, and habitat conservation – on the distribution of ecosystem services across the country. We calculated each climate solution's average ecosystem service impact on each relevant land cover type.

Note: This report has five sections: Human well-being, Clean Cooking, Village-Scale Solar, Agroforestry & Silvopasture, and Ecosystem Services. Each section provides a summary, methods, and results.

Author contributions

PCW and JSG conceptualized and designed the project. RB led the mapping of indicators of human well-being, ADS led the modeling and analysis estimating build requirements for off-grid solar and battery systems, YJ led the analysis for clean cooking and agroforestry. PH, EL, and CN co-led the analysis of ecosystem services. PCW led the project. PCW and JSG collaborated with each of the section leaders. Additional contributors for each section are listed in each section's summary. All authors contributed to the writing.

Acknowledgments
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Human Well-Being

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Summary

- Climate solutions can have significant benefits for people's health, food security, and livelihoods.
- Spatial analysis can help identify where the needs are greatest.
- Here we use demographic and geospatial data to map indicators of food security, land tenure, income and wealth, and access to electricity, clean cooking fuels, and clean water.
- The results can be used to target where climate solutions will have the largest benefit to people.

Introduction

Climate variability and change is projected, and has already begun, to adversely impact the health of populations globally (Black et al., 2008; Funk & Brown 2009; Gasparrini et al., 2017; Patz et al., 2005). Climate solutions like clean cooking fuels, community-scale solar, and agroforestry can provide the co-benefits of improved health and well-being in nearby populations. Identifying areas where these climate solutions could be most beneficial to communities is an important step in implementing solutions to reduce greenhouse gasses and improve the current and future health and well-being of populations.

Using individual-level population survey data can inform the implementation of these solutions by providing insight on local, household, and individual vulnerabilities and strategies used to manage climate risks. The Demographic and Health Surveys (DHS) are nationally representative to the first administrative level and widely used in population and demographic research and policy development. The DHS regularly collect individual-level population and health data in low- and middle-income countries and are spatially referenced to a sampling cluster with a latitude and longitude. However, to improve the understanding of local decision making and support solutions implementation, more disaggregated data are needed than what are currently available from the DHS data.

Responding to the need for more disaggregated population and health data, several studies have explored the use of geospatial modeling to interpolate the DHS data over a

large geographic area (Osgood-Zimmerman et al., 2018; Graetz et al., 2018; Mosser et al., 2019; Bhattacharjee et al., 2019). The DHS program has also employed similar methodology to create their own interpolated datasets (Mayala et al., 2019). In this analysis, we use the methodology outlined in the DHS Spatial Analysis Report 17 to create interpolated maps of health and well-being indicators from the DHS in Senegal in 2019 (Mayala et al., 2019). The goal of these interpolated maps is to use them in conjunction with climate solutions maps of clean cooking, community solar, and agroforestry to identify areas where these solutions could be most beneficial for health and well-being.

Methods

- We chose six variables from the Demographic and Health Surveys to be used as indicators for sanitation, wealth, energy, health, food and nutrition security, and gender equality. Below is an explanation of each variable and our reasoning for using these indicators.

Table 1. Six variables used as indicators of human well-being

Variable	**Explanation**	**Justification**
Households with unfinished floors	This variable reports the main material of the floor, as observed by the surveyor, of a household dwelling. Unfinished floors can include earth-based (dirt, mud, sand), dung-based, unfinished wood, palm, bamboo, broken bricks, adobe, and unfinished stone.	Floor type is a widely-used indicator of household economic status that reflects household resources in addition to income or salary. This indicator is particularly useful in settings where reliable data on household income and expenditures is not available and allows for a more comparable measure of economic status across geographic and social settings (Grace, 2017).
Females within households own land	This variable indicates whether a female in the household owns land alone or jointly.	Gender equality has strong linkages with health and wellbeing. When women own land they are more empowered and are more likely to participate in decision-making within the household (Mishra & Sam, 2016; Behram, 2017).

Children who are stunted	The DHS reports anthropometric measurements for children under age 5, namely height and weight, in terms of z-scores. Height-for-age refers to the difference between a child's height and the median height for a child of the same age and sex. A child with a HAZ value that is equal to or less than -2 is considered stunted.	Stunting in children reflects chronic, long-term undernutrition and potentially indicates that a household is food insecure. Anthropometric measures used to calculate stunting are routinely and widely collected across surveys and can be used to monitor progress on health and food security targets (Black et al., 2008).
Households with piped water	This variable indicates the main source of drinking water for a household. Piped water could include water piped into the dwelling or yard, a public tap, or water piped into a neighbor's dwelling.	Piped water is an indicator of a household's access to improved water quality. Safe drinking water, sanitation, and hygiene are crucial to health and wellbeing. Piped water is also a proxy measure for household income and degree of urbanization (DeSherbinin, 2011).
Households with unclean cooking fuel	This variable indicates the main type of fuel used for cooking in a household. Unclean cooking fuel refers to any coal, charcoal, wood, dung, or crop-based fuel. Note: coal and charcoal are not consistently defined. Some surveys and censuses group charcoal with coal and charcoal with wood.	Cooking fuels are a proxy for indoor air quality. Improved or clean cooking fuels are associated with improved air quality and lower respiratory illness and stunting risk (Shively & Schmiess, 2021).
Households with electricity	This variable reports whether a household has electricity.	Like floor type, access to electricity is a measure of a household's access to pooled resources. It is also an indicator of access to public infrastructure and is linked to improved health and wellbeing (Balk et al., 2005; Davenport et al., 2017).

- All data preparation and analysis performed in R Studio
- Prepare the DHS indicators for interpolation
    - Retrieve most recent survey data (2019) for Senegal from the DHS program website: https://dhsprogram.com/

- The indicators were summarized to each cluster location. The methods by which they were summarized are different depending on whether the variable is at the household or individual level.
- For household level indicators
  - Weighted average of number of "positive" households per cluster
- For individual (maternal or child-level) indicators
  - Weighted average of number of "positive" individuals per cluster
  - Here "positive" refers to a binary variable that flags whether the individual is positive for the variable of interest (i.e. stunted vs not stunted).
- Different DHS recode files for the different variables
  - HR – Household Recode file for household level variables
  - IR – Individual Recode file for maternal variables
  - KR – Children's Recode file for child-level variables
  - The geospatial coordinates were obtained via special permission from the DHS program and are downloaded as shapefiles
- Prepare the covariates for use in the interpolation models
  - Define a set of covariate layers from existing geospatial products. These covariates are correlated with the outcome of interest and can partially explain variation. In most cases, the covariate data layer is the same year as the DHS survey. When possible the covariates were the same as those used in the DHS SAR 17 report.

Table 2: Description of covariates used in this analysis. All data was downloaded from Google Earth Engine except for the Aridity Index. Data layers were retrieved from the most recent full year from the DHS survey. This covariate list is adapted from the DHS program Spatial Analysis Report 17.

Covariate	**Source**	**Temporal scale**	**Date**	**Spatial scale**
Travel time to cities with 50k pop	Global Friction Surface from Malaria Atlas Project https://www.map.ox.ac.uk/accessibility_to_cities/	Static	2019	1km
Aridity Index	CISGAR-CSI https://csidotinfo.wordpress.com/2019/01/24/global-aridity-index-and-potential-evapotranspiration-climate-database-v3/	Annual	2000	1km
VIIRS Nighttime Lights	Earth Observation Group, Payne Institute for Public Policy https://doi.org/10.3390/rs13050922	Annual	2018	500m

Enhanced Vegetation Index	NASA LP DAAC at the USGS EROS center https://doi.org/10.5067/MODIS/MOD13Q1.061	16-day	2018	250m
GPW Population density	NASA SEDAC Gridded Population of the World https://doi.org/10.7927/H49C6VHW	Static	2015	1km
Land surface temperature in the daytime	Global Change Observation Mission (GCOM) https://suzaku.eorc.jaxa.jp/GCOM_C/data/ATBD/ver1/LST-ATBD_2014.pdf	Daily	2018	5km
Land surface temperature in the daytime	Global Change Observation Mission (GCOM) https://suzaku.eorc.jaxa.jp/GCOM_C/data/ATBD/ver1/LST-ATBD_2014.pdf	Daily	2018	5km
Potential Evapotranspiration	TerraClimate doi:10.1038/sdata.2017.191	Monthly	2018	5km
Precipitation	Climate Hazards Group InfraRed Precipitation with Station Data doi:10.1038/sdata.2015.66	10-day	2018	5km

- The covariates were processed in R studio so they had the same spatial reference, projection, extent, and dimensions.
    - WGS projection
    - Cropped and masked to a standardized extent of Senegal
    - Regridded coarser and finer data sets to 5km using bilinear interpolation in R Studio.
- After the DHS variables and covariates have been prepared the corresponding covariate pixel values at each survey cluster point were extract
    - The output of this step is a data table with covariate value at each DHS cluster location and an indicator value for each point (number of rows will correspond to the number of DHS clusters)
- Geospatial modeling approach – The health indicators are interpolated resulting in three stacked generalization ensemble models. The prediction surfaces are generated from these stacked ensemble models are used in the final modeling approach. The result is a predicted surface with pixel-level estimates of each health indicator at a 5km resolution. This approach has been used by several research groups to map HIV, vaccine coverage, breastfeeding, child growth, and education attainment (Dwyer-Lindgren et al., 2019; Mosser et al., 2019; Bhattacharjee et al., 2019; Osgood-Zimmerman et al., 2018; Graetz et al., 2018).

This approach has also been used by the DHS in their own in interpolations and is well documented in their Spatial Analysis Reports (CITE).

o Using the Caret, mgcv, xgboost, glmnet packages in R I fit three submodels. The result of each model is a predictive surface of the health indicator.

- Generalized Additive Model (GAM)
- LASSO
- Gradient Boosting Machines (GBM)
- The results of these models are log transformed so they are all on the same scale.
- Each submodel is fit with the full dataset which will produce the in-sample predictions that will be used as covariates when generating the predictions from the full geostatistical model
- The final modeling approach takes results of these three stacked models (GAM, LASSO, and GBM) and uses them as covariates in a Bayseian geostatistical model.
    - Stochastic partial differential equation approach using INLA (Integrated Nested Laplace Approximation) in R

Results

Descriptive name	**File name**	**Level**	**Resolution**
Floor type – The main material of the floor of a household. Unfinished floor includes a floor with natural or rudimentary materials	Pred_floor_0515.tif	Household	5km
Own land – Indicates whether a woman in a household owns land.	Pred_ownland_0515.tif	Maternal	5km

Stunting – Indicates whether a child is stunted. Stunting is defined using the World Health Organization definition of a Height-for-Age z-score of -2 or below	Pred_stunt_0515.tif	Child	5km
Water – The main source of drinking water for a household. Piped water indicates the water is piped into or outside the residence.	Pred_water_0515.tif	Household	5km
Cooking fuel – The type of fuel used in cooking in the household. Unclean cooking fuel refers to coal, charcoal, wood, dung, or crop-based fuel.	Pred_cook_dirty.tif	Household	5km
Electricity – Indicates whether the household has electricity.	Pred_elec_0515.tif	Household	5km

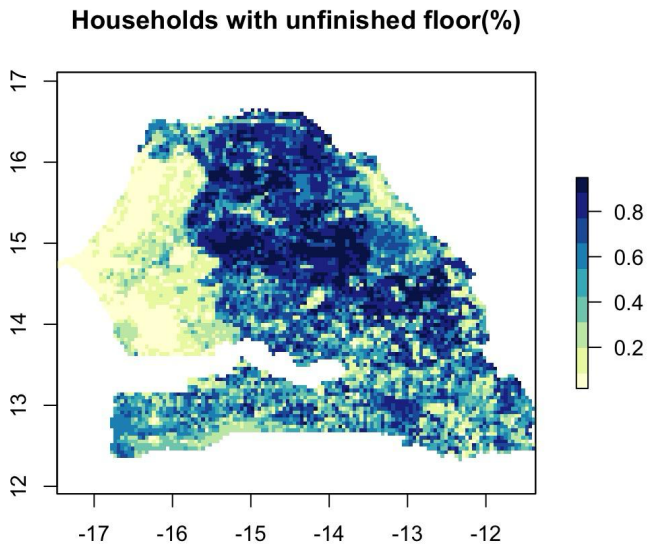

Figure 1: The percentage of households in Senegal with unfinished floors. The scale is indicated as a fraction. The percentage is highest in the central and western areas of the country. Households in the western and coastal areas including major cities, Dakar, Thies, Kaolack, and Saint Louis, mostly have finished floors.

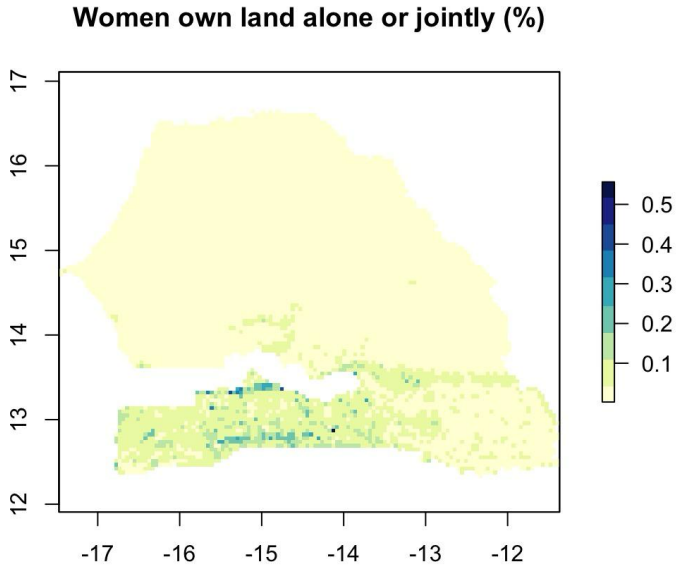

Figure 2: The percentage of women who own land alone or jointly. The scale is indicated as a fraction. The percentage is low throughout Senegal (less than 10%). The highest percentages of households where women own land are found in the southern areas of the country.

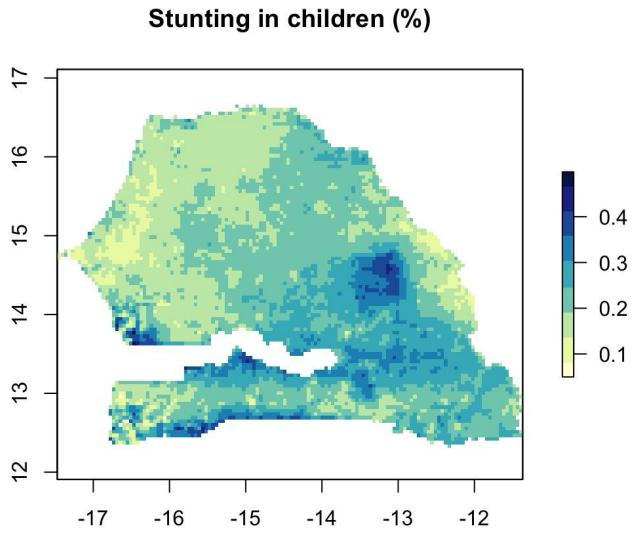

Figure 3: The percentage of children who are stunted in Senegal. The scale is indicated as a fraction. Stunting increases with increasing distance from urban areas like Dakar and Thies. Stunting is highest in the eastern and southern regions of the country.

