Acta Geophysica
https://doi.org/10.1007/s11600-021-00644-z

RESEARCH ARTICLE - ANTHROPOGENIC HAZARD

Quantifying ecosystem service interactions to support environmental restoration in a tropical semi-arid basin

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Received: 19 March 2021 / Accepted: 22 July 2021

Abstract

Understanding the role of ecosystem services (ESs) within environmental management has become a critical issue of the twenty-first century. This is because scientific study of ES interactions can aid effective planning and management of ESs, thus curtailing degradation and enhancing restoration. In this study, ES interactions of the climate-sensitive West African Sokoto-Rima basin were quantified using land cover and a series of GIS-derived data as inputs into the InVEST model. Crop production (CP), seasonal water yield (SWY), habitat quality (HQ), and nutrient retention ratio (NRR) between 1992 and 2015 were assessed. Climate change assessment was based Mann–Kendall trend of precipitation and temperature for both past (1951–2017) and future (2018–2050) climates. The climate dynamics present a drying-warming trend with localised cooling–warming spells in some locations and a general future wetting–warming trend. Areas dominated by cropland and CP exert significant influence on the spatiotemporal dynamics of ES interactions contributing to the manifestation of substantial trade-offs and synergies across the past (2015) and the future (2050) climates. This also regulates the overbearing pattern of multiple ES interactions such that the relationship CP > SWY > HQ > EVI > NRR was observed over the study area. The persistence of these diverse relationships will stimulate the possible degradation of natural regulating ESs. Improvement of existing crop cultivation clusters, cultivation of flood-resistant crop varieties, and agroforestry expansion were proposed as climate and ESs interaction-based restoration measures. When adopted, these measures will douse the increasing ES pressures within this semi-arid zone.

Keywords Ecosystem service interactions · InVEST model · Climate change · Ecological restoration · Sokoto-Rima basin

Introduction

Ecosystem services (ESs) are multidimensional and beneficial derivatives of nature that people enjoy from resource stocks to improve their well-being and satisfy varying needs (Costanza et al. 1997; MA, 2005a). According to the Millennium Ecosystem Assessment MA (2005a), ESs "are the benefits people obtain from ecosystems". These benefits have been classified into four specific processes (provisioning, regulation, cultural, and supporting) that define an area's ESs (MA, 2005a, b; Fu et al. 2017; Yang et al. 2018). Other studies such as the Common International Classification of Ecosystem Services (CICES) have also provided comprehensive classification of the global ESs. The CICES developed a five-level global to local taxonomy that cascades down to identifiable and measureable units. At the apex level are three of the four categories used in the MA, namely provisioning, regulation and maintenance and cultural ESs, while specific units tagged "class type" exist at the base (Haines-Young et al. 2016). Research interest in these ESs has emerged as a critical issue for the twenty-first century. Opinions on topical areas such as definition (Kremen 2005; Fu et al. 2013), classification (Wallace 2007; de Groot et al. 2010), and evaluation of ESs (Heal 2000; Jansson et al. 2000; Costanza et al. 2014) are still ever-persistent. More recently, research on ES interactions, often considered a conflict of relevance between specific ESs processes, has intensified (Haase et al. 2012). Indeed, more focus has been

Communicated by Caterina Samela, Ph.D. (ASSOCIATE EDITOR), Prof. Savka Dineva (CO-EDITOR-IN-CHIEF).

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Published online: 09 August 2021

geared towards provisioning and regulating ESs owing to their continuous support in the delivery of ecosystem goods and services for the satisfaction of bourgeoning needs and wants of the society (Burkhard et al. 2012, 2014). It is, therefore, critical to understand the relevance of these interactions and maximise the simultaneous benefits that they deliver (Burkhard et al. 2014; Haase et al. 2012).

Theoretically, interactions amongst ESs could be measured as trade-off or synergy (Haase et al. 2012; MA, 2005a, 2005b; Fu et al. 2017). A trade-off occurs when a competitive relationship develops between two units of ESs such that an increase in the supply of one unit analogously drives a decrease in the stock of another. In contrast, synergy is entirely complementary such that multiple ESs are enhanced concurrently. This shows that while synergies and their intensification represent the ideal land-cover planning scenario envisaged by decision-makers, trade-offs, which is conflict-oriented, offer sundry opportunities for extensive resource planning decisions (Burkhard et al. 2017; Fu et al. 2017, 2018; Wangai et al. 2016). In agricultural systems, particularly within semi-arid ecosystems, understanding the dynamics of ES interactions can help careful management, reduce trade-offs, and enlarge synergies. Raji et al. (2020a) have affirmed that the West African semi-arid ecosystem is dominated by provisioning systems, particularly crop cultivation, usually in conflict with woodlands development. Simultaneously, synergies such as agroforestry, usually at fringes, rank the least amongst landcover management decisions. Sustainable management of such conflicting yet vital ESs thus requires minimising high trade-offs to avoid degradation and create a swift restoration environment (Fu et al. 2018; Yang et al. 2018).

