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Impact of land-use change on ecosystem services in Africa's Great Green Wall

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ABSTRACT

Africa's Sahel faces severe land degradation, threatening livelihoods and regional stability. To address this challenge, the Great Green Wall (GGW) initiative aims to restore 100 million hectares of degraded land. Achieving this goal requires an improved understanding of recent land use and land cover (LULC) dynamics and their impacts on ecosystem services. This study quantifies the impacts of land-use transitions between 2007 and 2019 on multiple ecosystem services and identifies spatial trade-offs and synergies to inform restoration planning across the GGW region. We integrated MODIS land-use/land-cover data with geospatial ecosystem service models and applied the Ecosystem Service Contribution Index (ESCI) to quantify the effects of LULC transitions on carbon stock, water yield, soil conservation, sand stabilisation, and grain production. Bivariate Moran's I was applied to explore associations among services. Land use reconfigured substantially, with grasslands declining and cropland and barren land expanding. Ecosystem service responses were heterogeneous: carbon stock increased in the Ethiopian Highlands and Nigerian agricultural zones, and sand stabilisation improved in parts of Niger and Chad, whereas soil conservation and water yield declined in several arid areas. Grain production rose by 31.1%, but cropland conversion generated trade-offs with wind-erosion control and soil retention. Across climatic gradients, synergies emerged between carbon stock and soil conservation in wetter or highland zones, while trade-offs between provisioning and regulating services dominated in farmed and arid areas. These findings show that LULC in the GGW region is dynamic and variable, with changes enhancing ecosystem services in some areas and compromising them in others. To strengthen ecosystem resilience and support sustainable livelihoods, ecological restoration strategies need to vary in response to local ecological and social conditions.

1. Introduction

Drylands are water-limited ecosystems defined by low and highly variable rainfall, typically characterised by an aridity index below 0.65 (Reynolds et al., 2007). Drylands cover 41% of the Earth's land surface, support 40% of the global population, store 46% of terrestrial carbon, and encompass approximately one-third of the world's biodiversity hotspots (Feng and Fu, 2013; Huang et al., 2017). These areas provide ecosystem services, such as carbon sequestration, water regulation, and grain production (Ahlström et al., 2015; Guirado et al., 2022). However, drylands are increasingly exposed to degradation due to unsustainable land use, population pressures, and climate change; it is estimated that 10–20% of global drylands are already degraded (James et al., 2013; Gowda et al., 2013; Wang et al., 2015; Fernández et al., 2022), leading to reduced ecosystem services, food insecurity, and socio-political instability (Meseret, 2016; Yirdaw et al., 2017; Wassie, 2020).

To address land degradation and its impacts on ecosystem services and livelihoods, the United Nations declared 2021–2030 the Decade for Ecosystem Restoration (Tripathi et al., 2019; Ceccon et al., 2020) and incorporated the Land Degradation Neutrality (LDN) target into Sustainable Development Goal 15 (Feng et al., 2022). Key restoration commitments include the Bonn Challenge, the African Forest Landscape Restoration Initiative (AFR100) and the Kunming-Montreal Global Biodiversity Framework (targeting 30% restoration of degraded ecosystems by 2030). The UN Convention to Combat Desertification (UNCCD) plays a central role in dryland strategies. At the UNCCD COP16, the Riyadh Global Drought Resilience Partnership (UNCCD, 2024) was launched, supported by initiatives such as the International

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Drought Resilience Observatory and Global Drought Atlas.

While top-down initiatives have helped mobilise restoration efforts, their on-the-ground effectiveness remains contested (Leach et al., 2010; Mansourian and Vallauri, 2014). Programme success often depends on the active participation and long-term commitment of local stakeholders, which varies considerably across regions (Reed et al., 2016). These realities underscore the need for adaptive, context-specific approaches that align with the diverse socio-economic and ecological conditions of target landscapes (Berdugo et al., 2020). Landscape-based ecosystem restoration has become a key strategy for tackling land degradation and supporting sustainable development (Vardon et al., 2019; Luo et al., 2024). These initiatives typically involve deliberate LULC transformations through practices such as afforestation (Pérez-Silos et al., 2021; Liu et al., 2022), reforestation (Lamb, 2018; Nave et al., 2019; Qi et al., 2019), and sustainable agricultural practices (Piñeiro et al., 2020; Rehman et al., 2022), which can enhance ecosystem services such as carbon stock, water regulation and food provision. LULC therefore serves as an important indicator that links human activities with ecological outcomes (Luo et al., 2019). However, the ecological benefits of these interventions are not uniform. Trade-offs between ecosystem services often emerge, particularly in dryland regions where measures that improve soil retention may simultaneously reduce water availability (Galicia and Zarco-Arista, 2014; Wagner et al., 2014; Rodrigues et al., 2021). Moreover, tensions arise when efforts to increase provisioning services such as grain production compromise regulating functions like carbon sequestration and biodiversity conservation (Wang et al., 2012; Mátyás and Sun, 2014; Feng et al., 2016). Socio-economic and institutional constraints further complicate restoration outcomes, as stakeholder priorities may conflict with long-term sustainability objectives (Lazos-Chavero et al., 2016; Reed et al., 2018; Ruangpan et al., 2021). Understanding these trade-offs is crucial for policymakers to effectively prioritise ecosystem services and achieve sustainable development goals (Alexander et al., 2016; IPBES, 2019).

The Sahel region of Sub-Saharan Africa faces widespread land degradation and desertification (Nicholson et al., 1998; Bai et al., 2008; Masih et al., 2014; Nkonya et al., 2016). In response, the Great Green Wall (GGW) was launched in 2007. Initially conceived as an 8000-kilometre vegetative barrier, the GGW has subsequently evolved into a more comprehensive ecosystem management strategy encompassing sustainable dryland restoration, natural vegetation regeneration, water retention and biodiversity conservation (Mbow et al., 2017; Goffner et al., 2019; UNCCD, 2021; Mirzabaev et al., 2021). For instance, the GGW has facilitated planting 12 million drought-resistant trees in Senegal and restoring five million hectares of degraded land in Ethiopia and Nigeria (FAO, 2021). Additionally, the initiative supports community-based natural resource management practices, such as Farmer Managed Natural Regeneration (FMNR), which has proven effective in increasing tree cover and improving soil fertility (Kelly et al., 2021; Turner et al., 2021; Abasse et al., 2023). Through these community-centred interventions, the GGW seeks to enhance food security, improve livelihoods, and bolster socio-ecological resilience. The initiative has helped promote sustainable land use, improving local climate conditions, and supporting socio-economic development (O'Connor and Ford, 2014; Gadzama, 2017).

Research on the impacts of GGW implementation on ecosystem services has primarily concentrated on assessing the benefits in terms of the value of ecosystem services derived from large-scale afforestation. A review of global forest landscape restoration potential (Bernal et al., 2018), alongside soil carbon stock data (Mbow et al., 2017), estimated that the GGW intervention area could sequester up to 70 million tonnes of carbon in woody biomass and an additional 15.5 million tonnes in soil by 2030 (UNCCD, 2021). Mirzabaev et al. (2021) quantified the economic costs and benefits of the GGW initiative using a database of local ecosystem service valuations in the Sahel, concluding that restoration activities would require up to a decade to achieve a break-even point. Most studies on the mapping and valuation of ecosystem services in the Sahel have been conducted at the community-village scale, often using a combination of satellite imagery analyses and participatory surveys (Sinare et al., 2016; Malmborg et al., 2018). While community-level assessments help address the challenges of acquiring detailed secondary data, particularly in data-poor regions, and mitigate errors associated with spatial heterogeneity, the findings from such small-scale studies have limited applicability at broader scales. Moreover, these studies often overlook synergies and trade-offs among ecosystem services, which may result in misrepresentations or oversimplifications in service valuation. Given that the GGW spans an extensive and ecologically diverse corridor across Africa, analysing interactions among multiple ecosystem services is essential to understanding their spatial patterns of synergies and trade-offs.

This study quantifies the spatiotemporal changes in land use and ecosystem services in the GGW region from 2007 to 2019 and examines how these changes shape service synergies and trade-offs, employing remote sensing data and geospatial modelling. Specifically, the study aims to (1) quantify the spatial distribution and temporal trends in land-use change; (2) evaluate spatiotemporal changes in ecosystem services, including carbon stock, water yield, soil conservation, sand stabilisation, and grain production; (3) analyse the contribution of land-use change to these ecosystem services; and (4) investigate the spatial distribution of trade-offs and synergies among ecosystem services. By advancing the understanding of the complex interactions between land use and ecosystem services, this research aimed to provide critical insights for optimising restoration strategies and offer evidence-based guidance for the sustainable management of land and ecosystem resources in the GGW region.

2. Materials and methods

2.1. Study area

The GGW area (Fig. 1) was officially delineated for the Sahel by the African Union and FAO under the Africa Open DEAL programme (FAO & AU, 2022). It is the core focus of the continent-wide initiative and covers about 241 million ha across 11 countries from Senegal to Djibouti. The GGW–Sahel region forms an ecological transition zone between the Sudanian savannah and the arid Sahara Desert, with a buffer extending about 50–100 km (around 1 degree latitude) northward and southward to capture adjacent semi-arid ecosystems.

The region consists mainly of undulating plateaus interspersed with wetlands and major water bodies such as the Senegal Delta, Niger River and Lake Chad (Moser et al., 2014). The climate is arid to semi-arid tropical monsoon, with frequent sand and dust storms. Annual rainfall ranges from about 150 mm in the north to 700 mm in the south. Vegetation is dominated by open herbaceous cover with scattered woody species, particularly belonging to the *Acacia* and *Commiphora* genera (Wu et al., 2020; Zida et al., 2020). Local populations depend heavily on ecosystem services, including water conservation, food and medicine from desert-adapted plants, and sand-fixation services (Safriel et al., 2005; Belem and Saqalli, 2017; Ghazi et al., 2018; Malmborg et al., 2018; Sinare et al., 2022).