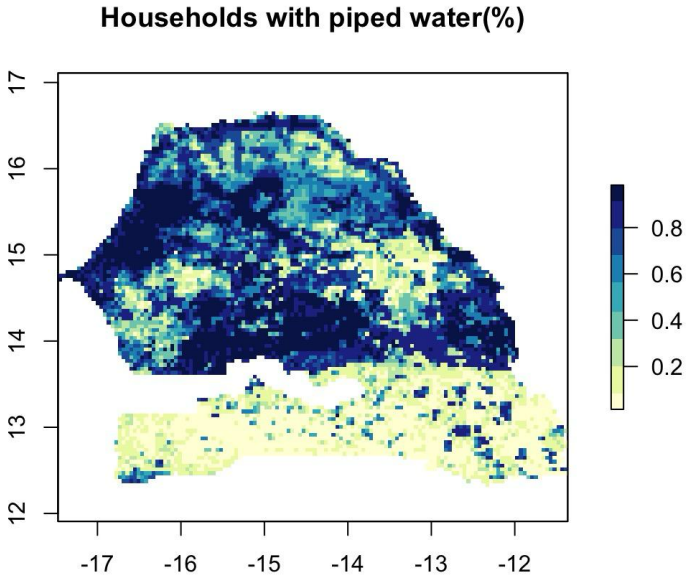

Figure 4: The percentage of households with piped water. The scale is indicated as a fraction. Households without access to piped water are generally concentrated in rural areas in the southern, eastern, and northern regions of the country.

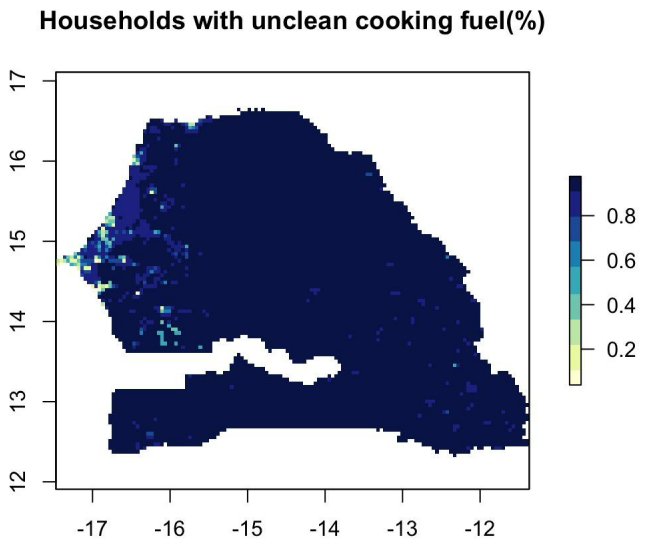

Figure 5: Percentage of households using unclean cooking fuel. The scale is indicated as a fraction.The majority of households in Senegal are using unclean cooking fuels. The percentages are the lowest in western and coastal areas of the country.

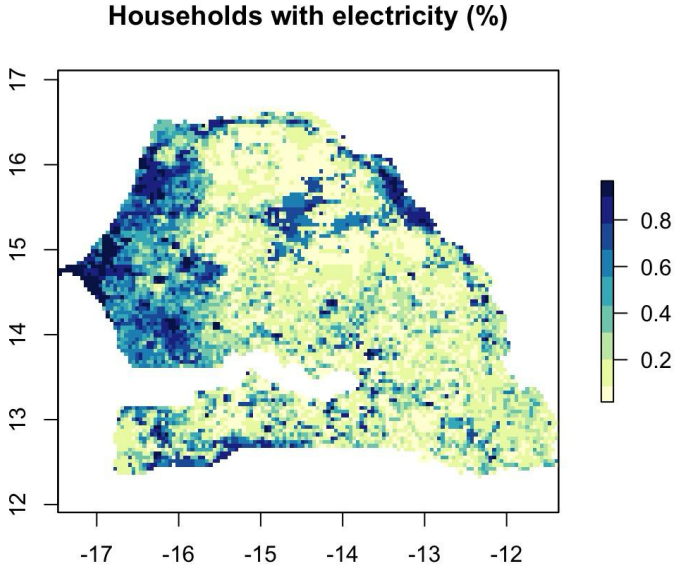

Figure 6: The percentage of households with access to electricity. The scale is indicated as a fraction. Lower percentages are found throughout rural Senegal. The percentage is highest in western and coastal areas of Senegal where households generally have more access to electricity.

Limitations

- Followed the same methodology as DHS SAR 17 and used the same covariates for each variable. There may be covariates that are better suited for each indicator.
- Some variables, especially rare or seasonal, will not be the best candidates for interpolation. For example, additional indicators of health in children like recent cough or acute undernutrition (wasting), occur over short time scales (weeks or month) are not always captured in DHS surveys as such we did not include them in this analysis.
- Cooking fuels are not consistently categorized between surveys. Coal and charcoal are not consistently distinguished. To overcome this we grouped these fuels into a larger category of “unclean” cooking fuels.

Files in repository

All related code and output raster files have filenames that start with “Human-well-being_” followed by:

Code:

pd_dhs_interpolation_0509_2024_floor.R

pd_dhs_interpolation_0509_2024_femaleland.R

pd_dhs_interpolation_0509_2024_stunting.R

pd_dhs_interpolation_0509_2024_water.R

pd_dhs_interpolation_0509_2024_cooking.R

pd_dhs_interpolation_0509_2024_electric.R

Model results:

Senegal_floor_interpolation.tif

Senegal_femaleland_interpolation.tif

Senegal_stunting_interpolation.tif

Senegal_water_interpolation.tif

Senegal_cooking_interpolation.tif

Senegal_electric_interpolation.tif

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Clean Cooking

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Summary

- Incomplete combustion of unclean cooking fuel produces black carbon, which causes adverse health impacts, is associated with time spent gathering fuel, and leads to greenhouse gas emissions.
- In Senegal, only 25% of the population has access to clean cooking.
- Based on a published model, switching to clean fuels in Senegal from the status quo could save more than 5 Mt CO_2-eq emissions per year, with savings of several hours per day for some households.
- The benefits of a transition to clean fuels are over 1 billion USD per year (lead by health benefits), exceeding by a factor of 3 the $300 million USD annual cost of implementing clean cooking solutions.
- The most common clean cooking fuel in a transition to the modeled clean cooking scenario is electricity, followed by LPG (liquified petroleum gas).
- Opportunities for implementing clean cooking solutions are distributed heterogeneously with hotspots in several densely populated cities, suggesting that targeted interventions could have outsized impacts.

Introduction

Unclean cooking fuel (Figure 1) is a significant source of climate pollution and health problems in low- and middle-income countries. Providing clean cooking fuel to households relying on unclean fuel is a powerful climate and human well-being solution. It reduces greenhouse gas emissions and improves the health and the livelihoods of billions of people in low-and middle-income countries.

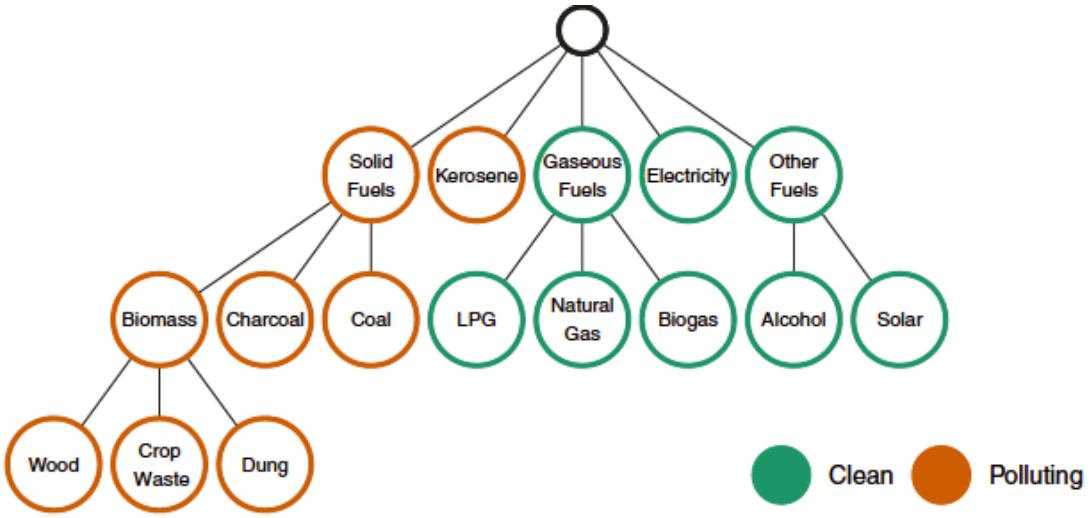

Figure 1: Classification of household cooking fuels as clean (green) and unclean (orange). Reproduced from Stoner et al. 2021.

In Senegal, about 75% of the population currently do not have access to clean cooking fuel. Unfortunately, access to clean cooking fuel has declined in the last 15 years; in 2005, about 60% of the population did not have clean fuel. This decline has resulted from strong demographic growth and the inability of clean cooking efforts to keep up. Implementing clean cooking solutions in Senegal represents a powerful opportunity to reduce greenhouse gas (GHG) emissions and improve the lives of millions of Senegalese.

In this analysis, we first estimate the greenhouse gas emissions from the existing cooking fuel mix in Senegal and identify the emissions hotspots. We then use the recently published OnStove model (Khavari et al. 2023), which relies on socioeconomic and technical conditions across Senegal to identify the clean cooking fuel mix that could result in the highest net benefit for health, climate, and development. We present our results at GADM level 3 boundaries (arrondissement) to provide information at a relevant scale for policymakers to take appropriate actions.

Methods

The analysis relies primarily on household cooking fuel estimates (Stoner et al. 2021) and the OnStove model (Khavari et al. 2023).

We use the household cooking fuel (Table 1) estimates along with data on the fuel efficiency of stove type, emissions factor of fuel, population, and household size to calculate the total GHG emissions from the existing cooking fuel mix in Senegal. We perform two hypothetical analyses where electricity and LPG (liquified petroleum gas) completely replace the existing fuel mix to calculate the potential reductions in GHG emissions after switching to clean cooking fuel.

Table 1: Distribution of clean (green) and unclean (red) cooking fuel in Senegal in 2020. Source: Stoner et al. 2021

	Rural (%)	Urban (%)
Electricity	0	1
LPG	3	34
Charcoal	15	45
Biomass	81	18

We use the OnStove tool to identify a realistic mix of clean cooking fuel that could be implemented (Khavari et al. 2023) right now. Briefly, the OnStove tool (Khavari et al. 2023) is a raster-based tool that evaluates the net benefit of different stoves for countries in sub-Saharan Africa. The tool relies on geographic, socio-economic, and technological data. It identifies the fuel mix that results in the highest net benefit (reduced morbidity and mortality, emissions, time savings, and costs).

For our analysis, we implemented the OnStove model for Senegal. First, we downloaded the Python code from GitHub and the required data to run the model from Mendeley. The GitHub repository provides extensive guidance on downloading, installing, and executing the OnStove tool. Second, we executed the model in Python and obtained the following outputs (Table 2). Finally, we summarized the information at the sub-national level for Senegal using GADM level 3 boundaries to present our findings.

Table 2: Outputs from the OnStove model.

Outputs
Optimum stove mix map
Clean cooking technology usage by % of population
Deaths avoided
Average time saved per household

Greenhouse gas (GHG) emissions avoided
Health and GHG emissions cost avoided.
Opportunity profit

Results

Optimum clean cooking fuel mix for Senegal

The OnStove tool estimates a mix of clean cooking fuel that maximizes health, climate, and economic co-benefits. The tool suggests that in Senegal, electricity is the most beneficial clean source of cooking fuel in 71% of the country followed by LPG and biogas in 19% and 10% of the country respectively (Figure 2). Shifting to these fuels will result in about 5.2 Mtons CO_2-eq of GHG reduction per year.

Electricity is the most beneficial choice of cooking fuel in urban areas. This is unsurprising because Senegal has a high level of electrification in urban areas (95%). In semi-urban areas, both electricity and biogas could serve as fuel. In rural areas, both LPG or biogas could be a clean fuel source. In remote areas, LPG is the only viable clean cooking option.

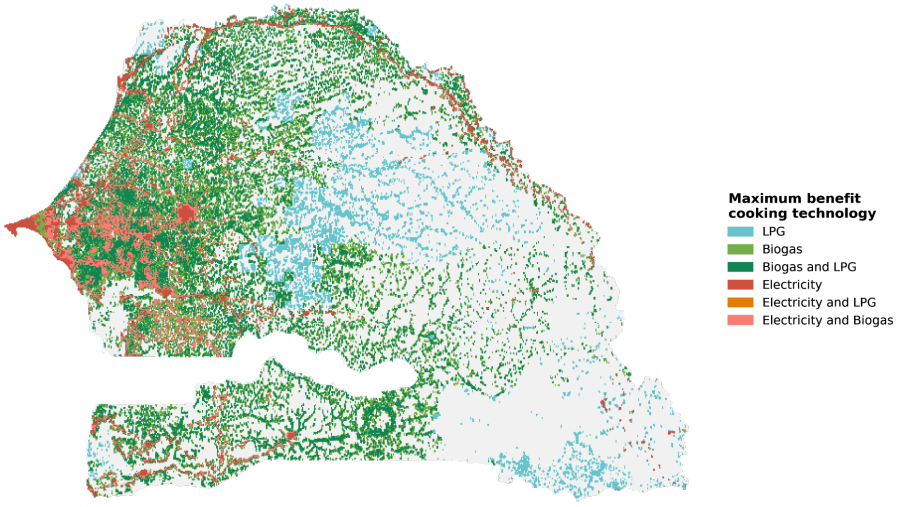

Figure 2: Cooking fuel mix with maximum benefit in Senegal. Source: Khaveri et al. 2023

The annual investment cost to implement the clean fuel mix identified by OnStove is $330 million, including investment costs (such as the cost of new stoves), the cost of the fuel, and operations and maintenance (O&M) costs.

Greenhouse gas pollutants from the cooking sector

There are four major fuel sources in Senegal. Two clean sources (electricity and LPG) and two unclean sources (charcoal and biomass). Charcoal is the most polluting fuel, with about 5.6 Kg of CO_2-eq emitted per household per meal (Figure 3). This is closely followed by biomass with GHG emissions of 4 Kg CO_2-eq per household for each meal. Electricity and LPG are significantly cleaner with GHG emissions lower than 0.5 Kg CO_2-eq per household per meal.

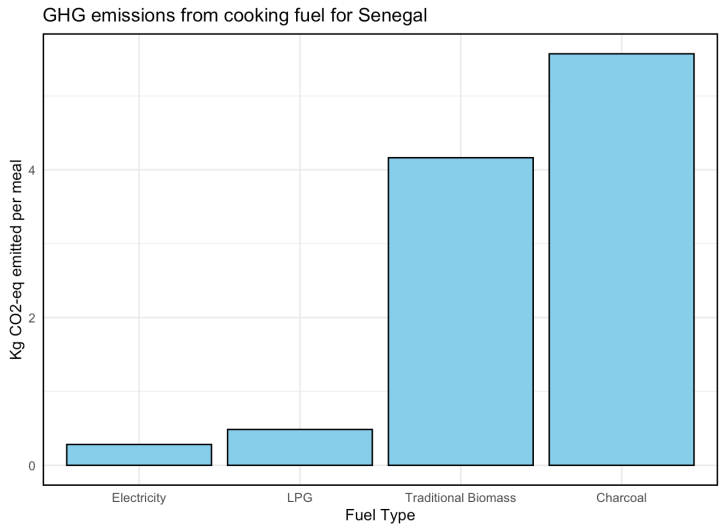

Figure 3: CO_2-eq of black carbon pollution from different fuel sources.

The annual emissions from the cooking sector in Senegal is 6 million tons of CO_2-eq with 3.6 and 2.4 million tons emitted from the rural and urban regions respectively (Figure 4). Biomass and charcoal contribute to over 90% of the total GHG emissions. In rural areas, biomass emissions dominate due to the prevalence of biomass (81%) as a fuel source. In urban areas, charcoal emissions dominate, contributing 70% of total GHG emissions associated with cookstoves. The disproportionate emissions attributable to charcoal in the urban areas are due to its higher emissions per cooked meal.