Over time, the study of ESs has embraced the utility of integrated research, which stimulates the advancement of proficient sustainable systems. This approach fuses spatial quantification with optimal combinations of multiple ESs to provide systematic support for decision-making (Burkhard et al. 2014; Costanza et al. 2014). The consideration of multiple ESs provides the opportunity to assess net landcover management gains since sustainability and maximisation of optimal resource utilisation are the guiding principles. A series of measures have been demonstrated in the literature within the context of quantification of multiple ecosystem service bundles focussing on areas of spatial overlap. Bivariate and multivariate statistics using correlation coefficients, principal component, cluster and factors analyses (Feld et al. 2010; Lee and Lautenbach 2016; Liu et al. 2017; Salata and Grillenzoni 2021) have been employed, while flower, spider web or polar chart diagrams (Renard et al. 2015; Fu et al. 2018) were used to display the connections between various ESs bundles within a defined geographical space or a specified random sampling unit. Significantly, detection of these interactions strength will help decision-makers towards delineating areas of critical ESs, which can be measured with multiple ecosystem service units. Thus, areas with high trade-offs' strength demand optimal land management strategy compared to high synergy locations, which is already fulfilling joint improvement aims. Therefore, joint evaluation of ESs and their interactions can provide suitable spatial guidance for managing ecosystem resources in a trade-off-dominated region such as the semi-arid areas of West Africa.

Undoubtedly, climate change is a vital environmental factor that drives ESs dynamics apart from landcover, with antecedent anthropogenic influences. While landcover change can modify the supply ESs via alteration of natural ecosystem service processes and patterns (Fu et al. 2015; Ncube et al. 2018; Ekka et al. 2020), climate change directly or indirectly modifies natural ecosystem service processes such as hydrological processes, biodiversity, carbon storage, nutrient flow pattern amongst several others (Locatelli 2016). Studies have shown that climate change has turned some of the world's environmentally fragile areas into environmental hotspots (Huang et al. 2017). One of these areas is the Sokoto-Rima basin, where studies on flow and interactions of ESs have been very minimal, and its nexus with climate change is poorly understood. Nevertheless, previous studies within this area considered issues such as climate change projections (Adeniyi 2016; Sylla et al. 2018), the impact of climate change on food production (Sarr 2012; Defrance et al. 2020), hydrology and water resources (Diallo et al. 2016; Donat et al. 2016) and anthropogenic landcover change (Sylla et al. 2016a, b) amongst several others. Within this context, it has been established that the semi-arid West Africa has been experiencing diverse climatic trends, the specifically prolonged drought of the 1970s, incidences of water shortages, intensified warming and short-duration high-intense summer rains (Adeniyi 2016; Diallo et al. 2016; Sylla et al. 2018; Defrance et al. 2020). Consequently, flooding, southward encroachment of the Sahara Desert, pest infestation, and crop losses have become seasonally normal with associated pressure on the ESs' sustainable usage. It is essential to develop suitable strategies for climate-driven ecosystem restoration to mitigate these adverse impacts.

Decision-making on ecosystem restoration requires that environmental planners and managers understand spatial features, change patterns, driving elements and ESs factors (Burkhard et al. 2012). These, when understood, will aid restoration measures as environmental and ecosystem challenges are location-based and context-specific. This is contrary to the prevailing non-spatial policy contexts, which are highly generalised and poorly designed without integrating elements that connect various facets of ESs to the extent of degradation (Burkhard et al. 2014). Previous ecosystem restoration approaches were singularly designed, creating gaps, lacking a cohesive approach and unsustainable (Wangai et al. 2016). This has been the experience in most semi-arid regions of Africa, where natural geography influences terrestrial ecosystem functions. This is because of the prevailing composite structure of the landscape such that the nexus between climate, hydrology, topography and geology dictates the natural flow of ESs. To a considerable degree, these natural elements also influence the sociocultural context of ESs. Any form of disruption within the units of these physiographic factors will trigger a cumulative impact on anthropogenic activities.