2.2. Data sources

We used multiple spatial datasets to assess land-use dynamics and ecosystem service changes. Land-cover information was taken from the official MODIS Land Cover Type product MCD12Q1 Version 6.1 for 2007, 2013 and 2019. These years correspond to GGW implementation milestones: the launch of the initiative (2007), the establishment of most national GGW agencies and major programmes such as SAWAP and FAO's Action Against Desertification (2013), and the completion of the 2000–2019 Africa Open DEAL assessment and release of harmonised land-use and biomass datasets for UNFCCC, UNCCD and CBD reporting (FAO & AU, 2022).

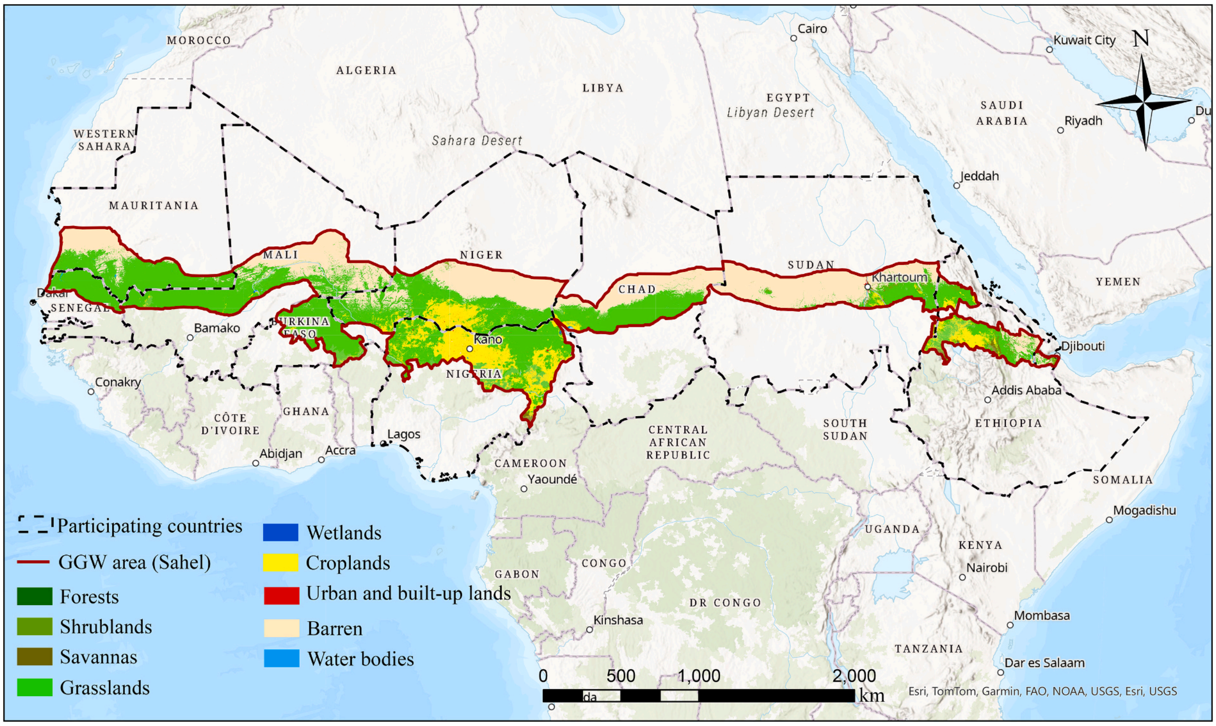

Fig. 1. Study area and LULC map of the Great Green Wall invention area in 2007. The GGW area (outlined in red) spans multiple Sahelian countries, with different land cover types including forests, shrublands, savannas, grasslands, wetlands, croplands, urban and built-up lands, barren (indicates sparsely vegetated or unvegetated surfaces in MODIS), and water bodies. Participating countries are indicated with dashed boundaries. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Meteorological, topographic, soil and vegetation datasets were used to drive the ecosystem service models. Precipitation, temperature and wind speed were used to estimate water yield and wind erosion. Elevation, slope and aspect (from a digital elevation model; DEM) informed water flow and soil erosion. Soil texture and soil organic carbon characterised soil erodibility, carbon storage and sand stabilisation. The Normalized Difference Vegetation Index (NDVI) was used as a proxy for vegetation productivity and to allocate national grain production to cropland grids. Datasets were chosen for their relevance to ecosystem service modelling and their availability across the region (Table 1).

All meteorological, topographic, soil, vegetation and land-cover datasets used as model inputs were harmonised to a common analysis grid. Each dataset was clipped to the GGW boundary (FAO & AU, 2022), reprojected to an equal-area coordinate system and resampled to 1 km × 1 km so that layers could be overlaid. For continuous variables (precipitation, NDVI and evapotranspiration) we used bilinear interpolation; for categorical variables such as land cover, we used nearest-neighbour resampling. The 500 m MODIS products (MCD12Q1, MOD13A1 and MOD16A2) and the 30 m ASTER DEM were aggregated to 1 km by averaging source pixels. Annual time series for 2007–2019 were created by aggregating the original temporal products. Biomass data were only clipped to the GGW boundary and reprojected and were always used at their original spatial resolution to avoid introducing additional uncertainty through resampling.

Before running the ecosystem service models, we removed no-data and out-of-range values based on the metadata of each product and visually inspected maps for obvious artefacts or unrealistic spatial patterns. For the MODIS vegetation and evapotranspiration products we

Table 1
Datasets used to calculate changes in land use and ecosystem services of the GGW area.

Specific data	Year	Type	Source	Resolution
Land use/land cover	2007, 2013, 2019	Raster	The Terra and Aqua combined MODIS Land Cover Type (MCD12Q1) Version 6.1(Friedl and Sulla-Menashe 2022b)	500 m × 500 m
Annual precipitation	2007–2019	Raster	Monthly precipitation in mm (multisource average) based on SM2RAIN-ASCAT, CHELSA Climate and WorldClim (Hengl and Parente 2022)	1 km × 1 km
Digital elevation model (DEM)	2009	Raster	ASTER Global Digital Elevation Model V003 (NASA/METI/AIST/Japan Spacesystems and U.S./Japan ASTER Science Team, 2001)	30 m × 30 m
Potential evapotranspiration	2007–2019	Raster	The MOD16A2 Version 6.1Evapotranspiration/Latent Heat Flux product (Running et al. 2021)	500 m × 500 m
NDVI	2007–2019	Raster	The Terra MODIS Vegetation Indices 16-Day (MOD13A1) Version 6.1 (Didan 2021)	500 m × 500 m
Soil database	2017	Raster	OpenLandMap Soil Texture Class (USDA System) (Tomislav, 2018) OpenLandMap Soil Organic Carbon Content (Tomislav and Ichsani, 2018)	250 m × 250 m
Aboveground Biomass (AGB)	2007–2019	Raster	Above-Ground Biomass (AGB) Stock and Change Product (Chloris Geospatial, 2024)	4633 m × 4633 m
Temperature	2007–2019	Numeric	Global Surface Summary of the Day – GSOD (NOAA National Centers of Environmental Information 1999a)	–
Wind speed	2007–2019	Numeric	Global Surface Summary of the Day – GSOD (NOAA National Centers of Environmental Information 1999b)	–
Grain production	2007–2019	Numeric	Our World in Data (https://ourworldindata.org/)	–

checked that major spatial and temporal gradients were consistent with the known rainfall and vegetation belts across the Sahel. We also relied on the published global validation of the MCD12Q1, MOD13A1 and MOD16A2 products (Didan, 2021; Running et al., 2021; Friedl and Sulla-Menashe, 2022), the ASTER DEM (NASA/METI/AIST/Japan Spacesystems and U.S./Japan ASTER Science Team, 2001), the OpenLandMap soil datasets (Tomislav, 2018; Tomislav and Ichsani, 2018) and the Chloris biomass dataset (Chloris Geospatial, 2024), and concluded that the combined datasets were suitable for large-scale ecosystem service assessment.

2.3. Methods

2.3.1. Quantifying spatial distribution and temporal trends in land-use change

Land cover data were obtained from the official MODIS Land Cover Type product MCD12Q1 Version 6.1, distributed by the NASA LP DAAC. This standard product integrates near-daily Terra and Aqua surface reflectance observations over each calendar year and uses supervised ensemble decision-tree classifiers, combined with ancillary information and temporal post-processing, to generate one global land cover map per year (Friedl et al., 2002; Friedl et al., 2010). Each yearly composite assigns a single predominant land cover class to each pixel based on the International Geosphere–Biosphere Programme (IGBP) classification scheme (Loveland and Belward, 1997). We used the annual MCD12Q1 maps for 2007, 2013 and 2019 as our three land-use snapshots. The 17 IGBP land cover types were aggregated into nine broader categories—forest, shrubland, savanna, grassland, cropland, urban/built-up, wetland, water body and barren (Table A1). In the MODIS IGBP scheme, “barren” corresponds to “barren or sparsely vegetated” areas (i.e., bare soil, sand, or rock with vegetation cover typically $<10\%$), which are common in desert and desert-margin environments. This aggregation ensures consistency with global classification systems relevant to monitoring dryland ecosystems and combating desertification.

1) Land-use transfer matrix

We used land-use transfer matrices to quantify the area and direction of conversion among land cover types (Fang et al., 2022). This approach describes how land-use structures evolve between two time points by summarising the mutual transformations among categories (Mostafazadeh, 2021). Transfer matrices were constructed for 2007–2013, 2013–2019 and 2007–2019 from the reclassified MODIS maps. These matrices reveal both short- and long-term land-use transitions, such as grassland-to-cropland or barren-to-vegetation and allow the dominant conversion pathways to be identified.