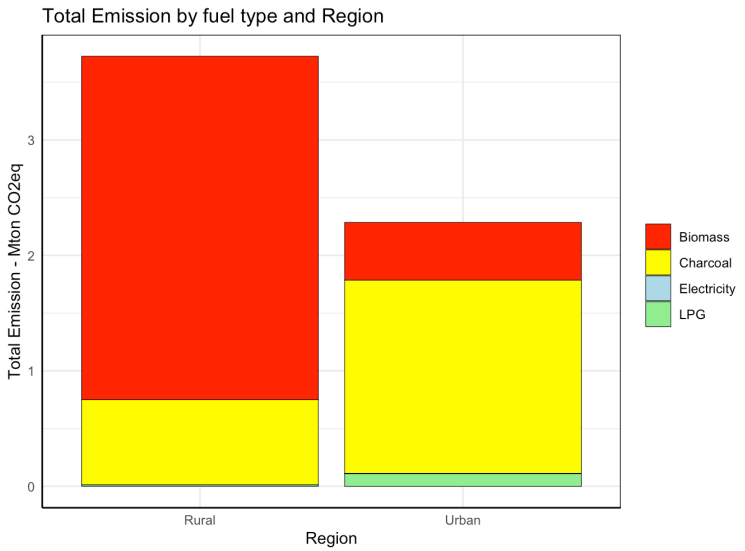

Figure 4: Contribution of different sources to urban and rural GHG emissions from cooking in Senegal.

Emission hotspots

Emission hotspots are located primarily in urban areas due to their high population density. Touba sub-division (French: arrondissement, Figure 5) is the biggest hotspot as it has the highest population among the sub-divisions. The Dakar metropolitan area is the largest hotspot, contributing to about 20% of total emissions. Kolack and St. Louis are other major hotspots.

Rural states in the southeast have the lowest overall emissions among the sub-division due to their low population density. However, their per capita emissions are still high as they rely primarily on unclean fuel sources.

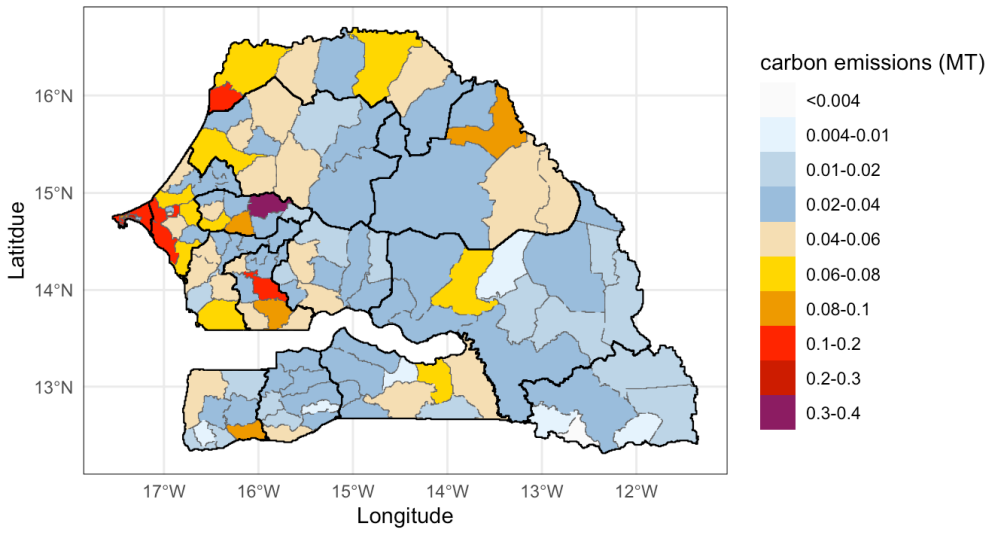

Figure 5: Annual GHG emissions for each sub-division (French: Arrondissement) in Senegal.

Emissions reduction by switching to clean fuel

We evaluated two scenarios: completely switching to electricity or LPG as a cooking fuel in Senegal. The analysis suggests a significant reduction in GHG emissions in both scenarios with more than an 80% reduction from current GHG emissions. The analyses reveal that providing clean cooking fuel could significantly reduce GHG emissions from the cooking sector.

Yet, completely switching to either fuel is challenging. For example, even though Senegal has much better electrification rates than other sub-Saharan African countries, completely replacing the current fuel mix with electricity in the near future in the rural areas would be challenging based on the existing electric infrastructure, and socio-economic challenges such as affordability.

Benefits for Human Well-being

Implementing clean cooking solutions results in several co-benefits (Khavari et al 2023, Jameel et al 2023). Implementing the clean cooking fuel mix identified by the OnStove tool results in prevention of more than 7000 premature deaths each year. The maximum health benefits in terms of lives saved are observed in Touba, Dakar, and St. Louis (Figure 6) due to switching from charcoal and biomass to electricity.

Switching to clean fuel also results in significant time savings. Households relying on biomass could save between 0.75 and 1.75 hours daily (Figure 7). The time saved is much higher in the northern and drier parts of the country. The time saved provides households with the opportunity to engage in economic activities. In households where school-age children are responsible for collecting fuel wood, clean cooking can increase school admissions.

The total monetary benefits from switching to clean cooking translates to approximately $ 1.08 billion for Senegal, the majority of which is due to health benefits from switching to clean cooking. This is almost 3 times the annual investments and cost associated with implementing clean cooking solutions.

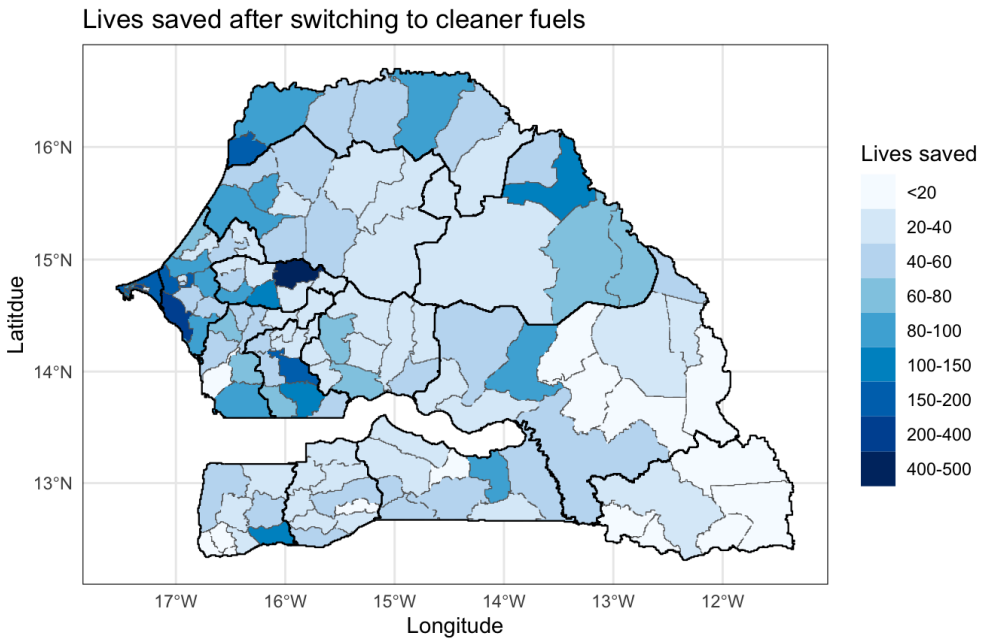

Figure 6: Annual reduction in premature deaths after switching completely to clean cooking fuel.

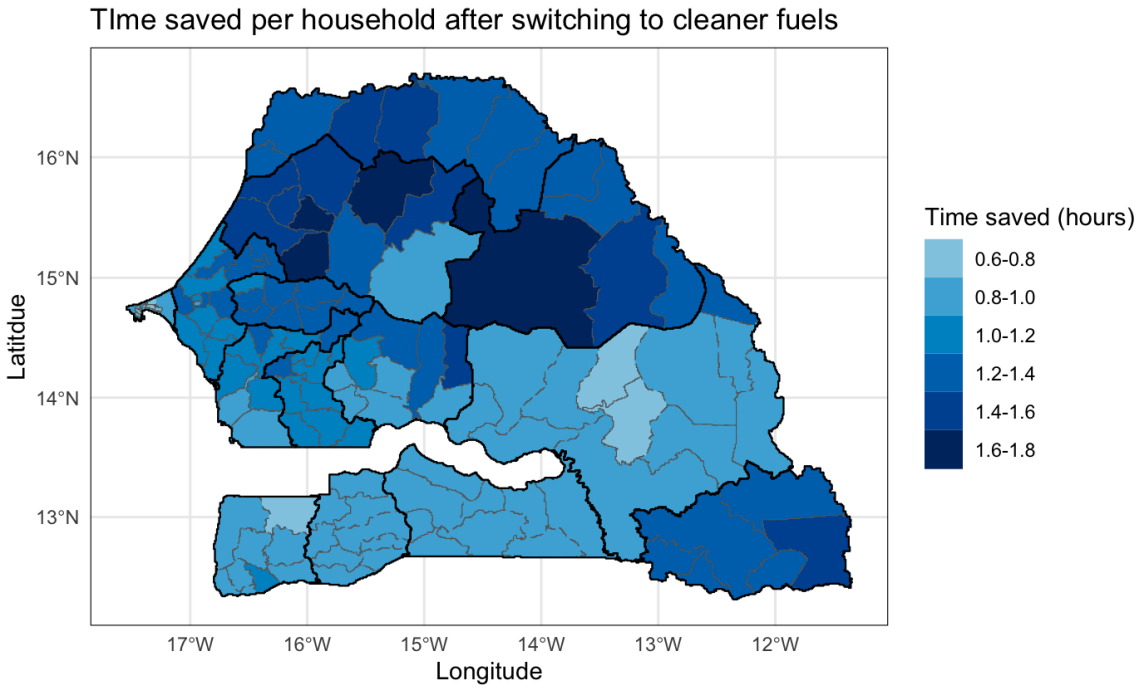

Figure 7: Time saved after switching completely to clean cooking fuel.

Limitations

There are two major limitations to our analysis:

First, the GHG emissions per meal per household from LPG do not include emissions associated with transporting the LPG fuel from production to the point of use. Therefore, our analysis slightly underestimates the actual emissions associated with LPG fuel.

Second, we assumed that the energy required to cook a standard meal per household is 3.64 MJ. This value is used in the OnStove model and is based on an analysis from Kenya. The average energy required to cook a meal per household in Senegal might differ from 3.64 MJ due to differences in cooking pattern and time. It is likely that the energy required to cook a standard meal in Senegal is higher than Kenya because of the larger household size.

Recommended Actions

1. **Sequence regional efforts - begin by focusing on Dakar and Touba for maximum climate and health benefits**: both cities are emissions hotspots and represent the most significant potential for human and climate benefits. Afterward, moving to focus on Kolack and St. Louis and secondary hotspots allows for smaller-scale efforts with outsized impacts.

2. **Sequence fuel efforts - begin by phasing out charcoal in urban areas:** charcoal is the most polluting fuel used in Senegal. Replacing it with cleaner fuels in urban areas can result in significant health and climate benefits. The OnStove model suggests that electricity is urban areas' most impactful clean fuel source. Should subsidies be used again in the future, it may be beneficial to subsidize electricity production instead of fuels such as butane to support a long-term transition. Replacing charcoal with other clean sources such as LPG would also result in large benefits. Policymakers should urgently roll out clean cooking initiatives, using LPG and electricity in urban areas with well-defined targets.

3. **Prioritize clean cooking fuel that results in long-term benefits:** Senegal plans to distribute 800,000 improved clean cookstoves (ICS) annually between 2020 and 2030 (2020 Senegal NDC report). The country aims to double this number to 1.5 million ICS annually with adequate international funding and technological support. While this is a step in the right direction and under the more ambitious scenario, 15 million Senegalese can gain access to ICS between 2020 and 2030, ICS should be seen as a transition solution. Increasingly, research has shown that

ICS's climate, health, and economic co-benefits are limited (Mortimer et al., 2016, Foote et al., 2013) . The OnStove model results demonstrate that Senegal has the infrastructure and capacity to implement advanced cooking solutions such as electricity, LPG, and biogas across much of the country and it should prioritize these fuels in the long-term.

4. **Explore carbon markets and innovative funding mechanisms:** widespread adoption of clean cooking fuel is impossible without access to capital. While Senegal has benefitted with funding and financial support from Green Climate Fund and Clean Cooking Alliance, it needs to urgently utilize the rapidly growing carbon market which has allowed clean cooking companies and carbon project developers to partner and create innovative financial mechanisms to fund clean cooking projects. Nordic Green Bank's Modern Cooking Facility for Africa and Spark+ Africa investment fund are a few examples that have chartered novel pathways to create the financial framework for clean cooking transition.

5. **Establish a national coordinating body:** To achieve universal access to clean cooking by 2030 Senegal needs an annual adoption rate of 10% or more per year. Implementing such high rates of adoption is inherently challenging. It requires coordination between several actors, including ministries, departments, offices, businesses, communities, and other stakeholders. Establishing or strengthening a regular working group as a point of coordination can maximize resources and avoid duplication of efforts.

6. **Strengthen data collection efforts:** clear and reliable data is essential to sequence activities and to impact the most people with the fewest resources. Dedicating a small proportion of human and financial resources to ensure adequate data collection on household fuel usage can ensure policies are unrolled effectively.

7. **Identify and deploy low-cost public education efforts:** building awareness of the importance of clean cooking is a critical hurdle in transitioning. Partnering with women's groups, markets, theater troupes, students, and other volunteers may be a low-cost and effective way to educate the public on the need for clean cooking solutions - especially in rural areas.

Files in repository

All related code and raster files have filenames that start with "Clean-cooking_" followed by:

Code:

Senegal clean cooking analysis.Rmd

Model results:

Annual GHG emissions from different fuel mix.xls

Emissions per meal for different fuel.xls

Annual_GHG_emission.tif

Avoided_death.tif

GHG_emissions_electric.tif

GHG_emissions_LPG.tif

GHG_emissions_max_benefit.tif

Time_saved.tif

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Village-Scale Solar

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Summary

- Access to electricity is critical for improving food security and many other aspects of human well-being.
- Here, we created a simple model to estimate the design requirements for off-grid solar systems for households, hamlets, small settlements, and built-up areas in rural Senegal.
- The modeled systems are designed to generate enough electricity and storage to provide 1.5 kWh/person/day with a reliability target of 95% of hours annually having their load covered by PV and/or battery. (This assumes a low night-time consumption profile.)
- Depending on the number of individuals in a household, and whether or not some appliances are shared among households, 1.5 kWh/person/day may be sufficient to provide enough electricity to power medium- and high-intensity appliances, such refrigerators, washing machines, and air circulation systems.
- While we estimate the design requirements here, the model is intended to be used as a starting point and, where data are available, be revised based on local climate, electricity demand, products, and costs.

Introduction

- Access to electricity is strongly linked to improved income, which is a leading indicator of food security.
- Access to electricity also improves food security by enabling the use of equipment and products for milling, processing, storing, and transporting food.
- Access to electricity is also linked to access to clean water, and improvements in health, education, and gender equality.
- 57% of the rural population in Senegal lacked access to electricity in 2019 (IEA et al. 2023)
- Off-grid solar installations can be implemented faster than waiting for grid expansion

- USAID, The World Bank, and other institutions are investing in communities and private companies to install off-grid solar systems

Methods

The following steps were used to create the model in the code notebooks based on the assumptions listed below.