To narrow these research gaps, this study assessed ES interactions in the Sokoto-Rima basin (a microcosm of the West African semi-arid zone) in conjunction with exploring the effect of climate change on ESs. The overarching objective of this study was to reveal how changes in landcover and climate with spatiotemporal variations of ESs influence ecosystem restoration measures in the Sokoto-Rima basin. The periods 1992 to 2015 was selected based on data availability constraints, while the year 2050 was suggested as the vital target period for mid-term review of the status of global ecosystem services (Alcamo et al. 2005). Given this, we put forward some research questions as follows: (1) What typified the ecosystem service change processes between 1992 and 2015 in the Sokoto-Rima basin? (2) How do anthropogenic landcover and climate change influence ESs, and where do the influences occur in the Sokoto-Rima basin? (3) What are the possible ecosystem restoration measures appropriate for the Sokoto-Rima basin in the face of degradation? The designed methodology is based on inductive science, which integrates geospatial science tools with spatial image analysis, spatial quantification and spatial statistics (Martin and Bertazzon 2010). This study can provide appropriate systematic support for the sustainable use of ESs of the Sokoto-Rima basin, and the methodology can be adaptable to other similar areas. To this end, this paper is structured as follows: it begins with a general introduction, followed by methodology, result and discussion, and conclusion rounds up the study.

Methods

Study area

This study was conducted within the Nigerian section of the West African Sokoto-Rima basin. It covers an area of 94,026.5 km^2 swathing the entire north-western axis of Nigeria with spatial extensions to the Niger Republic and Benin to the north and east, respectively (Fig. 1). The West African semi-arid climate governs the study area's environmental conditions with Sahelian imprints referred to as West African monsoon (Vizy and Cook 2018). Precipitation is seasonal, confined to the wet season, with a south–north decreasing pattern, ranging from 350 to 895 mm annually. Abiodun et al. (2012) stated that precipitation is influenced by mesoscale processes, which exert significant control on its pattern and distribution up to 75%. Daily temperature, like precipitation, is particularly seasonal and averages 30^0 C all-year-round (Oguntunde and Abiodun 2012; Vizy and Cook 2018).

Vital to ESs of the Sokoto-Rima basin is the hydrological network. Rivers of the basin flow westwards from the eastern highlands of Zamfara State and then southwards into the continental River Niger. Sokoto River is the principal hydrological system connected by Rima, Zamfara, Ka, Maradi, Bunsuru, and Gagere. Tripartite geo-topographical cum geological classifications which co-relate with the Sokoto-Rima basin ecosystem can be recognised. The eastern uplands mark the initiation zone of the earlier mentioned river systems. The central Sokoto plains typify the rippling topography with its associated rolling hills, and the southern lowland Niger valley is the terminal points of the rivers of the basin. The southern lowland constitutes the lowest topography based on elevation, while the peaks are spatially constrained to the east. Vegetation is a reflection of the influence of climate on the general environment (Li et al. 2019). Vegetation consists of short grasses, shrubs, and low-canopy short-leaved trees. The dominant tree species are of the Combretaceae and Caesalpinioideae family, with some notable Acacia species. Trees such as the baobab possess inherent long-term water storage ability and aridity-resistant root system and are used as woodlot alongside baobab, Shea, date palm and locust-bean trees. Andropogon Andropogoneae and Hyparrhenia Andropogoneae genera are the most dominant grass species.

Cropland remains the dominant landcover type in the Sokoto-Rima basin. Cultivated crops such as rice, cowpea, soybeans, maize, sorghum, millet, tomatoes, and groundnut are mainly rain-fed and on a small scale, often on seasonal and a few yearly. Apart from exclusive pastoralism, some crop farmers also engage in the domestication of cattle, rams, goats and sheep. Other landcover types include grassland, shrubland, water, bare lands and pockets of woodlands. The changing structure of these landcover typologies and climate dynamics has led to the Sahara desert's encroachment into the Sokoto-Rima basin, particularly at the northern end. Over the years, the occurrence of this phenomenon has subjected the ESs of the Sokoto-Rima basin to a series of distortions and disruptions.