2) Land-use dynamic degree

The land-use dynamic degree quantifies the rate and magnitude of land-use change over a given period (Schilling et al., 2010; Zhang et al., 2014; Mostafazadeh 2021; Liu et al., 2023). This method measures the intensity of land-use transformation and describes how rapidly land-use change over time (Redo et al., 2012). We calculated the dynamic degree for 2007–2013 and 2013–2019 to compare regional differences and broader trends in land-use dynamics, using the standard formulation

$$K_i = \frac{U_b - U_a}{U_a} \times \frac{1}{T} \times 100\% \tag{1}$$

where K_i is the dynamic degree of one land use type i; U_a and U_b indicate the area of the land use type at the beginning and end of the study period respectively; T is the length of study period.

2.3.2. Assessing spatiotemporal changes in ecosystem services

Ecosystem service indicator selection was guided by GGW objectives, data availability and the need for a framework that can be applied consistently over large areas and long time periods. Following the Common International Classification of Ecosystem Services (CICES; Haines-Young and Potschin 2012), the five selected ecosystem services fall into two categories: provisioning services (grain production) and regulating services (carbon stock, water yield, soil conservation, and sand stabilisation). This classification provides a consistent basis for interpreting spatial heterogeneity and trade-offs among services across the GGW region. Each selected service is ecologically important, directly relevant to regional livelihoods, and suitable for spatially explicit modelling. Among regulating services, carbon stock and water yield relate to climate regulation and hydrological balance in the arid and semi-arid Sahel (Song et al., 2023; Tucker et al., 2023), while soil conservation and sand stabilisation capture key processes linked to land degradation and desertification control, in line with GGW targets and SDG 15 (Zhao et al., 2021b; Han et al., 2023). The provisioning service, grain production, underpins SDG 2 (Zero Hunger) and food security in predominantly rain-fed agricultural systems (Liu et al., 2023a).

1) Carbon stock (Aboveground biomass)

Aboveground biomass (AGB), defined as the mass of living vegetation above ground, is widely used as a proxy for terrestrial carbon stock (Becknell et al., 2012; Mensah et al., 2020; Wang and Jiao 2020; Habib et al., 2023). We used spatial AGB data from the Chloris Global Biomass 2003–2019 dataset (Chloris Geospatial, 2024), which provides global annual estimates of biomass stock and change for woody vegetation at a ground sampling distance of 4633 m (i.e., the approximate ground dimension represented by one raster pixel). The product is generated by fusing ICESat/GLAS LiDAR reference observations with MODIS Terra and Aqua optical imagery using machine-learning algorithms that synthesise annual biomass maps from cloud-free observations. It has been validated against independent airborne LiDAR and field measurements (Baccini et al., 2012; Baccini et al., 2017). We used the Chloris dataset directly at its original spatial resolution. Annual AGB values for 2007–2019 were extracted for the GGW region, and biomass change was quantified using interannual variation across the full time series.

2) Water yield

Water yield represents the amount of available surface water and was used to evaluate hydrological responses to vegetation and land-use change. We simulated annual water yield Y_x (mm yr^{-1}) with the InVEST (v3.3.3) water-yield model, which is based on the Budyko framework and uses average annual precipitation (P_x) and actual evapotranspiration (AET_x):

$$Y_x = \left(1 - \frac{AET_x}{P_x}\right) \times P_x \tag{2}$$

Where Y_x is annual total water yield (mm yr^{-1}); AET_x is the actual annual evapotranspiration (mm) for pixel x and P_x is the mean annual precipitation (mm) in pixel x. The InVEST model was selected because it requires only widely available climate, soil and land-cover inputs, has been widely applied in regional ecosystem service assessments and is well suited to large-scale hydrological analysis in data-scarce dryland regions such as the GGW.

3) Soil conservation

Soil conservation is a regulating ecosystem service that reduces rainfall-induced erosion through vegetation cover and land surface structure (Li et al., 2022). We estimated annual soil conservation (t km^{-2} yr^{-1}) as the difference between potential soil erosion under bare soil and actual soil erosion under current land cover, using the Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1994; Renard 1997;

Mati and Veihe 2001). RUSLE provides a simple but robust representation of water-driven soil erosion that can be implemented with widely available spatial data. It has been extensively used in regional and global assessments, making it suitable for a large and data-scarce region, such as the GGW. Annual soil conservation S_c (t km^{-2} yr^{-1}) for each 1 km × 1 km grid cell was calculated as:

$$S_c = S_p - S_a \quad (3)$$

$$S_p = R \times K \times LS \quad (4)$$

$$S_a = R \times K \times LS \times C \times P \quad (5)$$

Where S_c is the annual soil conservation (t km^{-2} yr^{-1}), S_p and S_a are the potential and actual soil erosion (t km^{-2} yr^{-1}), respectively; R is rainfall erosivity factor (MJ mm km^{-2} h^{-1} yr^{-1}). K is soil erodibility factor (t km^{-2} h MJ^{-1} mm^{-1}); LS, C and P are the slope length and steepness, land use/cover, and support practice factors respectively (Appendix D3).

4) Sand stabilisation

Sand stabilisation is an ecosystem service that mitigates wind-driven soil erosion by enhancing surface stability through vegetation cover and soil properties (Becker and Segev, 2016; Li et al., 2018; Han et al., 2023). It was estimated on an annual basis (t km yr^{-1}) as the difference between potential soil erosion (i.e., erosion under bare soil conditions) and actual soil erosion, following the Revised Universal Soil Loss Equation (RUSLE) (Fryrear et al., 1999; Fenta et al., 2020; Zhao et al., 2021a):

$$SR = SL_p - SL_a \quad (6)$$

Where SR represents the amount of sand stabilisation (t km^{-2} yr^{-1}); SL_p is the potential wind erosion amount (t km^{-2} yr^{-1}); SL_a is the actual wind erosion amount (t km^{-2} yr^{-1});

RWEQ explicitly represents key climatic, surface and vegetation controls on wind erosion and has been widely applied in arid and semi-arid regions, which makes it an appropriate framework for assessing sand stabilisation across the GGW (Appendix D3).

5) Grain production

Grain production represents the capacity of agricultural ecosystems to provide staple food for humans and livestock. Following FAO and Our World in Data (FAO 2023), we used national statistics for eight major grains (wheat, rice, barley, maize, oats, millet, sorghum and potatoes) for 11 GGW countries and spatially allocated them to cropland grids.

To capture spatial variation within each country, national grain production was allocated to cropland based on annual mean NDVI from the MOD13A1 product (v6.1). For each year, 16-day NDVI composites were averaged to represent overall vegetation growth conditions. Previous studies have shown a strong linear relationship between NDVI and grain yield (GROTEN 1993; Ren et al., 2008). The NDVI-weighted allocation of national grain statistics provides a simple and consistent way to approximate the spatial distribution of grain production in the absence of harmonised subnational yield data. Grain production per cropland grid cell (1 km × 1 km) was calculated as (Peng et al., 2016; Peng et al., 2017; Hu et al., 2018):

$$G_i = \frac{NDVI_i}{NDVI_{sum}} \cdot \sum G_c \cdot E_c \quad (7)$$

where, G_i is the annual grain production (KJ km^{-2} yr^{-1}) of the i^{th} cropland grid and G_c is the production of grain c (t yr^{-1}) of each country in GGW area. $NDVI_i$ represents the NDVI of the i^{th} cropland grid, and $NDVI_{sum}$ is the sum of NDVI values of all cropland grids within the corresponding country, and E_c (KJ t^{-1}) is the caloric content of grain c. Converting yields into energy content facilitates comparison of grain-supply capacity across crop types.

6) Trend analysis of ecosystem services using the Sen-MK method

To assess long-term trends in ecosystem services across the GGW region, we applied the Theil–Sen median trend estimator in combination with the Mann–Kendall test (hereafter Sen–MK). This non-parametric approach does not require the data to be normally distributed, is robust to outliers and missing values, and performs well with relatively short time series, making it suitable for our 13-year records of ecosystem service indicators. It has been widely used in ecological and hydrological studies to distinguish persistent trends from natural variability in climate and vegetation time series (Fensholt et al., 2012; Zhang et al., 2024), and is therefore appropriate for evaluating gradual restoration signals in the data-scarce dryland context of the GGW.

For each ecosystem service and grid cell, the Sen slope β was used to quantify the rate of change over time as the median of all pairwise slopes between years. A positive β indicates an increasing trend and a negative β a decreasing trend. The Mann–Kendall statistic S and its standardised Z value were then used to test the significance of the monotonic trend (see details in SI). When |Z| exceeded the critical value $Z_{1-\alpha/2}$ at the 0.05 level, the trend was considered statistically significant. For mapping and summary statistics, we classified trends as highly significant, significant, marginally significant or non-significant according to Z-score thresholds (Appendix D4, Table A6).

2.3.3. *Evaluating the contribution of land-use change to ecosystem services using ESCI*

The Ecosystem Service Contribution Index (ESCI) quantifies how different land-use transitions affect ecosystem services in the GGW (Zhang et al., 2020). It measures the change in an ecosystem service per unit area of land-use change and therefore allows positive and negative effects on services to be assessed. Derived from the economic concept of elasticity, ESCI reflects the responsiveness of ecosystem services to changes in land use (Kreuter et al., 2001; Aschonitis et al., 2016). Grain production was excluded from ESCI calculations because it is specific to cropland, and changes in other land-use categories do not directly influence this service.

$$ESCI_{ij} = \frac{\Delta ES_{ij}}{\Delta S_{ij}} \times P_{ij} \quad (8)$$

where $ESCI_{ij}$ represents the contribution of land-use conversion from type i to type j; ΔES_{ij} is the change in the ecosystem service associated with conversion from i to j; ΔS_{ij} is the area converted; and P_{ij} is the proportion of conversion from i to j in the total converted area. $ESCI_{ij} > 0$ indicates a positive contribution, and larger values indicate stronger benefits to the service. Four ecosystem services were evaluated: carbon stock (CSCI), soil conservation (SCCI), sand stabilisation (SSCI), and water yield (WYCI).