- Research most likely PV array type and battery type by location (Senegal, or Africa in general) and cost.
- Use hourly load profile developed by Huld et al. (2017) and scale according to the number of people by:
    - Calculating the total electricity consumption per day in the load profile.
    - Estimating the electricity consumption per day per person for a microgrid consumer.
    - Scaling according the population for a variety of settlement sizes:
        - 8 people (average household size)
        - 25 people
        - 50 people
        - 500 people
        - 1000 people
        - 1500 people
        - 3000 people
    - Settlement categories and population estimates were based on a settlement dataset developed by Esri (2024). The UN estimates that the average household size is eight people (UN 2019).
- Use PVWatts to model electricity produced by the PV system using Dakar International solar radiation data in kWh per hour.
    - The 8 person system is modeled as rooftop PV with a 15 degree angle.
    - All larger system sizes modeled as ground-mounted PV with a 15 degree angle.
- Verify that PVWatts electricity production data (AC output) will scale with the size of the PV system in kWp (kW peak).
- Create a battery model in code and assign a simple charge/discharge algorithm to the battery, enforcing its maximum depth of discharge and rates of charging/discharging.
- Vary the PV system size in the computer model and scale the electricity production data to match.
- Vary the battery system size in the computer model and quantify the amount of unmet hours of demand for each population size.
- Use trial-and-error sizing to meet the desired reliability rate of 95% of hours having the demand covered by either PV or the battery system.
- Optimize PV size and battery system size sequentially so that the costs are minimized while the desired reliability is met.

- Calculate system cost estimate, including crystalline silicon PV panels purchase, cost-adder for balance of system and other costs (applied to PV cost date only), and Li-ion battery purchase, for each group size.
- Adjust computer model code with a Jupyter Python3 notebook so that:
    - the following quantities can be adjusted:
        - population size
        - daily electricity use (kWh) per person
        - PV system
            - panel efficiency
            - tilt
            - orientation
            - cost per kWp
        - battery
            - efficiency
            - max charge rate
            - min discharge rate
        - reliability requirement (% of hours that electric load is satisfied)
    - the following outputs will be provided in a CSV file (by population size):
        - PV capacity (kW_p)
        - PV panel area (m^2)
        - PV system + balance-of-system cost (USD)
        - Battery capacity (kWh)
        - Battery cost (USD)
        - Total cost (USD)

Assumptions

Daily electricity use per person in Senegal: 1.5 kWh

- Source: Ritchie, H., & Roser, M. (2024). *Senegal: Energy Country Profile*. https://ourworldindata.org/energy/country/senegal#per-capita-what-is-the-average-energy-consumption-per-person
    - Electricity consumption/person was not directly provided.
        - In 2021, average *total* energy consumption per capita was 2505 kWh (6.86 kWh/day).
        - In 2022, electricity *generation* per capita was 448 kWh (1.23 kWh/day)
        - Because Senegal is not a significant exporter or importer of electricity, generation per capita is used as a proxy for consumption per capita.
            - Source: *Senegal - Electricity*. (n.d.). IEA. https://www.iea.org/countries/senegal/electricity
        - Given that 70.4% have access to electricity as of 2022, this would be 1.75 kWh/day for those that do have access.

        - Because we are most interested in those communities the existing grid is not serving, it seems likely that most of their existing energy use is *not* electricity and that their electricity demands would be lower than the national average, so we have assumed 1.5 kWh/day.
    - For comparison, 1.5 kWh/day with a reliability of 95% of annual hours of the electricity load met is between the minimum thresholds for Tier 4 and Tier 5 electricity systems (World Bank 2015) [NOTE: The World Bank estimates in the notes below are based on *minimum* requirements. Depending on which appliance models are used, and the timing, these estimates may be overly optimistic.] https://www.worldbank.org/en/topic/energy/publication/energy-access-redefined
        - Tier 4 = 0.8 kWh/person/day for a system that provides electricity for 8 hours/day and assumes a household of four people. (report estimates 3.4 kWh/household/day and 4 people/household). Sufficient electricity for medium- and high-power appliances, 16 hours access per day, and < 14 power disruptions per week. Mini-grid, generator, or connected to electrical grid
        - Tier 5 = 2.1 kWh/person/day, which is sufficient for medium-, high-, and very high-powered appliances, at least 23 hours access per day and < 3 disruptions per week for < 2 hrs total. Generally connected to electrical grid
        - Table 6.4 = minimum hours a day of electricity supply
        - Table 6.5 = Reliability of supply (# of disruptions)
        - Table 6.11 = Access to electricity services (capacity for appliance categories)
        - Table 6.12 = household electricity consumption
        - Table 6.13 = electricity consumption by appliance (SEE BELOW)

Average household size in Senegal: 8 people
- Source: *Patterns and trends in household size and composition: Evidence from a United Nations dataset*. (2019). United Nations.
    - Rounded to a whole number from 8.3 reported in the document.

Load profile for electricity consumption
- Source: Huld, T., Moner-Girona, M., & Kriston, A. (2017). Geospatial Analysis of Photovoltaic Mini-Grid System Performance. *Energies*, *10*(2), 218. https://doi.org/10.3390/en10020218
    - The “low nighttime consumption” load profile was chosen to represent a diurnal pattern of electricity use. This was chosen because:
        - The other available profile was designed to represent very low energy consumption households, < 1 kWh/day (Tier 2).

        - ⅔ of electricity will be consumed between sunrise and sunset for the “low nighttime consumption” profile, which is ideal for timing electricity use of a PV system to available insolation.
    - This profile was extracted from Figure 4 using this software: *WebPlotDigitizer: Computer vision assisted tool to extract numerical data from plot images*. (n.d.). Github. https://github.com/automeris-io/WebPlotDigitizer
    - The profile was scaled to population according to the assumed daily electricity use per person in Senegal

Reliability target: 95% of hours annually have their load covered by PV and/or battery.
- Source: Huld, T., Moner-Girona, M., & Kriston, A. (2017). Geospatial Analysis of Photovoltaic Mini-Grid System Performance. *Energies*, *10*(2), 218.
    - Shows approximately 95% reliability in Senegal is possible with Figure 6.
    - 98-99% reliability is common in much of the US grid, but for off-grid systems this requires larger equipment and is prohibitively expensive.

PV power generation profile
- Source: *PVWatts Calculator*. (n.d.). https://pvwatts.nrel.gov/
    - A rooftop system (for single household system) and a fixed ground-mount system were simulated using weather data drawn from the weather station at Dakar International.
        - Unnecessary to simulate multiple system sizes. Verified that the AC output scales according to the system size in kWp. Therefore a single set of simulation results are present in the input data and were scaled with code.

PV panel efficiency: 19%
- Source: *PVWatts Calculator*. (n.d.). https://pvwatts.nrel.gov/
    - Default for crystalline silicon basic panels

PV system losses: 14.8%
- Source: *PVWatts Calculator*. (n.d.). https://pvwatts.nrel.gov/
    - Default value.
    - Individual losses comprising that number are reasonable in my judgment.

PV panel tilt angle: 15 degrees
- Source: Partner letter
- Also close to optimal for maximizing power production (near the latitude angle).

PV panel orientation: 180 degrees
- Source: Partner letter
- Also optimal for maximizing power production (due south for locations in the Northern hemisphere).

Battery type: Li-ion

- Most commonly purchased worldwide currently, and frequently mentioned in the references.

Battery round-trip efficiency: 95%
- Source: Kebede, A. A., Kalogiannis, T., Van Mierlo, J., & Berecibar, M. (2022). A comprehensive review of stationary energy storage devices for large scale renewable energy sources grid integration. *Renewable and Sustainable Energy Reviews*, *159*, 112213. https://doi.org/10.1016/j.rser.2022.112213
    - 85-95%
- Source: Jacqué, K., Koltermann, L., Figgener, J., Zurmühlen, S., & Sauer, D. U. (2022). The influence of frequency containment reserve on the efficiency of a hybrid stationary large-scale storage system. *Journal of Energy Storage*, *52*, 104961. https://doi.org/10.1016/j.est.2022.104961
    - 97.4%

Battery charge rate: 0.8 * capacity / hr
Battery discharge rate: 1.0 * capacity / hr
- These numbers are within the common range of possible rates of charge & discharge, but slightly conservative compared to what's possible with new Li-ion batteries.

Battery depth of discharge cut-off: 80%
- Source: Huld, T., Moner-Girona, M., & Kriston, A. (2017). Geospatial Analysis of Photovoltaic Mini-Grid System Performance. *Energies*, *10*(2), 218. https://doi.org/10.3390/en10020218

PV cost per kWp: (US$950 + US$1150) = US$2100
- includes materials, balance-of-system and installation costs
- Source: Szabó, S., Pinedo Pascua, I., Puig, D., Moner-Girona, M., Negre, M., Huld, T., Mulugetta, Y., Kougias, I., Szabó, L., & Kammen, D. (2021). Mapping of affordability levels for photovoltaic-based electricity generation in the solar belt of sub-Saharan Africa, East Asia and South Asia. *Scientific Reports*, *11*(1), 3226. https://doi.org/10.1038/s41598-021-82638-x

Battery cost per kWh: US$400
- Source: Szabó, S., Pinedo Pascua, I., Puig, D., Moner-Girona, M., Negre, M., Huld, T., Mulugetta, Y., Kougias, I., Szabó, L., & Kammen, D. (2021). Mapping of affordability levels for photovoltaic-based electricity generation in the solar belt of sub-Saharan Africa, East Asia and South Asia. *Scientific Reports*, *11*(1), 3226. https://doi.org/10.1038/s41598-021-82638-x

Results

- We developed a model to estimate the system requirements and costs of providing 1.5kWh/capitata/day using an off-grid photovoltaic and battery storage system.
- Two types of systems were modeled. Rooftop solar was modeled for an individual household. For communities ranging from 25 - 3,000 people, we modeled a ground-mounted system that distributed electricity across the community. Model code files in the repository: *Senegal solar PV rooftop.ipynb* and *Senegal solar PV fixed ground mount.ipynb*
- See PV and We estimated the system requirements and costs for off-grid photovoltaic systems with battery storage in rural Senegal are summarized (Table 1.)

Table 1. Estimated Requirements and Costs for Off-Grid Solar Systems in Rural Senegal.

Results assume panels are oriented south at a 15 degree tilt. *See Methods for additional assumptions.*

Category	Population Size (assumed)	System configuration	PV capacity (kWp)	PV panel area (m2)	PV system cost (US$)	Battery capacity (kWh)	Battery cost (US$)	Total cost (US$)
Household	8	Rooftop	3.5	18	7,350	6.5	2,600	9,950
Hamlet	25	Fixed ground mount	11	58	23,100	30	12,000	35,100
Hamlet	50	Fixed ground mount	20	105	42,000	40	16,000	58,000
Small Settlements	500	Fixed ground mount	200	1,053	420,000	320	128,000	548,000
Small Settlements	1000	Fixed ground mount	390	2,053	819,000	640	256,000	1,075,000
Small Settlements	1500	Fixed ground mount	570	3,000	1,197,000	960	384,000	1,581,000
Built-up Areas	3000	Fixed ground mount	1,130	5,947	2,373,000	1890	756,000	3,129,000

TABLE 6.13

Indicative Calculation of Electricity Consumption, by Tier

APPLIANCES	WATT EQUIVALENT PER UNIT	HOURS PER DAY	MINIMUM ANNUAL CONSUMPTION, IN kWh				
			TIER 1	TIER 2	TIER 3	TIER 4	TIER 5
Task lighting	1/2	4/8	1.5	2.9	2.9	5.8	5.8
Phone charging	2	2/4	1.5	2.9	2.9	2.9	2.9
Radio	2/4	2/4	1.5	5.8	5.8	5.8	5.8
General lighting	12	4/8/12		17.5	17.5	35.0	52.5
Air circulation	20/40	4/6/12/18		29.2	87.6	175.2	262.8
Television	20/40	2		14.6	29.2	29.2	29.2
Food processing	200	0.5			36.5	36.5	36.5
Washing machine	500	1			182.5	182.5	182.5
Refrigerator	300	6				657.0	657.0
Iron	1,100	0.3				120.5	120.5
Air conditioner	1,500	3					1,642.5
Total			4.5	73	365	1,250	3,000

From: Bhatia, Mikul; Angelou, Niki. 2015. Beyond Connections: Energy Access Redefined. ESMAP Technical Report;008/15. © World Bank, Washington, DC. http://hdl.handle.net/10986/24368 License: CC BY 3.0 IGO. NOTE: Tier 4 = 1250 kWh/yr = 0.86 kWh/day. Tier 5 = 3000 kWh/yr = 2.1 kWh/day. The World Bank's Tier 1-5 system is based on average, minimal annual consumption. The efficiency range of available appliances and time used may not be reflected. As such, the feasibility of using all the appliances listed under the tiers may be overly optimistic.

Limitations

- System sizing and reliability are highly sensitive to the load profile; that is, how much electricity is called for at a given time. The assumed load profile used to model electricity demand does not specify specific models of equipment or specific demand patterns that would be used in any particular household. The model further assumes that each household has the same electricity consumption, and that each day has the same electricity load profile. No ground-truth electric load data was available. Simulating the true variation in loads for a given community may demonstrate that the actual reliability is lower than indicated, or that the system is undersized to meet the reliability threshold: for example, if many households use high-intensity appliances at once, such that the power requirements become higher than those in the assumed load profile, the PV + battery system could be insufficient to meet the combined demand.

- Hourly solar radiation data in a format usable for the PVWatts tool was only available for Dakar. As such, all model results are based on those data. Dakar and the west of Senegal have above-average irradiance, while other areas, particularly the south of Senegal, daily PV output may be lower by up to 10% (SolarGIS, 2021). Therefore, system sizes may be underestimated for locations far from Dakar. Local weather data and the exact model of PV panels and batteries must be obtained to determine the appropriate size in each location.

- Cost data was drawn from a study considering the wider region of sub-Saharan Africa, East Asia and South Asia (Szabó et al, 2021). Actual cost data for the PV and batteries available in Senegal will vary according to local economies and supply chains.

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Files in the Repository

All related code and raster files have filenames that start with “Village-scale-solar_” followed by:

Code:
Senegal solar PV rooftop.ipynb
Senegal solar PV fixed ground mount.ipynb

Model results:
Results by population size for tilt=15deg, orientation=South.xls
Results by population size for tilt=15deg, orientation=South.csv

Additional Resources

Africa Energy Outlook 2019: Senegal Overview

www.iea.org/reports/africa-energy-outlook-2019

Scaling Up Renewable Energy (SURE) program in Senegal

https://www.climatelinks.org/projects/scaling-renewable-energy-senegal
Project runs January 2022 to December 2024
Implemented by Tetra Tech

Scaling Up Renewable Energy (SURE II) Factsheet

Four areas of focus: Modernization of pumping in rural boreholes, Youth- and women-led entrepreneurship via productive use of energy, Agriculture commercial and industrial uses, and Enterprise hubs of solar-powered service
https://www.climatelinks.org/sites/default/files/asset/document/2022-04/USAID_SUREII_ENFactSheet_ClearedMar2022_508c.pdf

USAID awards $1.1M for Solar Access in Senegal

Petlong Dakhling February 3, 2024
Summarizes how grants will be allocated
https://africanenergycouncil.org/usaid-awards-1-1m-for-solar-access-in-senegal/

Supporting Small Businesses in Off-Grid Areas With Cooling, Energy, and Electric Mobility Services Powered by Solar

"Most small businesses located in rural and peri-urban areas are not connected to the power grid which limits opportunities to grow their business. Solar solutions provide a more stable power supply while boosting efficiency, productivity, competitiveness, and business income. Energy as a service enables retail and service industries to provide uninterrupted services to customers and expand their offerings. Cooling and electric mobility as a service gets products to market in a timely way that reduces food loss and increases profit. These solar solutions also reduce carbon emissions in Senegal and dependency on fossil fuels that are vulnerable to price shocks and harm the environment."
https://www.climatelinks.org/sites/default/files/asset/document/2023-06/SURE%20Senegal%20Fact%20Sheet_GW4.pdf

Catalog of Solar-Related Products and Companies in Senegal

Off-grid Productive Use of Energy, 2020 Catalog: Senegal
https://www.usaid.gov/sites/default/files/2022-05/Power-Africa-PUE-2020-Catalog-Senegal.pdf

SURE (global)

USAID launched in 2017
Factsheet: https://www.climatelinks.org/sites/default/files/asset/document/2022-04/USAID_SUREII_ENFactSheet_ClearedMar2022_508c.pdf
Annual Report 2023: https://pdf.usaid.gov/pdf_docs/PA021DH5.pdf

Agroforestry and Silvopasture

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Summary

- Agroforestry and Silvopasture are practices that incorporate trees and shrubs with crop and livestock farming, with multiple benefits including increased farmer income, increased carbon storage relative to some farming methods, and benefits to biodiversity and soils.
- Here, we compare published maps of above ground biomass (AGB) to a simple model of AGB associated with these practices to explore potential benefits of their implementation in Senegal.
- We find significant potential for benefits conversion of current agricultural landcover (mostly within the Sudanian Savanna ecoregion) to agroforestry, and limited potential for benefits for conversion of current agricultural landcover to silvopasture.