Data description and sources

Multisource archival data were used in this study (Table 1). Pre-processed and pre-classified landcover maps were sourced from the climate change initiative (CCI) programme of the European Space Agency (ESA). The landcover maps have a spatial resolution of 300 m

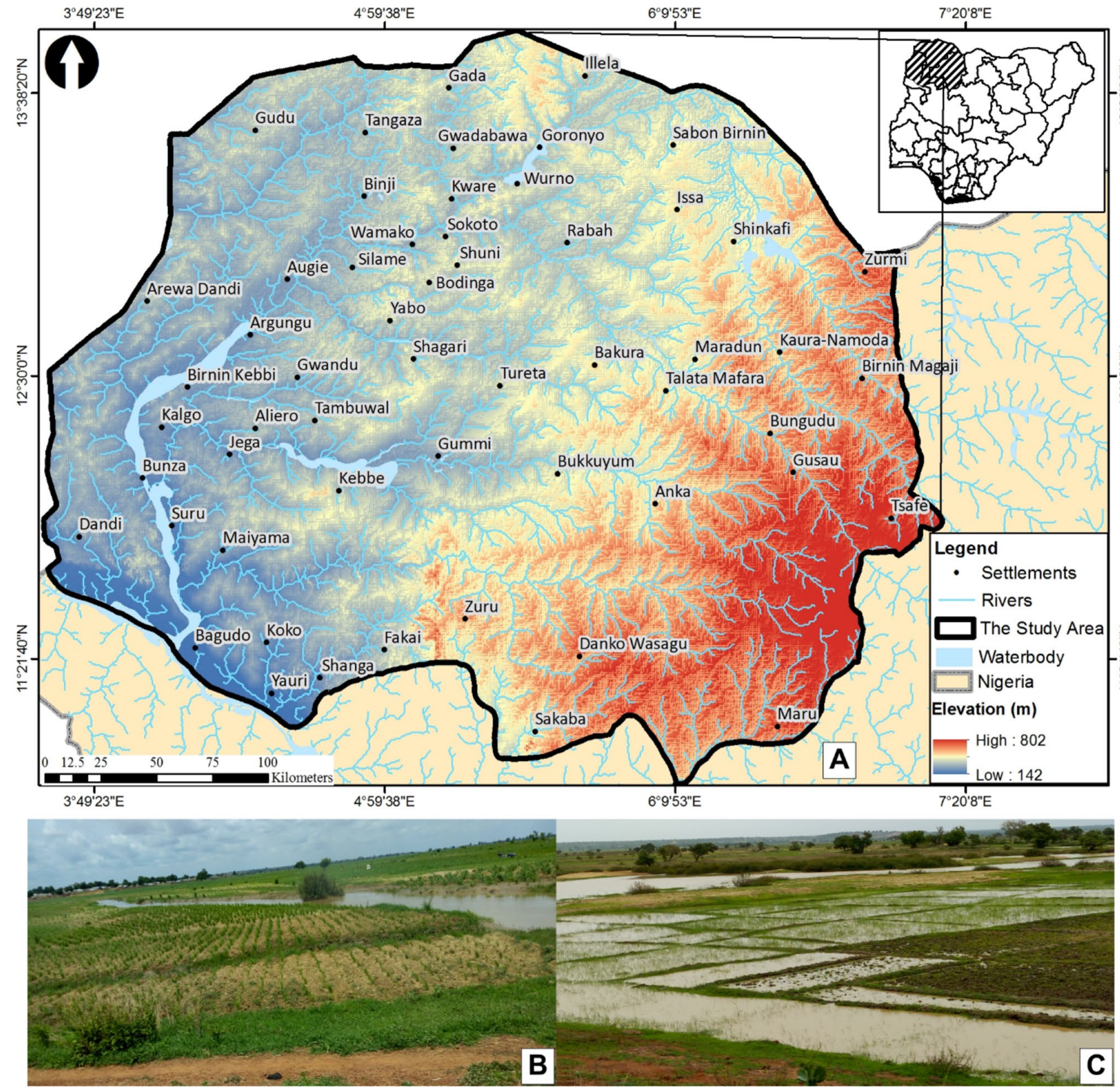


Fig. 1 The study area. **A** Location of the study area in context of Nigeria **B** The smallholder crop production adjoining River Zamfara in the northern part of Gusau (eastern part of the study area). **C** Wetland agriculture in Suru, a dominant landcover typology, in the southern part of the Sokoto-Rima basin

with a dynamic range of 32 bits, suitable for a synoptic study of an extensive basin such as the Sokoto-Rima. The image production technical details of the data are obtainable from Defourney et al. (2016). The usability of this data for agricultural assessment and crop yield observation from continental scale to regional analysis has been pragmatically revealed by Pérez-Hoyos et al. (2017). ALOS World 3D (Digital Surface Model) data, with 30-m and 16-m horizontal and vertical resolution details, was obtained from the Japanese Aerospace Exploration Agency (JAXA). Climate data (rainfall and maximum temperature) were obtained from the Nigerian Meteorological Agency's data archives (NIMET), appended with data from the Princeton University's Princeton Climate Analytics web portal. The former supplied data for synoptic stations within Nigeria (Sokoto, Yelwa, Birnin Kebbi, Argungu, Gusau, Goronyo, Wurno, Kano, and Kaduna), while the former provided data on Malanville (Benin