2.3.4. *Investigating trade-offs and synergies among ecosystem services using spatial autocorrelation analysis*

Geographical phenomena often show spatial correlation due to spatial interactions and diffusion (Wartenberg 1985). As a result, trade-offs and synergies among ecosystem services can vary across locations. To explore these spatial relationships, we used bivariate Moran's I, which describes the correlation between the spatial distributions of two variables (Anselin et al., 2002). We then mapped local clusters using Local Indicators of Spatial Association (LISA) to identify zones where pairs of ecosystem services show trade-offs or synergies (Liu et al., 2018; Zhou et al., 2019; Chen and Chi 2023). We constructed a spatial weight matrix using the Weight module in GeoDa, calculated bivariate local Moran's I between pairs of ecosystem services, and mapped the resulting LISA clusters (Anselin 2003; Zhou et al., 2019; Shi et al., 2022). In the LISA maps, High–High and Low–Low clusters indicate synergies, whereas High–Low and Low–High clusters indicate trade-offs.

3. Results

3.1. Spatial distribution and temporal trends in land-use change

Grasslands were the dominant land cover category (52% in 2007 falling to 51% in 2019; Fig. 2, Table 2). Barren ranked second (35% on average), followed by croplands (12% in 2007 rising to 13% in 2019), while forests occupied less than 0.01% on average. The LULC transfer matrices from 2007 to 2013 (Table A2), from 2013 to 2019 (Table A3), and from 2007 to 2019 (Table A4) with the corresponding Sankey diagram (Fig. 2) visualise the following results. Overall, the area of forests, croplands, urban/built-up lands, and barren increased between 2007 and 2019. Croplands increased by 16,853 km^2 with an expansion rate of 1404 km^2 yr^{-1} and a dynamic degree of 0.5%. The area of barren land increased by 7446 km^2.

Fig. 3 shows that western Mauritania, Mali, western Niger, central Chad, eastern Sudan, and northern Ethiopia experienced varied levels of grassland degradation. The areas of forest grew with a dynamic degree of 6.98%, but due to the low initial proportion of forest, there was little increase in its absolute area. Urban/built up lands showed an increase, with the dynamic degree remaining at 0.17%. Shrublands and grasslands both exhibited an overall declining trend. Shrubland area increased between 2007 and 2013 but subsequently declined, resulting in a net loss of 12.2% by 2019, with a dynamic degree of −0.93%. This decline was mainly due to the conversion of shrubland to grassland. The most notable transitions occurred along the north-western coast of Senegal (Fig. 3a), near the border with Mauritania, as well as in south-eastern Mali (Fig. 3b). The intimate, often linear patterns of bidirectional transitions between barren land and grassland in this area likely reflect traditional agro-pastoral land management combined with interannual rainfall variability (Brottem et al., 2014; Ouedraogo et al., 2014; Wu et al., 2020). Notable transitions were also observed in Nigeria (Fig. 3c), Ethiopia and south-east Djibouti (Fig. 3d). Grassland, the dominant land cover in the region, declined by 23,305 km^2 over the study period. The main transitions from grassland were to cropland, barren land, shrubland, and savanna. Wetlands expanded between 2007 and 2013, then declined between 2013 and 2019, resulting in a net change of +22.5% over the entire period. Water bodies showed a slow growing and fluctuating trend, expanding by 48 km^2.

Table 2
Area and dynamic degree (K) of various LULC types in the GGW area from 2007 to 2019 (Area unit: $\times 10^3$ km^2, K unit: %).

LULC	2007	2013	2019	Dynamic Degree K (%)
	Area ($\times 10^3$ km^2)			
Forests	0.07	0.07	0.12	6.98
Shrublands	17.03	23.84	14.97	−0.93
Savannas	11.71	9.92	12.39	0.45
Grasslands	1238.16	1209.91	1214.86	−0.14
Croplands	286.48	301.89	303.33	0.45
Barren	839.27	846.71	846.72	0.07
Wetlands	0.76	0.97	0.94	1.73
Urban/built-up lands	4.53	4.57	4.62	0.17
Water bodies	3.50	3.62	3.55	0.11

3.2. Spatiotemporal changes in ecosystem services

3.2.1. Carbon stock (Aboveground biomass)

The spatial distribution of AGB was heterogeneous, with lower values in the arid northern regions (<5000 t km^{-2}) and higher values in the southern areas, primarily concentrated in the Ethiopian Highlands and Nigeria (Fig. 4a, b). AGB in the Sudanic savannah region declined markedly, particularly in the southernmost part of the GGW; overall, AGB decreases covered 9.1% of the entire GGW area (Fig. A2, Fig. 5). These declines were concentrated in locations where shrubland and grassland were converted to cropland and urban land. Conversely, regions experiencing significant increases in AGB were mainly located in the eastern Ethiopian Highlands and northern Nigeria within the GGW (Fig. 4a, 4b), where land-cover transitions from cropland to grassland and shrubland were most frequent. Overall, total AGB within the GGW increased from 495 million tonnes in 2007 to 521 million tonnes in 2019, representing a cumulative gain of approximately 26 million tonnes, equivalent to roughly 13 million tonnes of carbon.

3.2.2. Water yield

Water yield exhibited a distinct north–south spatial gradient, with maximum values reaching 1720 mm yr^{-1} in 2019 (Fig. A3). The regional mean water yield increased from 171 mm yr^{-1} in 2007 to 191mm yr^{-1} in 2019, representing an 11.7% rise, driven by a combination of regional precipitation recovery and land cover change. The Sen-MK trend analysis showed that 70.3% of the study area experienced significant or

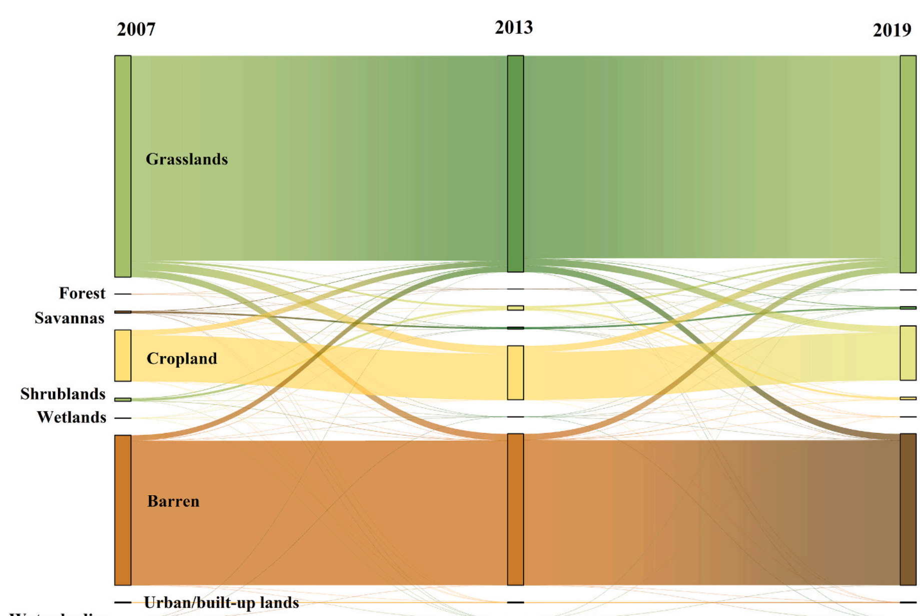

Fig. 2. Sankey diagram of shifts among different land use types in GGW area between 2007 and 2019.

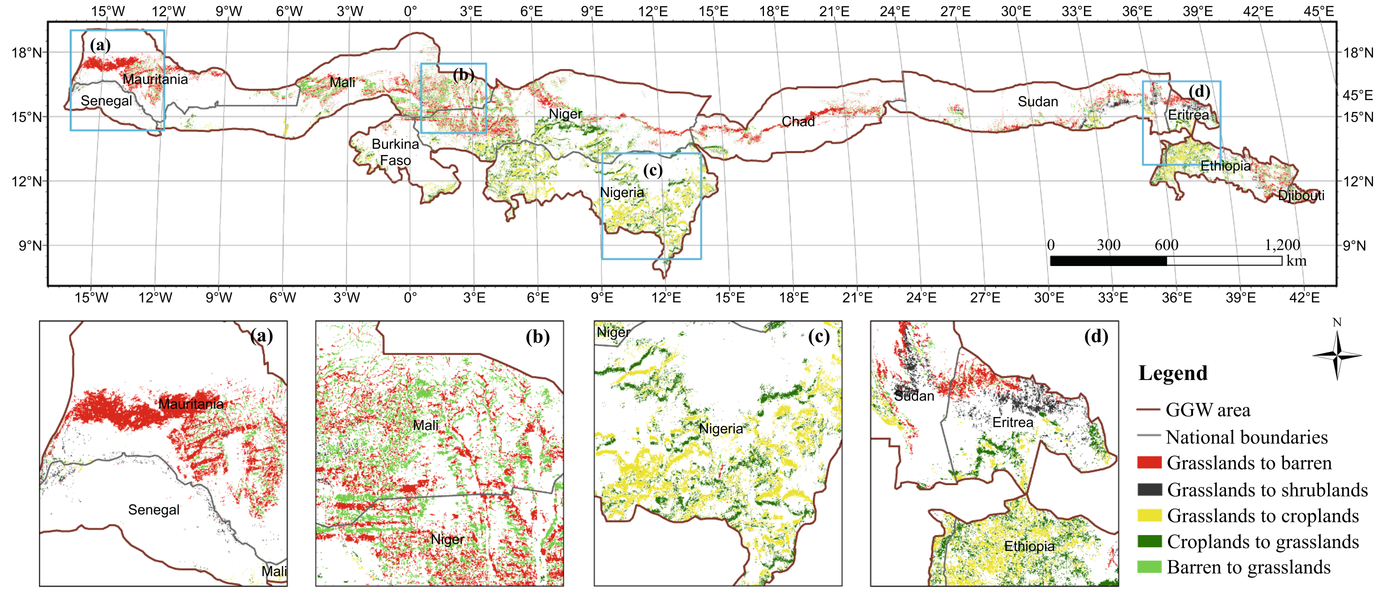

Fig. 3. Spatial distribution of main LULC transitions from 2007 to 2019 The GGW project area is outlined in red, with detailed insets showing specific regions in (a) Senegal, (b) Mali, (c) Nigeria, and (d) Ethiopia, where significant transitions have occurred. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