Introduction

Agroforestry and silvopasture are sustainable agricultural methods that integrate trees and shrubs with farming and livestock grazing to enhance carbon sequestration and improve ecosystem resilience. In agroforestry, trees are interplanted with crops, whereas in silvopasture, trees are incorporated into grazing lands.

Agroforestry and silvopasture also offer extensive co-benefits. They provide livestock with necessary shade and shelter, reducing heat stress. These systems also reduce soil erosion, and enhance soil health and water absorption, thereby boosting agricultural productivity and increasing farmer incomes (Smith et al. 2022, Pezo et al. 2018, Castle et al. 2021, Felix et al. 2018). Furthermore, these practices foster more varied habitats by integrating diverse plant species. They can support an increased range of wildlife, including insects, birds, and mammals, thus promoting biodiversity (Smith et al. 2022, Pezo et al 2018).

In Senegal, where land degradation and deforestation are pressing issues, adopting agroforestry and silvopasture can significantly advance climate resilience and sustainable agricultural practices. Here we present a GIS-based analysis that identifies regions in Senegal suitable for these practices and quantify the potential increase in above-ground biomass (AGB) following their implementation.

Methods

Overview

We derived results using a simple model, in which there are two possible states of above-ground biomass (AGB). One is the estimated actual ABG, obtained from Spawn et al (2020). The other state is the estimated potential AGB associated with agroforestry/silvopasture. This is calculated via some simple approximations from the potential AGB, which is sourced from Nature's Frontiers dataset (Demania et al 2023). We create maps of the suitability of agroforestry/silvopasture as a climate solution by exploring transitions from the actual AGB to the potential AGB.

Data acquisition

We compiled the data from multiple sources. Above-ground biomass (AGB) data was obtained from Spawn et al. (2020), which provides global AGB density at a spatial resolution of 300 m. There are four ecoregions in Senegal (Dinerstein et al (2017)). For each ecoregion, we assumed the potential AGB (Table 1) for the dominant potential natural vegetation type for the ecoregion. AGB data were from the Nature's Frontiers dataset (Demania et al 2023).

Table 1. Maximum potential above-ground biomass for the different ecoregions

Ecoregion	Maximum potential above-ground biomass (tons/ha)
Guinean Mangroves	80
Sahelian Savanna	3
Sudanian Savanna	15
Forest Savanna	40

The Nature's Frontiers landcover data set (Demania et al. 2023) was modified from the ESA landcover data set, which merged several landcover types to create six broad categories (cropland, grazing, mixed, forestry, natural forests, and natural shrubs). Natural forests that are harvested sustainably are classified as forestry.

Model description

We created a simple model to identify the regions where agroforestry and silvopasture could contribute to increasing AGB. We assumed the AGB in agroforestry and silvopasture to be 50% and 30%, respectively, of the maximum potential AGB. These values may be higher than the maximum potential AGB used in this analysis, but we wanted to be conservative. We estimate the AGB by subtracting the actual AGB from the assumed AGB in agroforestry and silvopasture systems within the ecoregion.

Results

Senegal's four ecoregions (Figure 1a) in Senegal broadly correspond with the precipitation pattern in the country. Forest savanna dominates the wetter southern part of the country. Most of the country (>60%) - mostly the west-east middle third - is classified as Sudanian savanna. The Sahelian savanna is the northern, drier ecoregion. The mouth of the River Gambia and River Casamance are dominated by mangroves and classified as Guinean mangroves.

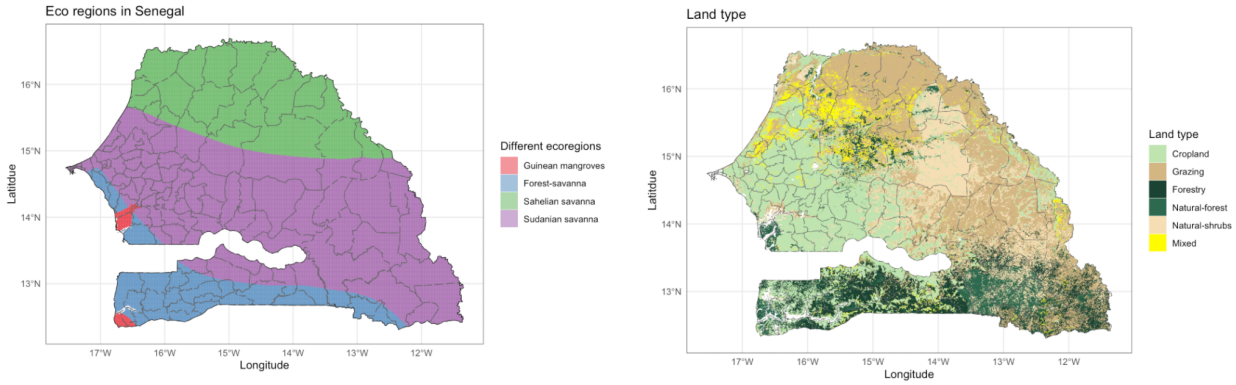

Figure 1: Ecoregions (a) and land type classification (b) in Senegal

There are six broad categories of land usage types used in this analysis (Cropland, Grazing, Forestry, Natural Forest, Natural Shrubland, Mixed). (Figure 1b). Most of the cropland is situated in the western part of the Sudanian savanna ecoregion, however, cropland is also scattered in the forest-savanna region. Rangeland is spread across the eastern part of the Sudanian savanna ecoregion and the Sahelian savanna ecoregion in the north. Forests are present in the southern part of the country.

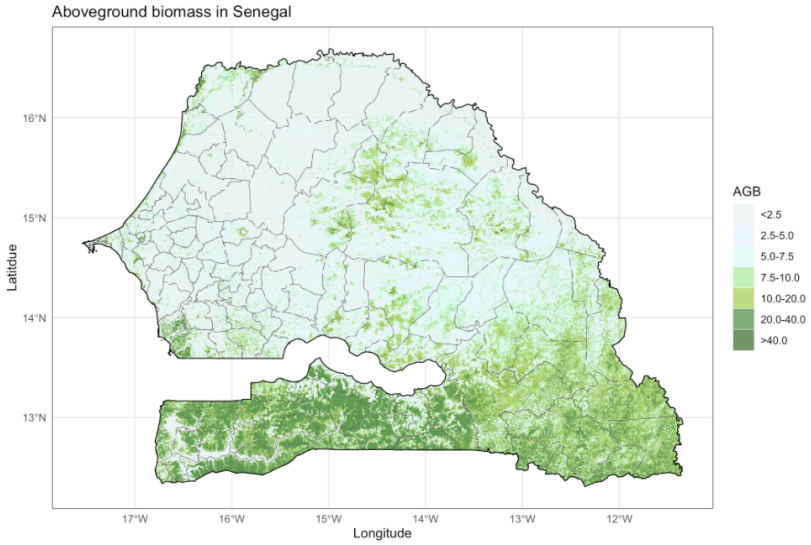

Figure 2: Aboveground biomass (AGB) in Senegal. Unit: tons/ha Data: Spawn et al. 2020

The AGB ranges from 1 - 40 tons/ha and above (Figure 2). The Guinean mangroves at the mouth of the River Gambia and River Casamance and the Forest Savanna in the

south have the highest AGB. In general, there is a trend of decreasing AGB from south to north that corresponds with the ecoregions. High AGB is associated with forest savanna ecoregion in the south. The lowest AGB values are observed in the Sahelian savanna region in the north. AGB across the ecoregions are similar except for the Sudanian savanna region, which has significant AGB variation. The AGB is higher in the sparsely populated eastern region and lower in the agriculture-dominated western region.

Suitability of agroforestry and silvopasture

Across much of Senegal, the actual AGB is lower than the potential AGB (in blue, Figure 3) suggesting that anthropogenic activities and climate change have contributed to the reduction in AGB. The largest difference is observed in the Guinean mangroves (> 50 tons/ha) showing pervasive destruction of the mangrove ecoregion. In parts of the forest-savanna that have been converted to agricultural lands; the reduction in AGB is high (> 30 tons/hectare, Figure 3). In the Sudanian Savanna ecoregion, which is predominantly utilized for agriculture and pastoral activities, there is an average reduction in AGB of 23.5 tons/ha. The Sahelian savanna region of the north and the protected areas, such as the Ferlo Nord Wildlife Reserve, have AGB comparable to the potential AGB.

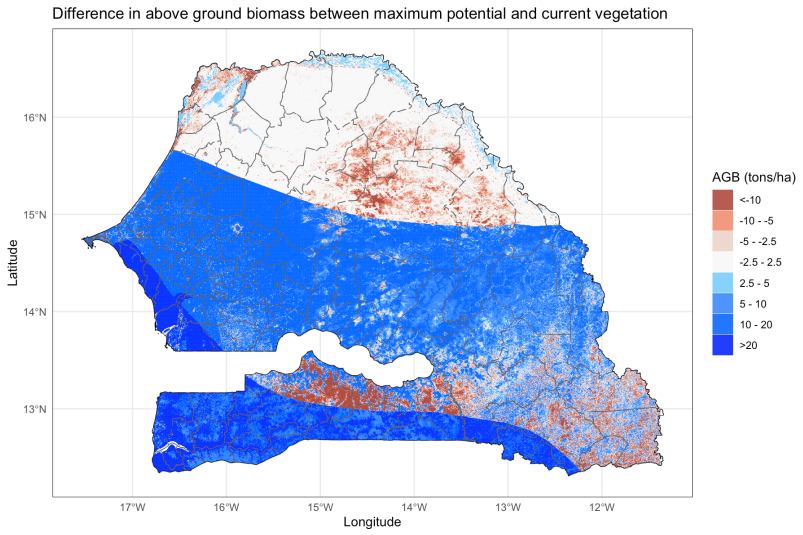

Figure 3: Difference in the maximum potential AGB and current AGB in Senegal. Unit: tons/ha

Agroforestry demonstrates substantial potential to enhance AGB across Senegal (in blue, Figure 4a), particularly in agricultural zones. Our analysis indicates that in the western region, which is predominantly agricultural, agroforestry could increase AGB by 2.5 to 10 tons per hectare - the mean increase across all the land classified as agroforestry being 3.2 tons/ha. In the southern part, where Forest savanna is converted to agriculture land, the average increase in AGB after implementing agroforestry is much higher at 18

tons/ha. Implementation of agroforestry on lands classified as 'cropland' could increase AGB by 1.8 million tons (80 million tons of CO_2-e).

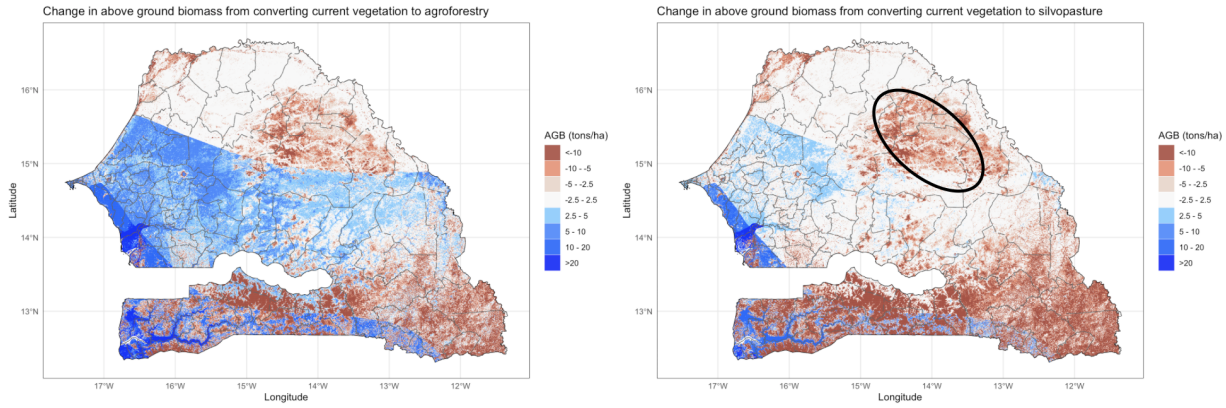

Figure 4: Changes in AGB after converting current vegetation to agroforestry (a) and silvopasture (b).

In contrast, the observed increase in AGB following the implementation of silvopasture (Figure 4b) appears to be modest, especially in the eastern part which is dominated by pastureland where the increase in AGB after silvopasture is typically <2.5 tons/ha. The apparent lower effectiveness of silvopasture may be due to our conservative estimate of 30% of the maximal potential AGB attainable through silvopasture. Indeed, the AGB across protected areas (such as the Ferlo Nord Wildlife Reserve and Sylvo-Pastoral National Park) in the vicinity of pastoral lands are slightly higher (shown by black circle in Figure 4b), suggesting that actual increase in AGB after implementing silvopasture might be higher than our calculations.

Our analysis further indicates that implementing agroforestry and silvopasture is inadvisable in the southeastern regions, which exhibit high AGB. Converting these forests to agroforestry or silvopasture systems will likely reduce AGB (as depicted in red in Figures 4a and 4b). Similarly, introducing these land management practices in the northeastern regions, designated as protected areas (for example, Ferlo Nord Wildlife Reserve), would also result in diminished AGB.

Recommendations

Promote Agroforestry in low AGB hotspots: Agroforestry in the western agricultural and southern Forest savanna regions can potentially increase AGB by 2.5 to 18 tons per hectare. The government should implement policies that offer incentives for integrating

tree planting with cropping to boost carbon sequestration and biodiversity. They should also explore the potential of the carbon market as a crucial mechanism to finance these solutions, which can provide small farmers with additional income through compensation for sustainable agriculture and help them transition to these farming systems.

Protect High AGB Ecosystems: Enforce regulations to save and prevent the conversion of high AGB ecosystems like Guinean mangroves and natural southeastern forests into agroforestry or silvopasture systems. Implementing strict land-use controls and increasing monitoring to preserve biodiversity is vital for their preservation.

Adapt Silvopasture Practices: Promote customized silvopasture practices in the eastern Sudanian savanna, where AGB is below potential. Provide training and resources to implement sustainable practices that combine livestock grazing with forestry, aiming for gradual ecological improvement.

Limitations and caveats

Our analysis, while providing high-resolution maps on the suitability of agroforestry and silvopasture, has some limitations.

First, we assume a fixed value of the maximum potential AGB for each ecoregion. While these values are a good first-order approximation, the maximum AGB can vary within an ecoregion depending on multiple factors, including soil quality, microclimate, and water availability.

Second, we do not identify the combination of trees and shrubs that can result in maximum climate and human well-being benefits. The benefits of agroforestry and silvopasture can vary depending on the choices of trees and shrubs. For example, a review study in West Africa revealed that shrubs might be better suited than trees for integrating with millet and sorghum to increase yields (Felix et al. 2018). Studies in the USA have shown that the increase in income from agroforestry can vary greatly depending on the agroforestry system (Greene et al. 2023). Consultation with local farmers and practitioners who have adopted agroforestry and silvopasture will provide useful insights to maximize the benefits of implementing these practices.

Files in repository

All related code and raster files have filenames that start with “Agroforestry_” followed by:

Codes:

Diff between max potential AGB and current AGB.R

Max potential AGB for different ecoregions after implementing agroforestry and silvopasture.R

Max_AGB_potential for each ecoregion.R

LCLU classification in Senegal.R

Geotiff rasters:

AGB Senegal.tif

Ecoregion Senegal.tif

land_type_Senegal.tif

Change in above ground biomass from converting current vegetation to agroforestry.tif

Change in above ground biomass from converting current vegetation to silvopasture.tif

Difference in the maximum potential AGB and current AGB.tif

Maximum potential AGB.tif

Maximum potential AGB - silvopasture.tif

Maximum potential AGB - silvopasture.tif

Cropland above and below median AGB.tif

Rangeland above and below median AGB.tif

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Ecosystem Services

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August 2024

Summary

Nature provides a foundation of services critical to maintaining human well-being, particularly for people whose livelihoods depend directly on nature-based activities or who, due to economic insecurity, are more exposed to environmental risks. In order to assess baseline provision of these services, we analyzed the current distribution of six critical functions (pollination, carbon storage, watershed baseflow, sediment retention, nitrogen retention, and phosphorus retention) across Senegal. We then assessed landscape-level impacts of five nature-based climate solutions – three agroforestry practices (agroforestry parkland systems, silvopasture, cashew plantations), habitat restoration, and habitat conservation – on the distribution of ecosystem services across the country. We calculated each climate solution's average ecosystem service impact on each relevant land cover type. Results were generated at the pixel-level and summarized at the regional level.

Methods

Ecosystem service model selection: we modeled six ecosystem services using the InVEST ecosystem service modeling suite (Natural Capital Project 2023) and one model adapted from a recent World Bank study (Damania et al. 2023), as detailed in Table 1.

Software: all analyses were performed in Python (3.11) using InVEST version 3.14.1

Current ecosystem services:

- We first gathered all input data (see README file for relevant documentation) and projected all into a shared coordinate system (World Eckert IV, ESRI:54012)
    - This included biophysical tables for each model linking landcover from the European Space Agency (ESA) Climate Change Initiative (CCI) 2015 (Defourny et al. in prep) to model parameters. Tables were either sourced from Johnson et al. (2020) or generated using code detailed in the README, then amended with local literature review following Table 4.
- We then ran each model (Carbon, Pollination, SDR, NDR, SWY) on the current landscape, summarizing the relevant output rasters to the Database of Global Administrative Areas (GADM) Level 3 boundaries for reporting (Figure 1).

Applying climate solutions to the landscape:

- We grouped existing land cover classifications from the European Space Agency's Climate Change Initiative's 2015 dataset into three broad categories that could each be impacted by different climate solutions (Table 2).
- Impact assessments of each climate solution required new landcover maps detailing where that solution can be applied across the country. We replaced existing land cover classes with each climate solution according to Table 3 (and shown visually in Figure 2).
- Finally, we parameterized the three new land cover types derived from the climate solutions (parkland system, silvopasture, cashew plantation) for use in each ecosystem service model following Table 4.

Changes in ecosystem services in response to climate solutions:

- We re-ran each model (Carbon, Pollination, SDR, NDR, SWY) on each of the new climate solution scenario maps, summarizing the relevant output rasters to the Database of Global Administrative Areas (GADM) Level 3 boundaries for reporting. See Figures 3-7.
- We subtracted the results of each climate solution scenario from those of the current landscape to get pixel-level maps of changes in ecosystem services.
    - NOTE: since the scenario map for Conservation was the landscape under full agricultural expansion, we reversed this math (i.e., current minus scenario) so that areas with the highest reduction of ecosystem services under agricultural development show up as positive values, highlighting the value of protecting that land rather than the direct loss of value from agricultural expansion. This facilitates comparison with the other climate solution scenarios.
- Finally, we calculated the average ecosystem service impact of each climate solution within each generalized landcover type from Table 2 to create a matrix showing, for each ecosystem service, how each climate solution fares compared to each underlying landcover type (Table 5).

Results

The analysis produced six raster maps of current ecosystem services and 30 raster maps of changes in ecosystem services (6 services crossed with 5 climate solutions). These results were summarized to GADM Level 3 administrative regions and are contained in a single GeoPackage (senegal_ecosystem_services.gpkg). We present here figures showing the regional summaries, leaving the raster data as supplemental information. Table 1 contains a summary of the model, data types, file names, and field labels of each result. Table 5 contains the generalized summary of the ecosystem service impact of each climate solution on the three land cover types from Table 2.

In general, the three proposed agroforestry climate solutions (cashew plantations, parkland systems, and silvopasture) had varying effects depending on the land cover they were applied to. All three reduced sediment and nutrient export and increased carbon storage when applied to existing agriculture, but had the inverse effect when applied to either forests or herbaceous land covers. These impacts were more intense on parklands and silvopasture than cashew plantations, likely influenced by the extreme nature of the scenario analyzed on the former (i.e., all natural/agricultural lands transitioned to agroforestry) compared to the limited scope of latter (cashews only within the southern ecoregion).

Both restoration and conservation had positive impacts on all ecosystem services measured, although there were regional differences in the magnitude of change (see Figures 2 and 5).

Limitations

Input Data
Models are only as good as the data they ingest and there are a few quirks to the data available for this study. A prime example of this is the parameterization of the carbon model, which derives from Spawn et al. (2020). The data from Spawn et al. are ecoregionally dependent and for several of the ecoregions within Senegal biomass carbon is reportedly higher in Shrubland categories than Forest categories. This creates somewhat nonsensical results that indicate that reforesting shrubland actually reduces carbon storage (see Table 5); these should be viewed with skepticism, as it is unlikely shrubland is more carbon-dense than forests in Senegal.

Scenarios
The climate solution scenarios analyzed here represent extreme scenarios of landscape change: all agriculture converted to natural vegetation, all forests converted to agroforestry, etc. This was necessary from a computational perspective: to test how each hectare of land in Senegal would respond to each scenario in isolation (e.g., with no other areas changed from the original landscape) would require over 19 million individual model runs *per climate solution*. As model run times for NDR and SDR can number in minutes to hours, such a complete analysis was beyond current computational viability. Thus, the scale of land use change in these scenario maps is inherently unrealistic (i.e., the restoration scenario cannot actually remove all agriculture in the country) and as such represents the upper (or lower) bound of ecosystem service impact per climate solution. However, these calculations do provide an estimate of per hectare value and could serve

as the basis for planning a more practical implementation of nature-based climate solutions.

Ecosystem Service impact by Land Cover and Climate Solution
Summarizing the general ecosystem service impact of transitioning land cover *X* to climate solution *Y* can provide quick answers to questions such as “what happens to carbon storage when silvopasture replaces agricultural land vs forests?” but can mask the spatial heterogeneity of ecosystem services within a type of land cover (e.g., forests along riparian corridors retain more sediment than forests in upland areas).

This summary method also ignores the indirect effects an action on one land use has on adjacent land uses. Changing a forest to agriculture has impacts on watershed processes upstream of that forest yet by summarizing the impacts only within the forest itself we fail to capture some part of the ecosystem service benefits that extend beyond its borders. However, since these indirect effects will be of the same type (i.e., increasing or decreasing a service) as and typically smaller than their direct counterparts, the summary method still provides a reasonable heuristic.

Figures

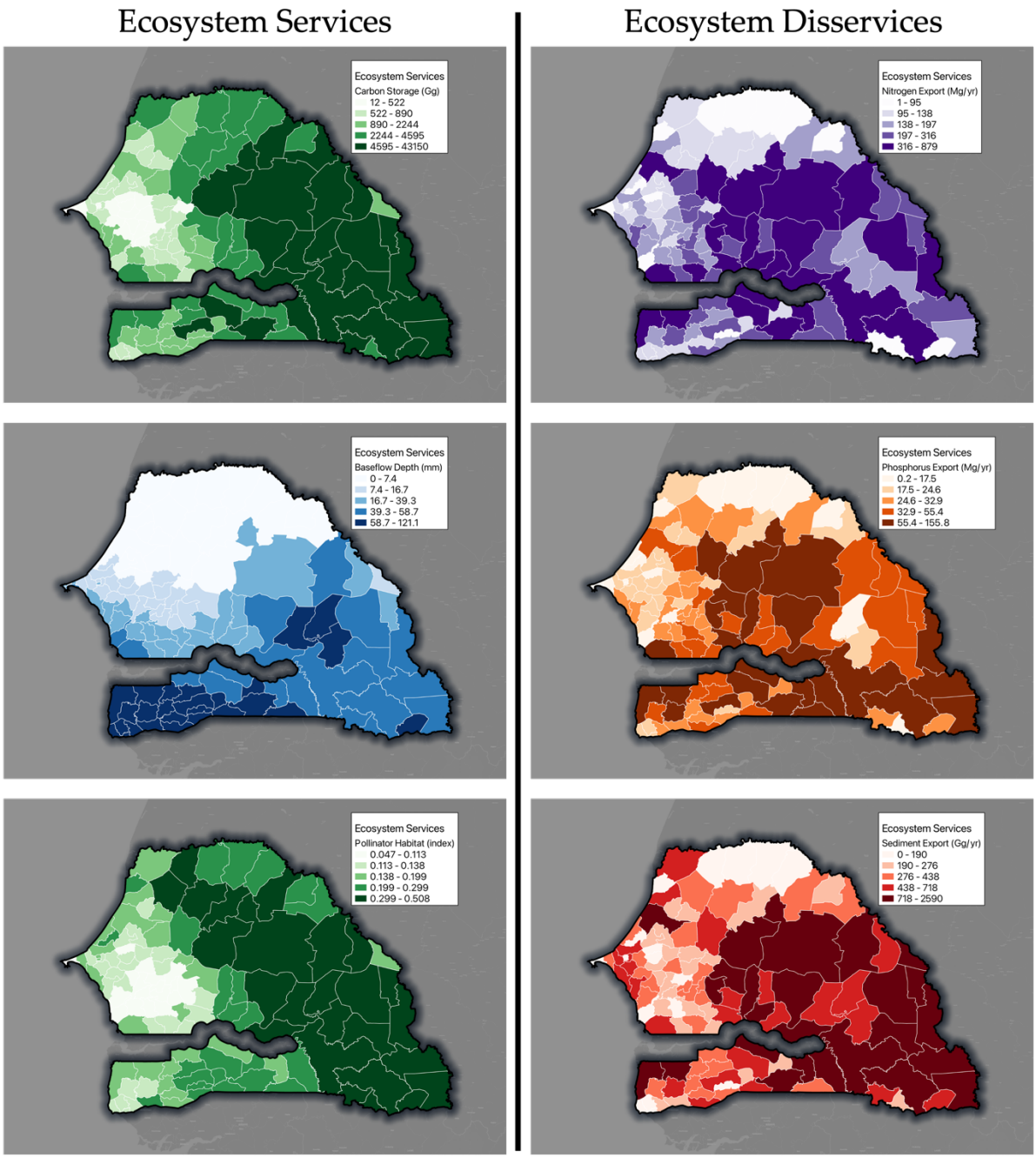

Figure 1. Current supply of ecosystem services, aggregated to the GADM Level 3 regions. Carbon storage, nitrogen export, phosphorus export, and sediment export are summed to the region level, while pollinator habitat and baseflow depth represent the average values across the region. Note that color saturation on the righthand maps indicate higher *disservices* from the export of sediment and nutrients to the watershed.

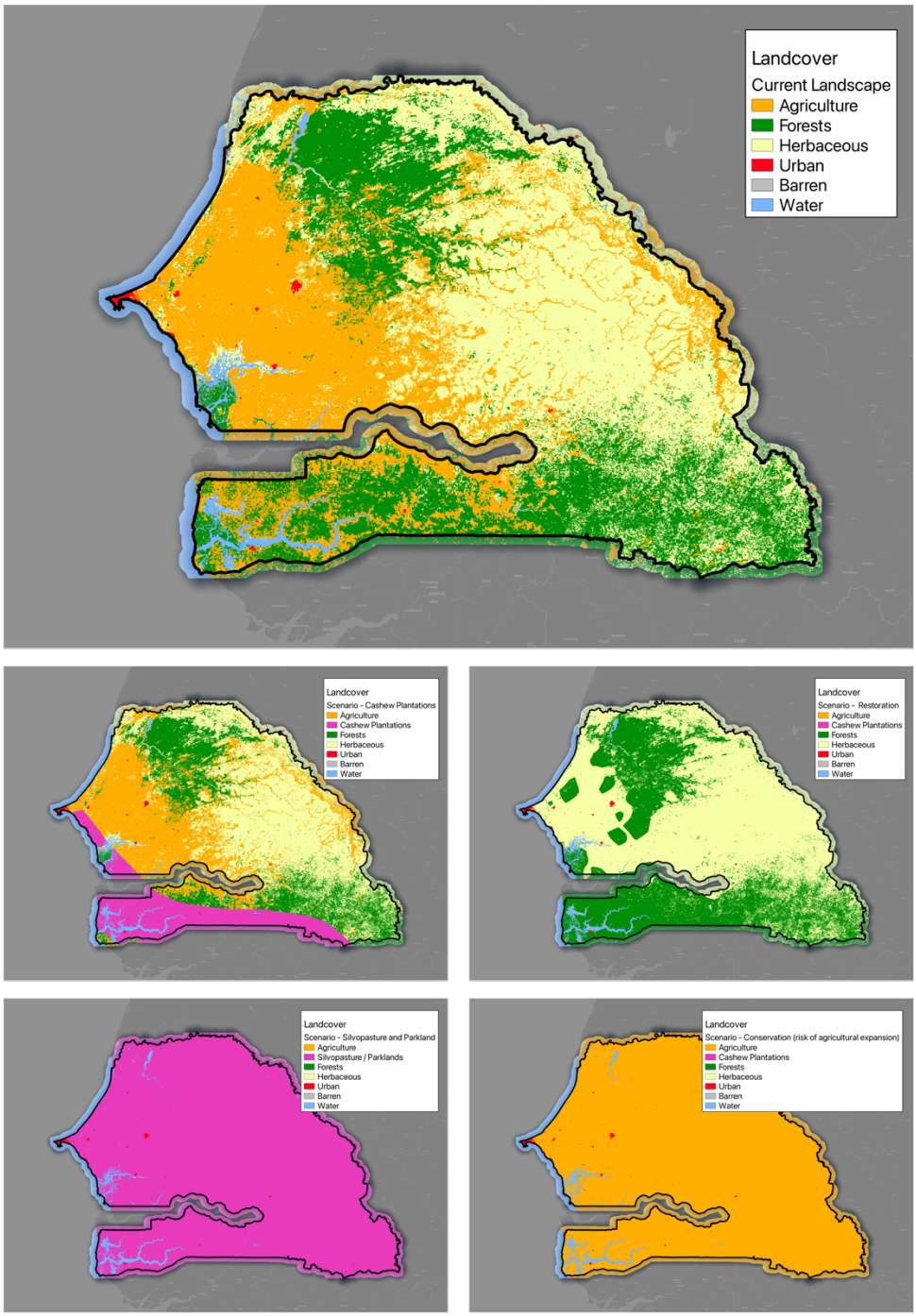

Figure 2. Simplified landcover maps for the current (2015) landscape and the five climate solution scenarios (cashew plantations, silvopasture, agroforestry parklands, restoration, conservation). Note that the silvopasture and parklands scenarios share a landcover map and differ simply in parameter values. Land cover classes here represent aggregate types (i.e., there are many subclassifications of Agriculture, Forests, etc) for visualization purposes—modeling was performed using all available land cover types.