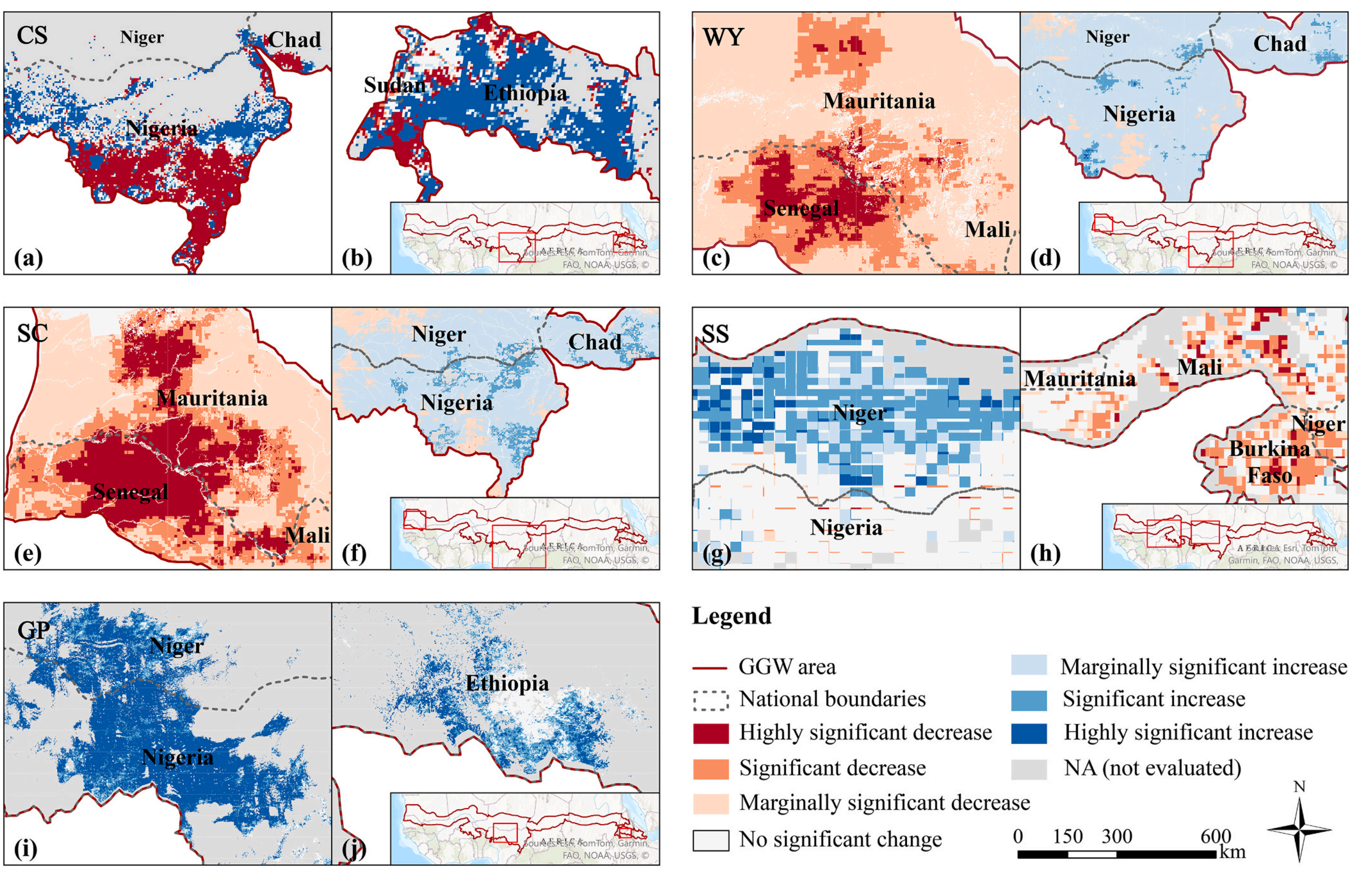

Fig. 4. Spatial patterns of ecosystem service trends across the GGW region from 2007 to 2019 derived from the Sen–MK analysis. Panels show trends in (a, b) carbon stock (above-ground biomass), (c, d) water yield, (e, f) soil conservation, (g, h) sand stabilisation and (i, j) grain production. Colours indicate highly significant, significant and marginally significant increases or decreases, areas with no significant change, and pixels not evaluated, as defined in the legend. In the ecosystem service maps and summary statistics, cells labelled as "NA (not evaluated)" denote locations where the corresponding service was not modelled because the land cover does not provide that service (e.g. non-cropland for grain production, non-vegetated land for AGB) or key input variables (e.g. soil properties needed for the wind erodibility factor EF) are missing.

highly significant increases in water yield (Fig. 5), while decreases were restricted to localised zones, notably across 62,651 km^2 in Senegal and

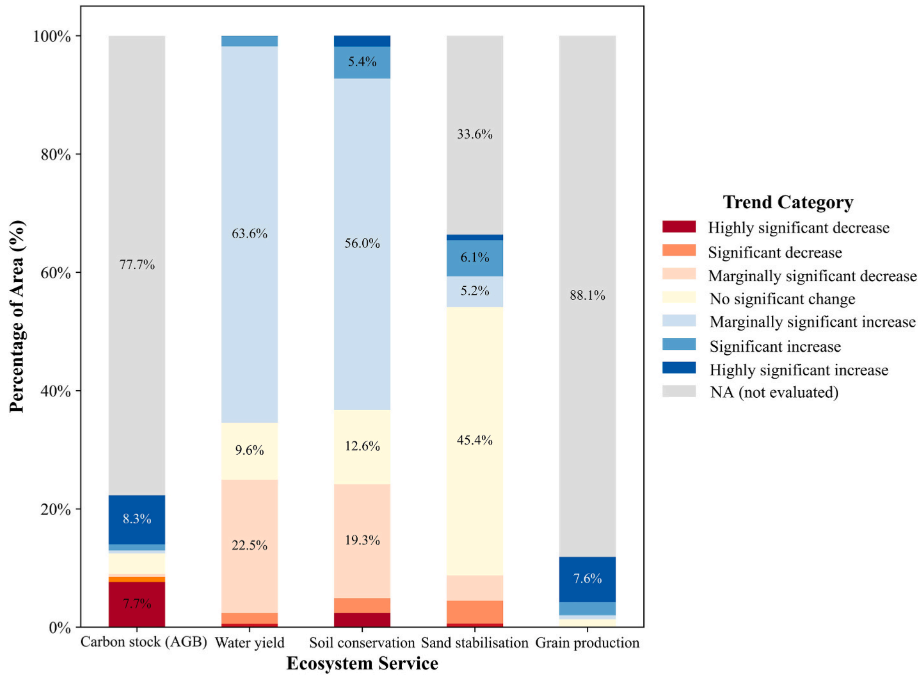

Fig. 5. Proportional distribution of ecosystem service changes from 2007 to 2019 by magnitude category.

Mauritania (Fig. 4c). Significant and highly significant decreases in water yield in these zones occurred in areas that remained grassland throughout the study period, whereas marginally significant decreases elsewhere coincided with transitions from barren land to grassland or shrubland.

3.2.3. Soil conservation

Soil conservation generally increased from north to south across the region. The central and northern areas had weaker soil conservation capacity, with soil retention per unit area falling below 1000 t km^{-2} yr^{-1}. In regions with dense vegetation and higher elevations, such as the Jos Plateau in Nigeria and the Ethiopian Highlands, soil conservation reached its highest levels (Fig. A4). Total annual soil conservation across the region increased from 952 million tonnes in 2007 to 1045 million tonnes. 56.0% of the area experienced a slight growth, with patches in northern Burkina Faso, central Nigeria, southern Chad, and eastern Ethiopia showing significant increase in soil conservation (Fig. 4f, Fig. A4). Conversely, similar to the trends in water yield, soil conservation levels in the western coastal regions have significantly declined (Fig. 4e), covering 4.9% of the area (Fig. 5). The enhancement of soil conservation in central and eastern regions coincided with land-cover transitions from cropland and barren land to grassland or shrubland, whereas decreases in the western coastal regions occurred predominantly in areas where grassland was replaced by cropland, urban land or barren surfaces.

3.2.4. Sand stabilisation

Sand stabilisation services were primarily concentrated in the central and northern areas, particularly in Mali, Niger, and northern Chad (Fig. A5). In 2007, the average sand stabilisation service across the entire GGW region was 97t km^{-2} yr^{-1}. By 2019, sand stabilisation had significantly improved in central Niger and Chad, with the regional average increasing to 469 t km^{-2} yr^{-1} (Fig. 4g, Fig. 5). These increases occurred mainly in areas mapped as grassland and cropland throughout the study period, with local patches where barren land was converted to grassland. However, 4.5% of the region experienced a decline in sand stabilisation, particularly in southern Mali and Burkina Faso, where the strongest declines were concentrated in zones where grassland was replaced by barren land or cropland (Fig. 4h, Fig. 5).