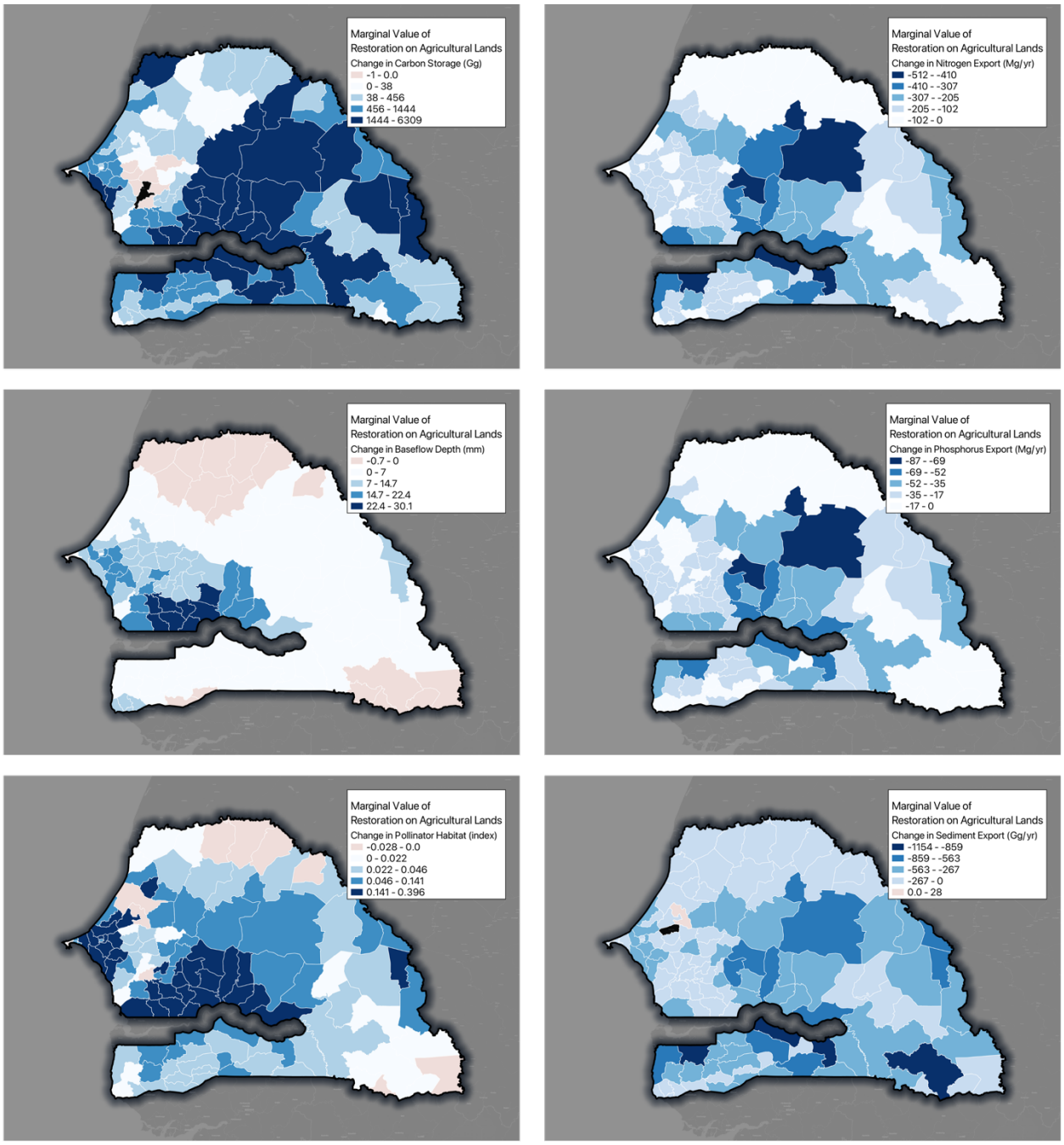

Figure 3. Change in ecosystem services supply ("marginal value") under the Restoration climate solution scenario, with agriculture restored to potential vegetation. Aggregated to the GADM Level 3 regions. Carbon storage, nitrogen export, phosphorus export, and sediment export are summed to the region level, while pollinator habitat and baseflow depth represent the average values across the region.

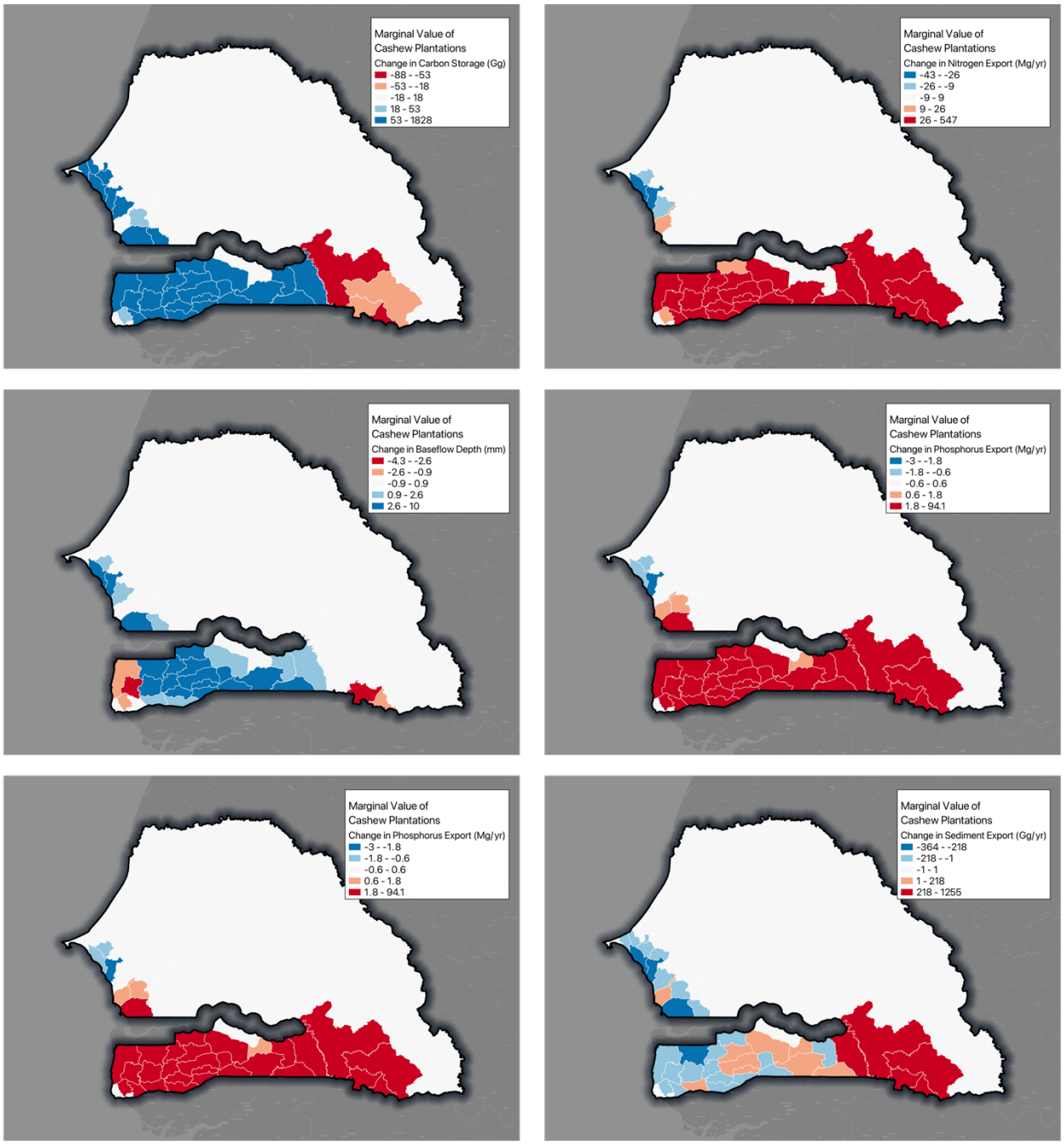

Figure 4. Change in ecosystem services supply ("marginal value") under the Cashew Plantations climate solution scenario, with agriculture and natural land converted to cashew plantations in the southern part of the county. Aggregated to the GADM Level 3 regions. Carbon storage, nitrogen export, phosphorus export, and sediment export are summed to the region level, while pollinator habitat and baseflow depth represent the average values across the region.

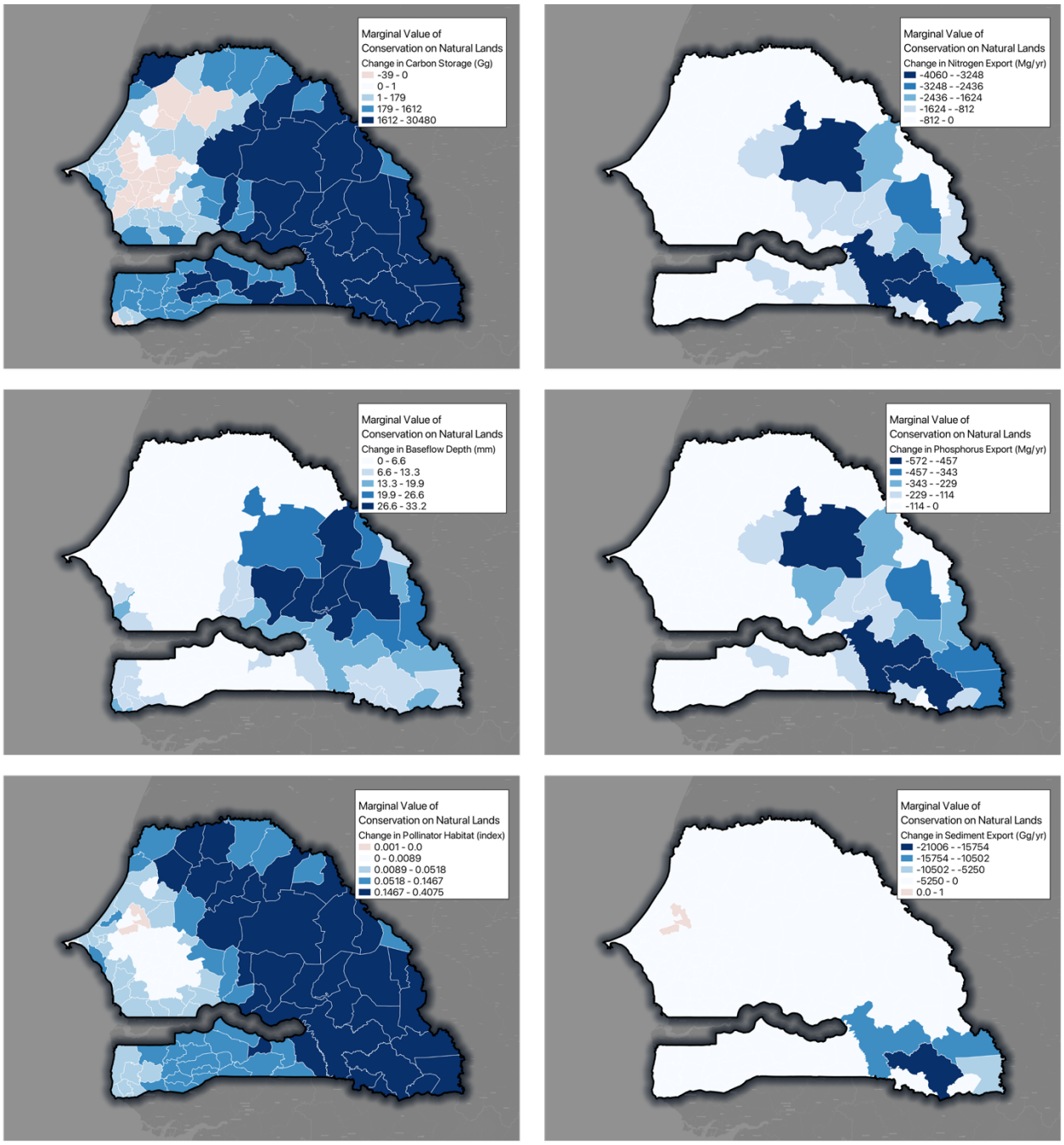

Figure 5. Change in ecosystem services supply ("marginal value") under the Conservation climate solution scenario, showing the difference in ecosystem services on natural lands undergoing simulated agricultural development. Aggregated to the GADM Level 3 regions. Carbon storage, nitrogen export, phosphorus export, and sediment export are summed to the region level, while pollinator habitat and baseflow depth represent the average values across the region.

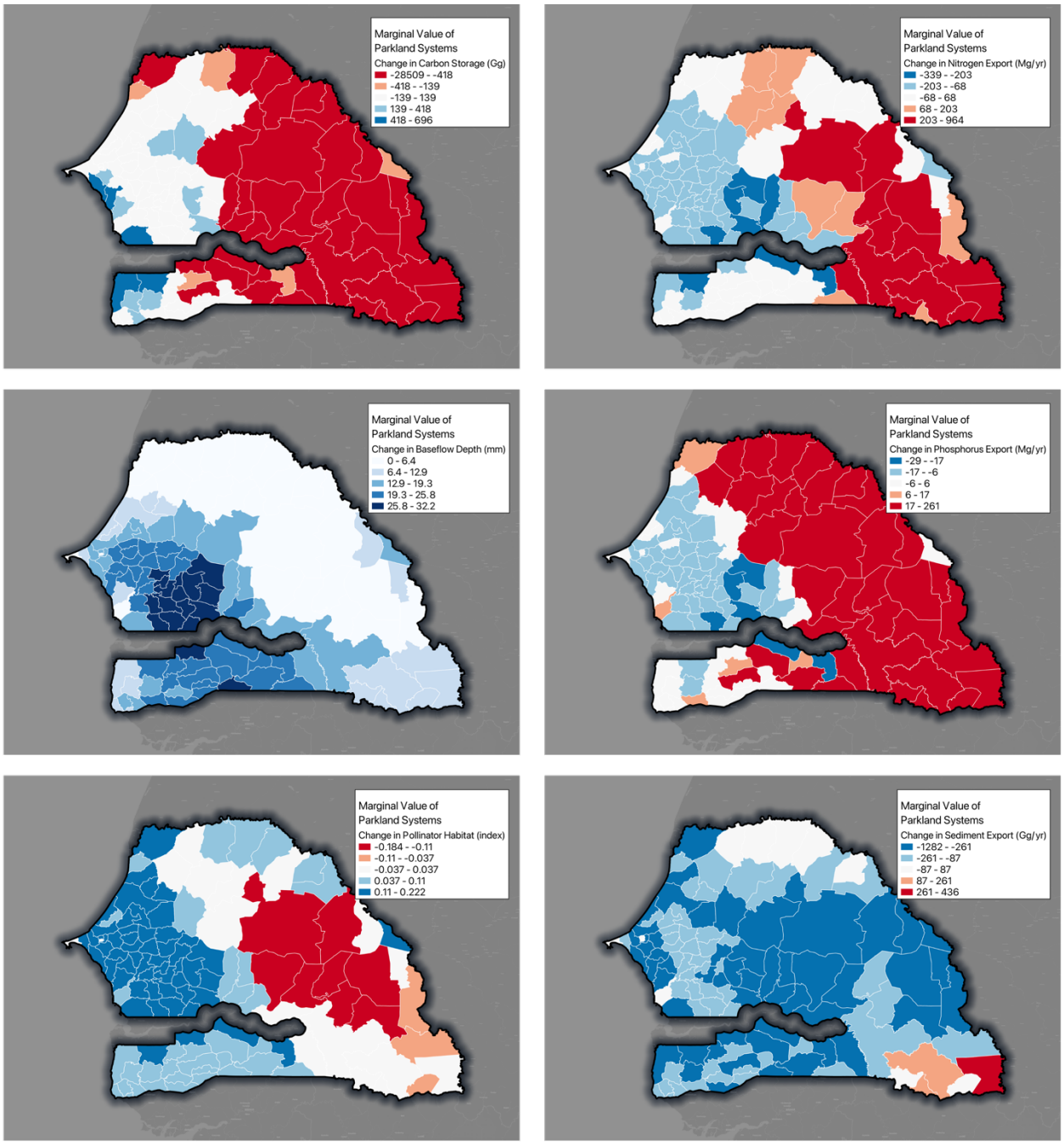

Figure 6. Change in ecosystem services supply ("marginal value") under the Agroforestry Parkland System climate solution scenario, with agriculture and natural land converted to parklands. Aggregated to the GADM Level 3 regions. Carbon storage, nitrogen export, phosphorus export, and sediment export are summed to the region level, while pollinator habitat and baseflow depth represent the average values across the region.