3.2.5. Grain production

Grain production across the GGW region exhibited an overall increasing trend, with production concentrated in agricultural zones and following a north-to-south gradient in the central study area (Fig. A6). The highest production value in 2007 (762,428 KJ km^{-2} yr^{-1}) was recorded in southern Nigeria, while western Ethiopia also exhibited relatively high levels. Between 2007 and 2019, 11.0% of the study area experienced increases in grain production, with the regional mean rising by approximately 31.1%, from 328,013 to 429,991 KJ km^{-2} yr^{-1} (Fig. 4i, Fig. 5). In contrast, production declines were minimal, affecting only 0.03% of the total area, primarily in central Niger and northern Burkina Faso (Fig. 4j).

3.3. Contribution of land-use change to ecosystem services

From 2007 to 2019, land-use change differentially affected four ecosystem services (soil conservation, sand stabilisation, water yield, and carbon stock) with impacts varying significantly by land cover. The directions and magnitudes of the impacts were quantified using ESCI, including SCCI, SSCI, WYCI, and CSCI (Fig. 6).

Increases in forest, grassland, savanna, and shrubland cover were associated with enhanced carbon stock, with the most substantial contribution from the conversion of cropland to grassland (CSCI = 6.43). Conversely, conversions to urban/built-up areas, barren land, and croplands had negative impacts on carbon stock. Land conversions from barren areas generally improved ecosystem services, particularly sand stabilisation, with the conversion of barren to grassland having the most significant effect (SSCI = 26.27). Conversion of grassland to cropland had a strongly negative impact on sand stabilisation. The degradation of shrubs, forests, and savanna also reduced sand stabilisation capacity. Transitions from cropland to forest, savanna, shrubland, and grassland enhanced soil conservation, with the conversion to grassland having the most pronounced effect (SCCI = 354.63). The transition from forest to other land use negatively affected soil conservation, particularly in the case of forest-to-grassland conversion (SCCI = −13.14). For water yield, the conversion of grassland to cropland showed the largest positive

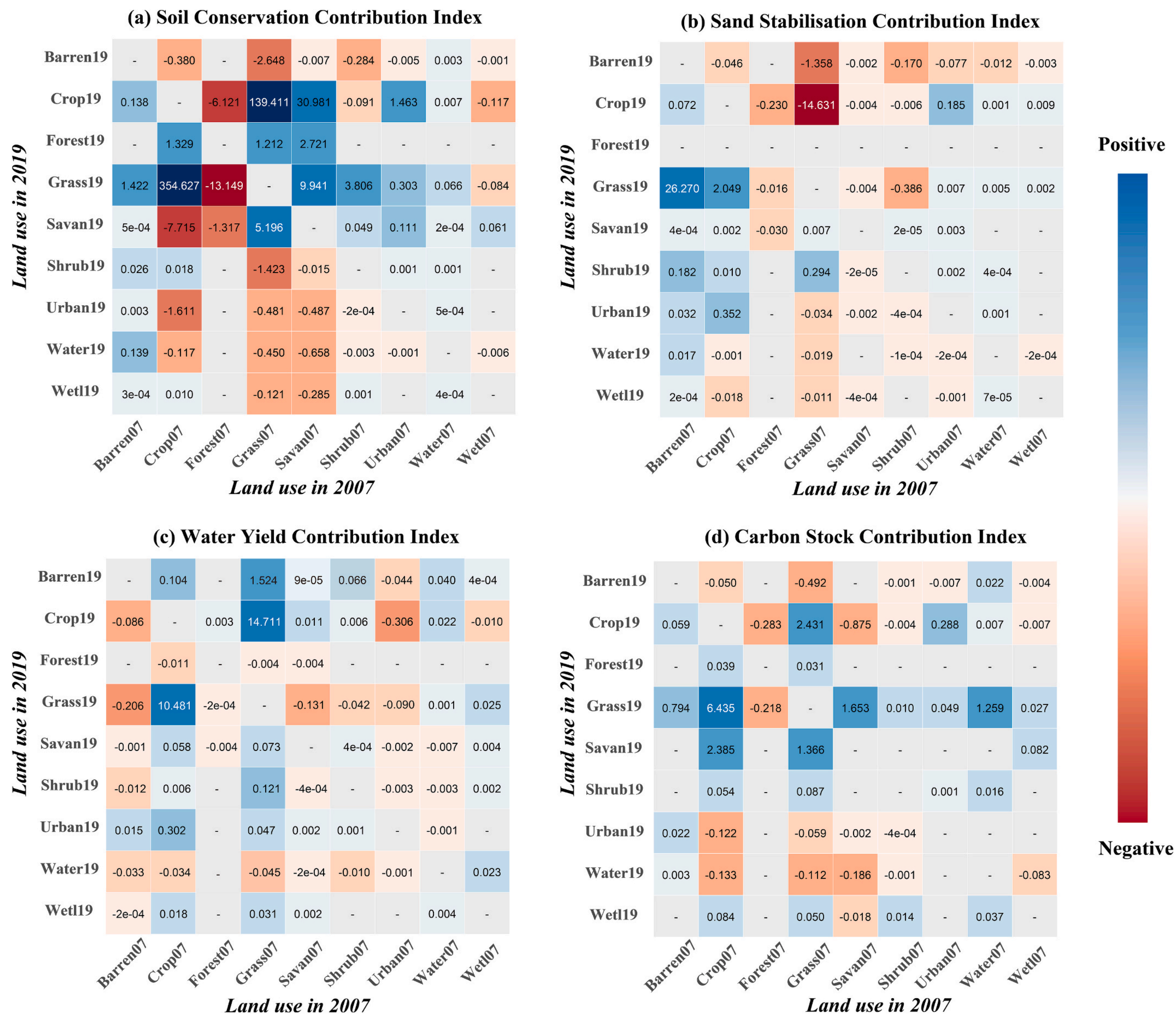

Fig. 6. Contribution index of land-use conversion on changes in ecosystem services (2007–2019). Panels show the Soil Conservation Contribution Index (SCCI), Sand Stabilisation Contribution Index (SSCI), Water Yield Contribution Index (WYCI), and Carbon Stock Contribution Index (CSCI). Each matrix cell represents the contribution of land-use conversion from 2007 (x-axis) to 2019 (y-axis) to the corresponding ecosystem service. Positive values (blue) indicate improved service provision, while negative values (red) indicate declines. Colour intensity reflects the magnitude of the effect. "Barren" = Barren land, "Crop" = Cropland, "Grass" = Grassland, "Savan" = Savanna, "Shrub" = Shrubland, "Urban" = Urban and built-up land, "Water" = Water bodies, "Wetl" = Wetland. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

contribution (WYCI = 14.71), likely because annual crops have lower evapotranspiration than perennial grassland vegetation. Land-cover transitions to forest generally showed negative WYCI values, indicating reduced water yield. Conversions from barren land to vegetated types such as grassland and shrubland also predominantly had negative WYCI values, whereas transitions from most land cover types to urban and built-up areas were associated with positive WYCI values.

3.4. Ecosystem service trade-offs/synergies and influencing mechanisms

In the eastern Ethiopian Highlands, carbon stock was positively correlated with water yield and soil conservation (Fig. 7a–d). Synergies between carbon stock and sand stabilisation were observed in the arid regions of Sudan and Eritrea in the northeast (Fig. 7c). However, a trade-off between carbon stock and water yield was evident in the central region, where increased carbon stock coincided with reduced water yield (Fig. 7a).

In the arid north, soil conservation and water yield exhibited a trade-off, where soil conservation increases were associated with reduced water yield (Fig. 7e). Sand stabilisation and water yield showed a positive correlation in the dry northern regions, while sand stabilisation and soil conservation displayed a trade-off (Fig. 7f). In contrast, in the wetter and more densely vegetated southern regions, including southern Nigeria and the Ethiopian Plateau, sand stabilisation and water yield, as well as soil conservation, were counterbalanced (Fig. 7f).

In the south-central and western parts of the region, higher cropland and grassland cover coincided with increased grain production. Grain production was concentrated in the central and southern agricultural zones. In these areas, cropland expansion corresponded with a decline in wind erosion control capacity (Fig. 7k). In the central region, a trade-off between grain production and soil conservation was evident, with limited synergies (Fig. 7j). Grain production and water yield were

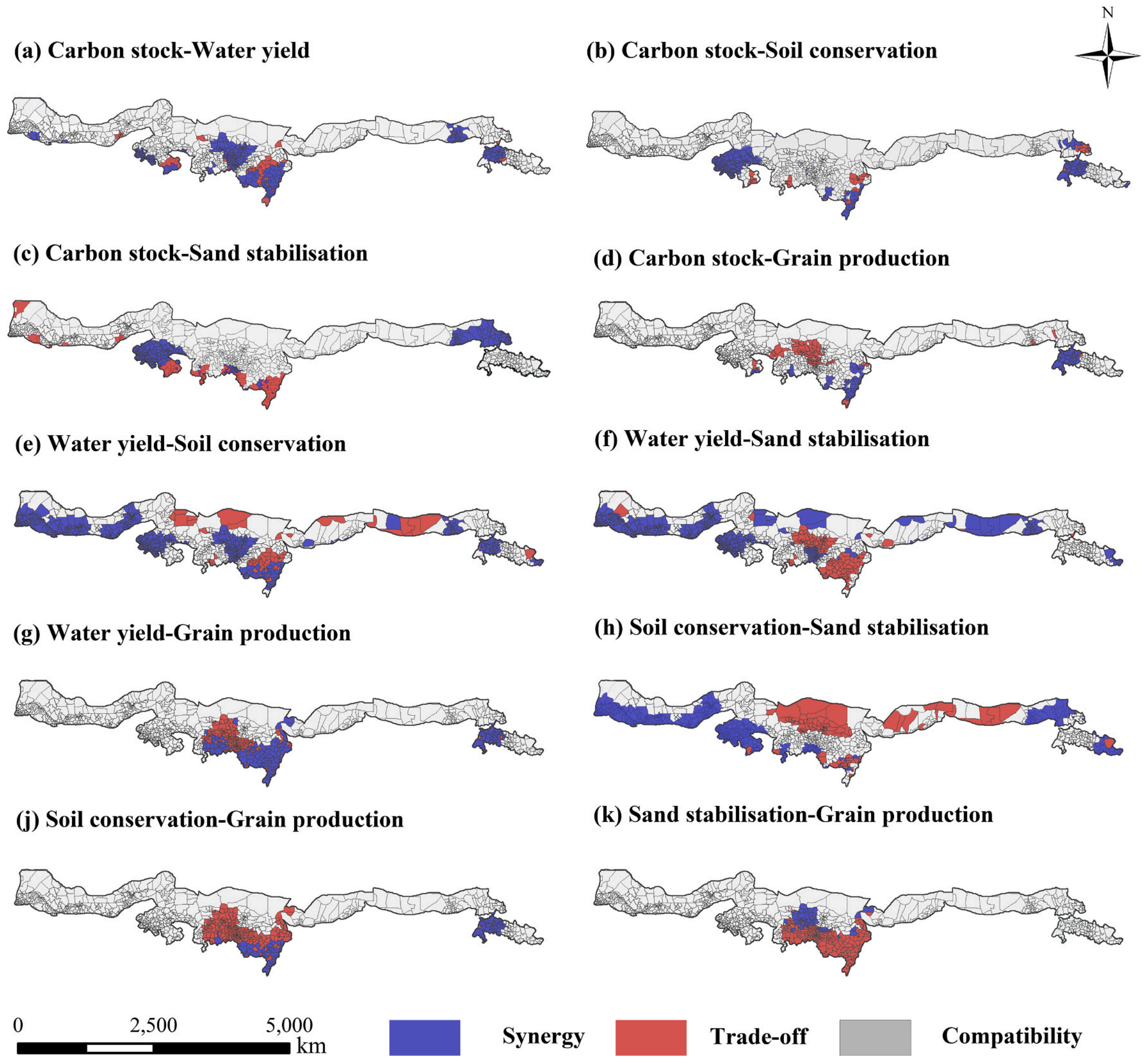

Fig. 7. Local indicators of spatial association (LISA) cluster map showing ecosystem service interactions in the GGW region (2007–2019). This figure illustrates the spatial relationships between pairs of ecosystem services in the Great Green Wall region from 2007 to 2019. Each map represents a different ecosystem service pair, with synergies (in blue) indicating areas where both services improve together, trade-offs (in red) showing areas where improvements in one service result in declines in the other, and compatibility (in grey) marking areas with no significant interaction. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

positively correlated in the southern farmland region but exhibited a trade-off in the central region (Fig. 7g).

4. Discussion

Land-use change between 2007 and 2019 strongly altered ecosystem service provision across the GGW region. Grasslands remain the dominant land cover despite an overall decline in grassland caused by cropland and barren expansion. In contrast to the overall trend, Southern Nigeria and the Ethiopian Highlands exhibited localized grassland gains, resulting mainly from cropland-to-grassland transitions. These changes produced spatial differences in ecosystem service dynamics. Regulating services such as carbon stock, soil conservation and sand stabilisation increased in several restored or naturally regenerating areas, whereas provisioning services, especially grain production, expanded in agriculturally favourable zones. However, grain production was accompanied by trade-offs with regulating services, notably reduced erosion control and soil stability. Our findings highlight both the ecological gains achieved through restoration and the continuing pressure from agricultural expansion, underlining the need for adaptive, region-specific strategies that balance restoration, production and resilience across the GGW landscape.

4.1. Spatial distribution and temporal trends in land-use change

Concerns about land-use dynamics in the GGW region centre on whether vegetation has been restored and the degree to which observed landscape changes can be attributed to GGW interventions. Our analysis reveals clear land-cover transitions, including shifts from barren or sparsely vegetated areas to shrub- and grass-dominated cover, as well as frequent exchanges between cropland and natural vegetation. The bidirectional exchanges between cropland and natural vegetation likely reflect traditional agroforestry and fallow systems, including farmer-managed natural regeneration practices that are widespread across the Sahel (Reij and Garrity 2016; Chomba et al., 2020). Such land-use systems may offer a sustainable pathway for integrating food production with vegetation restoration goals. Taken together, these patterns indicate that vegetation dynamics are shaped by a combination of restoration efforts, natural regeneration and ongoing agricultural expansion, with grassland loss emerging as a persistent concern.

Official reporting, however, paints a more optimistic picture. The UNCCD estimates that over 18 million hectares of degraded land have been rehabilitated across the GGW, mostly through non-traditional afforestation interventions (UNCCD, 2021). At first sight, this appears inconsistent with the modest forest gains detected in our land-cover maps between 2007 and 2019. This apparent discrepancy reflects how restoration is implemented in practice. Forest regeneration represents only a small share of reported outcomes and is largely confined to scattered community woodlots in places such as Nigeria's Adamawa and Taraba States, driven by local demand for fuelwood and construction timber (Borokini et al., 2012; Liman and Ngah 2015). Much of the reported restoration instead involves the dispersed planting of native, drought-tolerant species (Goffner et al., 2019). In most land-use classification systems, such vegetation is mapped as shrubland, sparse woodland or grassland rather than forest (Brandt et al., 2016). This helps to explain why MODIS-based maps detect extensive transitions from barren land to shrub- and grass-dominated classes, but only limited expansion of pixels classified as forest, and suggests that newly regenerating tree-dominated landscapes may be under-represented in coarse-resolution land-cover products.

Not all restoration is the result of direct planting. A substantial fraction is driven by FMNR, undertaken by smallholder farmers around their settlements (Abasse et al., 2023). These efforts are embedded within traditional land use systems characterized by cyclical rotations of vegetation, cultivation, and fallow phases (Mala et al., 2020), which enhance agroecosystem resilience while facilitating natural vegetation recovery. This dynamic helps to explain the complex, bidirectional transitions observed in our results between natural vegetation types (e.g. savanna, shrubland) and cultivated land, and the coexistence of vegetation restoration and agricultural expansion across the GGW zone.

An important limitation of our analysis, however, lies in the available information base. There is no region-wide, spatially explicit inventory of GGW interventions or standardised time-series monitoring framework, which prevents us from definitively attributing observed vegetation changes to specific restoration actions and from directly comparing our independent assessment with official progress reports (Turner et al., 2023; Vieitez-García and Roca 2024; Orou Sannou and Guenther 2025). In addition, our land-cover analysis relies on coarse-resolution satellite products such as MODIS (500 m). Many GGW interventions create small, mosaic-like patches of restored vegetation scattered across desert margins, rural settlements and savanna ecosystems. At this spatial resolution, land-use maps cannot always detect such small patches of change or reliably separate anthropogenically restored vegetation from naturally regenerated areas, which limits our ability to quantify fine-scale ecological responses to GGW activities and to fully reconcile our maps with reported restoration figures.

4.2. Spatiotemporal changes in ecosystem services

Between 2007 and 2019, the five ecosystem services showed pronounced spatial heterogeneity and temporal change. Patterns were shaped by both climatic and geomorphological conditions and by differences in policy implementation, land-use practices and community engagement.

In the wetter southern and highland areas, such as the Ethiopian Highlands and southern Nigeria, there were notable improvements in multiple regulating services, including carbon stock, water yield, and soil conservation. These patterns may reflect the effects of coordinated restoration programmes, such as Soil and Water Conservation and Sustainable Land Management initiatives, which directly target regulating service enhancement through vegetation recovery and erosion control (Abera et al., 2020). Both countries also have decentralised environmental governance structures that may have better enabled local policy makers to facilitate communities to participate in land management (Belay et al., 2014; Osawe and Magnus 2016; Atisa et al., 2021). In contrast, drier and more arid parts of central and northern GGW countries, constrained by low rainfall, sparse vegetation, and limited technical capacity, showed much lower gains in regulating service provision (Terefe et al., 2020; Desta et al., 2021; Fantahun et al., 2024).

Provisioning services, particularly grain production, increased in many parts of the GGW, especially in agriculturally favourable areas such as south-western Nigeria and western Ethiopia. This expansion may be partly driven by agricultural policies, improved infrastructure and higher land-use intensity by smallholders (Gollin 2023; Umer et al., 2024). However, in ecologically fragile zones such as central Niger and northern Burkina Faso, we found less evidence of provision service expansion. In these areas, crop productivity gains may be limited by land degradation, declining soil fertility, and limited access to more climate resilient agricultural technologies (Sawadogo 2022; Mahamadou et al., 2024).

Improvements in regulating services appear to depend strongly on the suitability of vegetation types and on whether land-management practices are compatible with local environmental conditions (Lu et al., 2018). In dryland areas, herbaceous and low-canopy shrub species can enhance sand stabilisation and soil conservation without increasing water stress (Feng et al., 2016). Restoration efforts that build on local land-use customs, including indigenous knowledge and seasonal land rotation, also offer effective pathways to maintaining vegetation cover and ecosystem stability (Chomba et al., 2020). Where such practices are maintained, natural regeneration can occur with relatively low external inputs and can reinforce long-term ecological resilience (Reij and Garrity 2016).