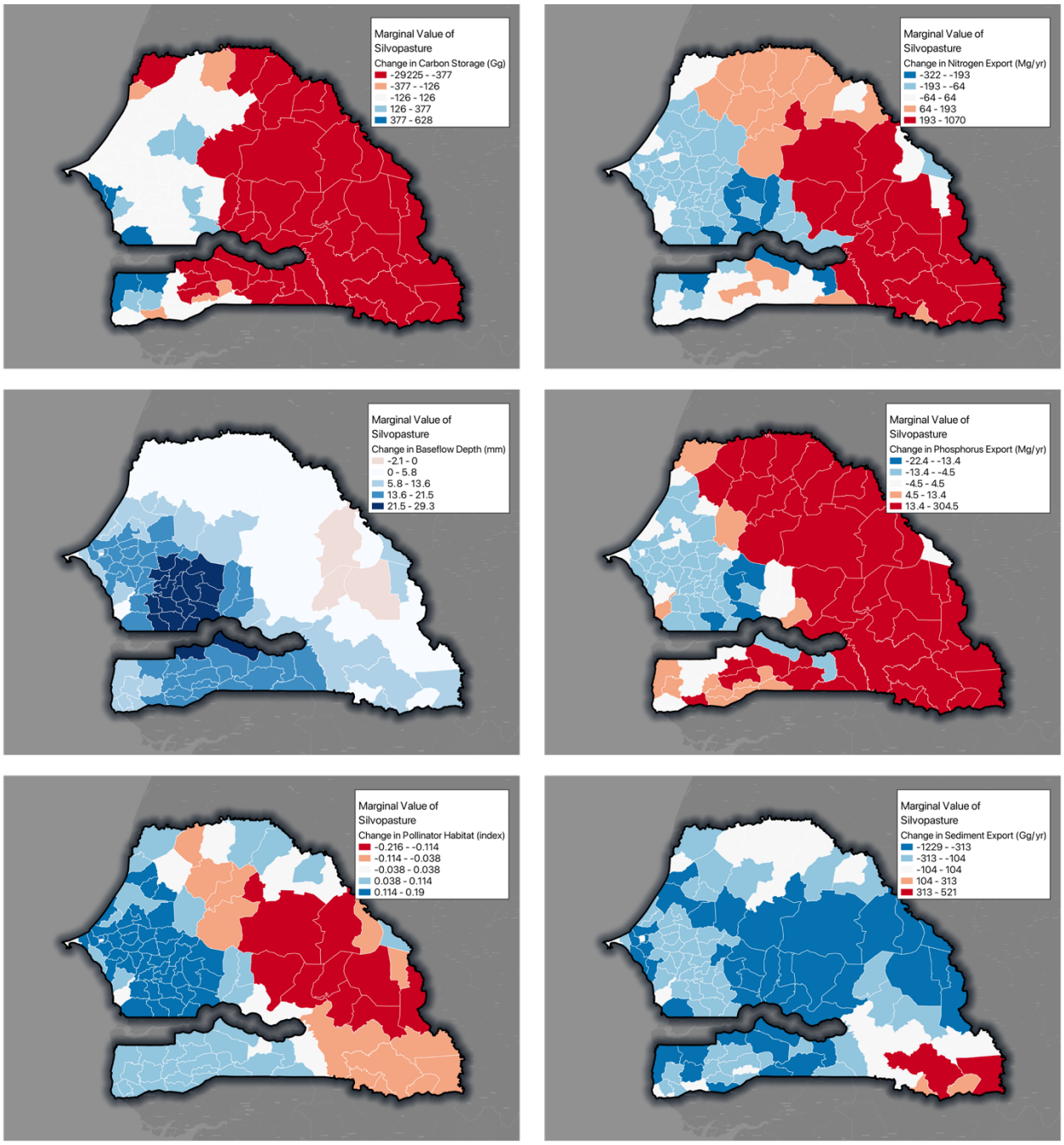

Figure 7. Change in ecosystem services supply ("marginal value") under the Silvopasture climate solution scenario, with agriculture and natural land converted to silvopasture. Aggregated to the GADM Level 3 regions. Carbon storage, nitrogen export, phosphorus export, and sediment export are summed to the region level, while pollinator habitat and baseflow depth represent the average values across the region.

Tables

Table 1. Ecosystem service model descriptions and results file format.

Ecosystem service	Description	Model Source	Results File**
Pollination	Index of predicted pollinator abundance (generalist species) based on underlying spatial patterns of floral resources and nesting habitat. Units: index from 0 (no pollinators) to 1 (theoretical maximum pollinator abundance, often much lower in real landscape contexts).	InVEST Pollinator Abundance (Pollination)	pollinator_habitat _index__{scenario*}.tif
Carbon storage	Carbon stored on the landscape in vegetation (aboveground, belowground) and soils. Units: Mg/pixel	Nature's Frontiers (Damania et al. 2023), adapted from Spawn et al. (2020)	carbon_mg_{scenario*}.tif
Water quantity (baseflow)	Map of annual baseflow (streamflow fed from subsurface storage between precipitation events), representing the contribution of a pixel to baseflow (i.e. water that reaches the stream from that pixel). Units: mm/pixel, but should be interpreted as relative values, not absolute	InVEST Seasonal Water Yield (SWY)	baseflow_mm_{scenario*}.tif
Water quality (sediment retention)	The contribution of vegetation to keeping erosion from entering a stream. This combines local sediment retention with trapping of upslope erosion. Units: Mg/pixel/year	InVEST Sediment Delivery Ratio (SDR)	n_export_kg_{scenario*}.tif
Water quality (nitrogen retention)	The amount of a nutrient—nitrogen (N), phosphorus (P)—that eventually reaches the local watershed, either via surface or subsurface flow. Units: kg/pixel/year	InVEST Nutrient Delivery Ratio (NDR)	p_export_kg_{scenario*}.tif
Water quality (phosphorus retention)			n_export_kg_{scenario*}.tif

* For scenarios in Table 3, plus the current "baseline" scenario

** GeoPackage fields follow the pattern: **{*raster file*}__sum** and **change_in_{*raster file*}__sum** (or "__mean" for pollination and baseflow)

Table 2. Landcover simplification for scenario generation.

Landcover Classification	ESA CCI 2015 Categories
Agriculture	10 - Cropland, rainfed 11 - Cropland, rainfed (Herbaceous cover) 12 - Cropland, rainfed (Tree or shrub cover) 20 - Cropland, irrigated or post-flooding 30 - Mosaic cropland (>50%) / natural vegetation (tree, shrub, herbaceous cover) (<50%) 40 - Mosaic natural vegetation (tree, shrub, herbaceous cover) (>50%) / cropland (<50%)
Forest	50 - Tree cover, broadleaved, evergreen, closed to open (>15%) 60 - Tree cover, broadleaved, deciduous, closed to open (>15%) 61 - Tree cover, broadleaved, deciduous, closed (>40%) 62 - Tree cover, broadleaved, deciduous, open (15-40%) 70 - Tree cover, needleleaved, evergreen, closed to open (>15%) 71 - Tree cover, needleleaved, evergreen, closed (>40%) 72 - Tree cover, needleleaved, evergreen, open (15-40%) 80 - Tree cover, needleleaved, deciduous, closed to open (>15%) 81 - Tree cover, needleleaved, deciduous, closed (>40%) 82 - Tree cover, needleleaved, deciduous, open (15-40%) 90 - Tree cover, mixed leaf type (broadleaved and needleleaved) 100 - Mosaic tree and shrub (>50%) / herbaceous cover (<50%) 160 - Tree cover, flooded, fresh or brackish water 170 - Tree cover, flooded, saline water
Herbaceous	110 - Mosaic herbaceous cover (>50%) / tree and shrub (<50%) 120 - Shrubland 121 - Evergreen shrubland 122 - Deciduous shrubland 130 - Grassland 150 - Sparse vegetation (tree, shrub, herbaceous cover) (<15%) 152 - Sparse shrub (<15%) 153 - Sparse herbaceous cover (<15%) 180 - Shrub or herbaceous cover, flooded, fresh/saline/brackish water

Table 3. Climate solution description and spatial design.

Climate Solution	Description	Spatial Pattern
Agroforestry: Parkland Systems	"landscapes in which mature trees occur scattered in cultivated or recently fallowed fields" (Boffa 1999)	Replace any agriculture, forest, or herbaceous area with parkland systems.
Agroforestry: Silvopasture	Intermittent grazing amongst trees.	Replace any agriculture, forest, or herbaceous area with silvopasture.
Agroforestry: Cashew Plantations	Monocropped cashew plantations.	Within the southern climate zone (from modeling in (Damania et al. 2023)), replace any agriculture, forest, or herbaceous area with cashew plantations.
Habitat Restoration	Restoring cropland to potential vegetation	Replace agricultural areas with potential natural vegetation (from modeling in (Damania et al. 2023)).
Habitat Conservation	Conserving natural landscapes	Replace forest or herbaceous areas with *Cropland, rainfed* to simulate the value of

		conservation compared to the risks of agricultural development.

Table 4. Parameterization methods for each ecosystem service model under each climate solution.

Climate Solution	Model	Parameter Change	Citations
Agroforestry: Parkland Systems	Carbon	**Carbon storage**: midway between ESA classes 40[4] and 100[6]	(Kuyah et al. 2019; Leroux et al. 2022)
	Pollination	**Nectar and Floral Resources**: same as ESA class 40[4]	
	SWY	**Kc (monthly)**: same as ESA class 40[4] **Curve Number (soil group)**: same as ESA class 40[4]	(Bayala et al. 2014; Kuyah et al. 2019; Leroux et al. 2022)
	SDR	**USLE C Factor**: Five-fold reduction from ESA class 10[1] **USLE P Factor**: same as ESA class 40[1]	(Kuyah et al. 2019; Leroux et al. 2022)
	NDR	**Nutrient Loading (N and P):** same as ESA class 40[4] **Retention Efficiency** ● **N:** same as ESA class 12[2] ● **P:** same as ESA class 40[4] **Proportion Subsurface (N):** same as ESA class 12[2]	(Kuyah et al. 2019; Leroux et al. 2022)
Agroforestry: Silvopasture	Carbon	**Carbon storage**: 5% reduction from Agroforestry Parkland Systems	Assumed silvopasture to be a mildly degraded version of the Parkland Systems (5% reduction in parameter quality)
	Pollination	**Nectar and Floral Resources**: 5% reduction from Agroforestry Parkland Systems	
	SWY	**Kc (monthly)**: 5% increase from Agroforestry Parkland Systems **Curve Number (soil group)**: 5% increase from Agroforestry Parkland Systems (capped at maximum value from ESA class 10[1])	
	SDR	**USLE C Factor**: 5% increase from Agroforestry Parkland Systems **USLE P Factor**: same as ESA class 40[4]	
	NDR	**Nutrient Loading (N and P):** 5% increase from Agroforestry Parkland Systems **Retention Efficiency (N and P):** 5% decrease from Agroforestry Parkland Systems	
Agroforestry: Cashew Plantations	Carbon	**Carbon storage**: midway between ESA classes 40[4] and 61[5]	(Lenka et al. 2012)
	Pollination	**Nectar and Floral Resources**: same as ESA class 30[3]	(Rege and Lee 2023)
	SWY	**Kc (monthly)**: midway between ESA classes 10[1] and 40[4] **Curve Number (soil group)**: midway between ESA classes 10[1] and 40[4]	(Mahajan et al. 2021)
	SDR	**USLE C and P Factors**: same as ESA class 40[4]	(Mahajan et al. 2021)
	NDR	**Nutrient Loading (N and P):** same as ESA class 30[3] **Retention Efficiency (N and P):** same as ESA class 30[3] **Proportion Subsurface (N):** same as ESA class 30[3]	(Aminu et al. 2021; Mahajan et al. 2021; Yin et al. 2023)

[1] ESA CCI Landcover Class 10 - Cropland, rainfed
[2] ESA CCI Landcover Class 12 - Cropland, rainfed (Tree or shrub cover)
[3] ESA CCI Landcover Class 30 - Mosaic cropland (>50%) / natural vegetation (tree, shrub, herbaceous cover) (<50%)

[4] ESA CCI Landcover Class 40 - Mosaic natural vegetation (tree, shrub, herbaceous cover) (>50%) / cropland (<50%)

[5] ESA CCI Landcover Class 61 - Tree cover, broadleaved, deciduous, closed (>40%)

[6] ESA CCI Landcover Class 100 - Mosaic tree and shrub (>50%) / herbaceous cover (<50%)

Table 5: Generalized ecosystem service impact of each climate solution scenario on three land cover types. Numbers indicate the average change in ecosystem services from an original land cover (rows) to a new climate solution (columns), with one column ('Current') showing the current average level of that service on the original land cover type.

Carbon (Mg/ha)

	Current	Cashew Plantations	Parkland Systems	Silvopasture	Restoration	Conservation
Agriculture	11	19	3	2	23	
Forest	26	0	-16	-12		16
Herbaceous	33	0	-24	-25		27

Nitrogen Export (kg/ha)

	Current	Cashew Plantations	Parkland Systems	Silvopasture	Restoration	Conservation
Agriculture	4.03	-0.26	-2.60	-2.49	-3.64	
Forest	0.23	1.23	1.56	1.70		-5.51
Herbaceous	0.44	0.11	1.05	1.17		-4.36

Phosphorus Export (kg/ha)

	Current	Cashew Plantations	Parkland Systems	Silvopasture	Restoration	Conservation
Agriculture	0.65	-0.02	-0.24	-0.20	-0.54	
Forest	0.22	0.17	0.29	0.34		-0.70
Herbaceous	0.03	0.02	0.38	0.43		-0.72

Sediment Export (Mg/ha)

	Current	Cashew Plantations	Parkland Systems	Silvopasture	Restoration	Conservation
Agriculture	8.37	-1.21	-7.26	-7.18	-7.03	
Forest	0.64	1.77	1.42	1.56		-17.88
Herbaceous	2.14	0.11	-0.91	-0.82		-9.15

Pollinator Habitat (Index)

	Current	Cashew Plantations	Parkland Systems	Silvopasture	Restoration	Conservation
Agriculture	0.13	0.01	0.19	0.16	0.22	
Forest	0.33	-0.03	-0.01	-0.04		0.23

Herbaceous	0.42	-0.01	-0.10	-0.13		0.32

Baseflow (mm)

	Current	Cashew Plantations	Parkland Systems	Silvopasture	Restoration	Conservation
Agriculture	20	1	23	20	14	
Forest	35	1	16	13		4
Herbaceous	43	0	-1	-3		25

Files in repository

All related out files have filenames that start with “Ecoservices_” Input filenames start with “InVEST-input-data_”:

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