4.3. The contribution of land-use change to ecosystem service provision

The impact of land-use change on ecosystem services in the GGW region varied across both land use types and spatial contexts. It should be noted that the ESCI reflects the aggregate contribution of each land-use conversion type to regional ecosystem service change, rather than the isolated causal effect of the conversion itself. This index does not account for the spatial locations where conversions occur. As a result, bidirectional conversions (e.g., grassland-to-cropland and cropland-to-grassland) may both show positive contributions when they occur in different locations with distinct underlying biophysical conditions, such as soil type, slope, or baseline vegetation quality. Similar patterns have been observed in other regions where bidirectional conversions between cropland and grassland both showed negative contributions to soil conservation due to site-specific conditions (Wu et al., 2026). This methodological consideration should be taken into account when interpreting the contribution matrices in Fig. 6.

The conversion of barren land to grassland or shrubland significantly enhanced key regulating services, including carbon stock, wind and sand stabilisation, and soil conservation (Sileshi et al., 2023). These improvements were particularly evident in northern Senegal and Niger, aligning with established patterns of ecosystem recovery in arid environments (Ellison and Ifejika Speranza 2020; Gore et al., 2023). However, as illustrated in our data, the long-term sustainability of these positive effects is contingent upon continued management and protection, as arid ecosystems remain highly susceptible to climate variability and anthropogenic disturbances such as overgrazing (Huang et al., 2017; Middleton 2018; Burrell et al., 2020).

The conversion of cropland to grassland contributed to measurable gains in carbon storage and wind erosion control yet also involved trade-offs relating to reduced agricultural productivity. Grassland restoration, particularly through the reintroduction of native species, can significantly enhance carbon stock and improve soil stability (Su et al., 2010; He et al., 2016). Nevertheless, in areas where smallholder farming is a key livelihood activity, large-scale cropland abandonment may undermine local livelihood resilience (Li and Li 2017). These findings highlight the inherent trade-offs between ecological restoration and food security and emphasise the importance of integrating agro-pastoral systems and climate-resilient agricultural practices to balance ecological and socio-economic goals.

The conversion of forest to grassland was associated with a marked decline in soil retention capacity. This transition likely reflects forest degradation that is potentially driven by increased dependence on wood and fuelwood (Iiyama et al., 2014; FAO and UNEP 2020; Kumar et al., 2022). This reinforces the need to prioritise the protection of remaining forest resources in the GGW region and to promote multifunctional forest management approaches to mitigate degradation risks (Muluneh and Sime 2024).

Although urban expansion remains spatially limited, it has nonetheless exerted adverse effects on ecosystem services in the southern parts of the region. The spread of impervious surfaces has reduced local water retention and carbon storage, leading to fragmentation of ecosystem functionality (Ogunrinde et al., 2019). Evidence suggests that embedding green infrastructure principles into urban planning could help mitigate these effects by enhancing ecological connectivity and preserving essential regulating services (Schmidt and Tadesse 2019).

4.4. The spatial distribution of trade-offs and synergies among ecosystem services

Ecosystem service interactions in the GGW region exhibited marked spatial variation, with synergies and trade-offs shaped by climatic, ecological, and land-use contexts. Applying the CICES framework, these patterns can be interpreted as interactions between provisioning and regulating services, where provisioning services such as grain production often compete with regulating services including carbon storage, soil conservation, and sand stabilisation. In several zones, particularly those undergoing intensive land-use change, trade-offs emerged between provisioning services (e.g., grain production) and regulating services (e.g., soil conservation and carbon storage). This tension was especially apparent in southern agricultural zones, where cropland expansion, while improving grain output, often resulted in reduced capacity for erosion control and soil stability. Such patterns reflect broader concerns about the sustainability of extensive agricultural development models and underscore the need for integrated land use strategies (Ali 2023). These results indicate that short term gains in provisioning services can undermine the regulating services that sustain land productivity and ecological resilience and highlight the ecological limits of land use intensification in dryland environments.

The mechanisms underlying these trade-offs are closely linked to vegetation structure, soil function, and management intensity. In dryland systems, the conversion of perennial or semi-natural vegetation to cropland typically reduces root density and soil organic matter inputs, weakening soil aggregation and increasing erosion risk (Su et al., 2010; He et al., 2016). Similarly, reductions in vegetation cover diminish evapotranspiration buffering and carbon accumulation capacities, leading to a decline in regulating service (Ahlström et al., 2015). These cumulative effects show that agricultural expansion without adequate soil and vegetation management compromises ecosystem multifunctionality, even where provisioning services initially increase.

In contrast, other areas demonstrated synergies among ecosystem services. This was particularly apparent where restoration efforts were ecologically compatible with local environmental potential. In the relatively humid eastern regions, for example, carbon stock, soil conservation, and sand stabilisation exhibited strong positive correlations (Duboz et al., 2019; Fassinou et al., 2024). Such synergies suggest that in favourable biophysical contexts, multiple regulating services can be enhanced simultaneously through positive feedback among vegetation structure, hydrological processes, and soil retention capacity. These findings are consistent with previous research showing that ecologically aligned interventions such as reforestation, assisted natural regeneration, and agroforestry can deliver cumulative synergies (Yosef et al., 2018). These “service synergy zones” offer greater ecological returns and are likely to be more cost-effective, as mutually reinforcing services amplify the impact of restoration interventions. In this sense, the GGW could also draw on agrivoltaics “photovoltaic pasture” models (Hua et al., 2022; Wu et al., 2024), which combine solar energy production, vegetation restoration and controlled grazing. Such systems can create synergies between regulating and provisioning services while supporting local agricultural and pastoral development. Prioritising such areas for investment can support a more efficient allocation of resources and increase restoration effectiveness through multifunctional landscape planning (Mu et al., 2022).

From a governance perspective, recognising spatially distinct trade-offs and synergies provides a critical foundation for designing effective, place-based restoration strategies (Van Noordwijk et al., 2020; Bennett et al., 2021). In regions where trade-offs are prominent, policy instruments such as ecological compensation schemes, targeted land zoning, or incentives for sustainable land practices may be necessary to manage competing demands between provisioning and regulating services (Deng et al., 2016; Vlek et al., 2017; Zheng et al., 2019). Meanwhile, in synergy-dominated landscapes, policies could focus on reinforcing positive feedback between ecosystem functions through supportive infrastructure and community-based resource governance. To strengthen the evidence base for such interventions, restoration monitoring can be aligned with the SEEA-EA ecosystem accounting framework, using spatial indicators such as the ESCI to link land-use transitions to ecosystem extent and condition accounts and to track the synergies of land-based climate and biodiversity policies. Equally important is the role of participatory planning in addressing trade-offs (Hare et al., 2003; Reed, 2008). Local authorities and planners should engage communities in defining ecosystem service priorities, ensuring that land management decisions reflect both ecological realities and livelihood needs (Goossen 2020). Stakeholder-inclusive processes increase the likelihood of long-term project acceptance, while also improving the targeting of interventions towards locally relevant goals. Participatory and multi-level governance structures, including FMNR, can therefore help balance provisioning and regulating services by aligning restoration priorities with both ecological resilience and local livelihood needs.

5. Conclusion

By assessing the impacts of land-use change on key ecosystem services, this study shows how specific land transitions shape ecosystem service provision and trade-offs across Africa’s Great Green Wall. Conversions of barren or degraded land to grassland and shrubland were associated with higher carbon sequestration, soil conservation and wind erosion control, while our maps and ESCI results indicate that continued cropland expansion and urbanisation, especially in intensively farmed southern zones, tend to undermine these benefits and undermine long-term sustainability. Vegetation recovery, whether achieved through active revegetation or natural regeneration, therefore needs to be targeted to ecologically suitable areas and combined with land-management practices that maintain regulating services.

Restoration success cannot be measured by the total restored area alone, but by ecological functioning and the spatial variation in ecosystem service responses. Our spatial analysis suggests that wetter highland regions, where carbon stock, soil conservation and sand stabilisation often increase together, are suitable for afforestation and agroforestry that can maximise synergies among these services, whereas arid and semi-arid zones, where cropland expansion is frequently accompanied by declines in soil conservation and sand stabilisation, are better served by herbaceous and shrub-based systems that stabilise sand and conserve soil moisture. For policymakers, recognising these trade-offs between grain production and regulating services highlights the need to embed sustainable land management in agricultural policy, through measures such as conservation agriculture, agroforestry on erosion-prone slopes and land-use zoning that protects the most vulnerable areas. For practitioners and donors, the results point to the value of prioritising low-canopy, drought-tolerant vegetation that can support both ecosystem recovery and livelihood resilience.

Despite these advances, important limitations remain. Reliance on medium-resolution satellite imagery constrains the detection of small-scale, localised restoration efforts that are often critical in fragmented landscapes. Future work should combine higher-resolution ecological monitoring with socio-economic information, including land tenure, policy incentives and community participation, to help refine GGW planning and evaluation.

In summary, this study advances knowledge on the GGW through a comprehensive regional synthesis. Moving beyond previous work focused on project descriptions, policy analyses, or small-scale case studies, we provide the first systematic and spatially explicit assessment of how land-use transitions affect multiple ecosystem services across the entire GGW. Mapping ecosystem service interactions provides a diagnostic tool for understanding the outcomes of land-use change and a practical basis for evidence-based restoration. The Ecosystem Service Contribution Index calculated here shifts the focus from simply detecting whether change has occurred to its ecological consequences, helping identify which land-use transitions are most likely to support or undermine multiple services. Shifting from a simple focus on restored area to a more function-oriented perspective can improve the effectiveness and fairness of dryland restoration in the Sahel. By linking spatial patterns of ecosystem service change to concrete management and policy options, this study offers a foundation for more informed decision-making in large-scale restoration initiatives.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) used ChatGPT (OpenAI) and DeepL to improve the readability and language clarity of the manuscript. After using these tools, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

CRediT authorship contribution statement

Yizhuo Wang: Writing – original draft, Software, Methodology, Formal analysis, Conceptualization. **Catherine E. Scott:** Writing – review & editing, Supervision, Funding acquisition. **Martin Dallimer:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoser.2026.101833.

Data availability

Data will be made available on request.

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