Table 1 Characteristics of data used for the study

Data	Type	Resolution/Scale	Year	Data source
Landcover (LC) maps	Raster	300 m	1992, 2002, 2012, 2015	European Space Agency (ESA) Climate Change Initiative http://maps.elie.ucl.ac.be/CCI/viewer/profiles.php
ALOS World 3D DSM data	Raster	30 m (horizontal) 16 m (vertical accuracy)	2014	Japan Aerospace Exploration Agency (JAXA) https://www.eorc.jaxa.jp
Climate data	Point	Synoptic stations across the basin	1951–2017	NIMET (Nigeria Meteorological Agency) and PCA (Princeton University station-based data via the Princeton Climate Analytics) https://platform.princetonclimate.com/PCA_Platform/)
Statistically Downscaled MRI–CGCM3.0	Netcdf	$1.12^0 \times 1.125^0$ graticule resolution	2018–2050	CMIP5 via the ESGF with platform provided by LLNL Lawrence Livermore National Laboratory https://esgf-node.llnl.gov/search/cmip5/
Soil	Raster	250 m	2016	NASA's Distributed Active Archive Centre for Biogeochemical Analysis (DAAC) https://daac.ornl.gov/SOILS/guides/Global_Hydrologic_Soil_Group.html
Basin boundary	Polygon	Administrative data	2016	Laboratory for Remote Sensing and GIS, Department of Geography, University of Lagos
eMODIS NDVI Data	Raster	250 m	2002, 2012, 2015	USGS Famine Early Warning System (FEWS) Data for West Africa

Republic) and Dabnou (Niger Republic) for the period 1951 to 2017. The future climate data were acquired from the Lawrence Livermore National Laboratory of the Department of Energy of the United States. The MRI–CGCM3.0 data CMIP5 (Climate Model Intercomparison Project Phase 5) under the stabilisation scenario (Representative Concentration Pathway (RCP) 4.5) data was thus selected, and it has a corresponding graticule resolution of 1.125 by 1.125 degrees. This datum was adopted because it possesses optimal simulation of the climatology and spatiotemporal variability of the West African monsoon system for the past and future periods (Yukimoto et al. 2012; Dunning et al. 2018). Also, the data resolution is sufficient for basin wide minimum mapping unit needed for point-based climate data modelling. Soil data were acquired from NASA's Distributed Active Archive Biogeochemical Analysis portal. It has a resolution of 250 m, which sufficiently covered the Sokoto-Rima basin. eMODIS NDVI data were acquired from the USGS (United States Geological Survey) Famine Early Warning System (FEWS) Data for West Africa. The data has 250 m spatial resolution, which also defines its minimum mapping unit. The basin boundary data were created from merging polygonal GIS data of Sokoto, Zamfara and Kebbi States of northwest Nigeria. The Laboratory for Remote Sensing and Geographic Information System of the Department of Geography, University of Lagos, supplied the data.

Study procedure

The methodology framework shown in Fig. 2 gives a flow of the data and associated methods designed to achieve the study's aim. The study's entire data spine is the landcover data (CCI LC), which was sourced from the data archives of the European Space Agency (ESA). Using the Food and Agriculture Organisation (FAO)'s landcover schema to match on-the-ground realities at the Sokoto-Rima basin, the datasets were reclassified using raster reclassification tool of ArcGIS software. The reclassified landcover data for the years 1992, 2002, 2012 and 2015 were used as input data to quantify the selected ESs as required by the InVEST software.

Next, data series ranging from archived (soil, geology, terrain, population, NDVI, and administrative), climate (station-based and modelled), and CCI-LC data were gathered sequel to data transfer from analogue to GIS format. As stated in Table 1, the essential characteristics of these datasets were used to examine their fitness for the study focusing on their spatial traits. ALOS World DSM data were used to extract elevation, slope, and aspect using extract by mask algorithm in ArcGIS software. Climate data were first classified as (1951–2017) and future (2018–2050) and then

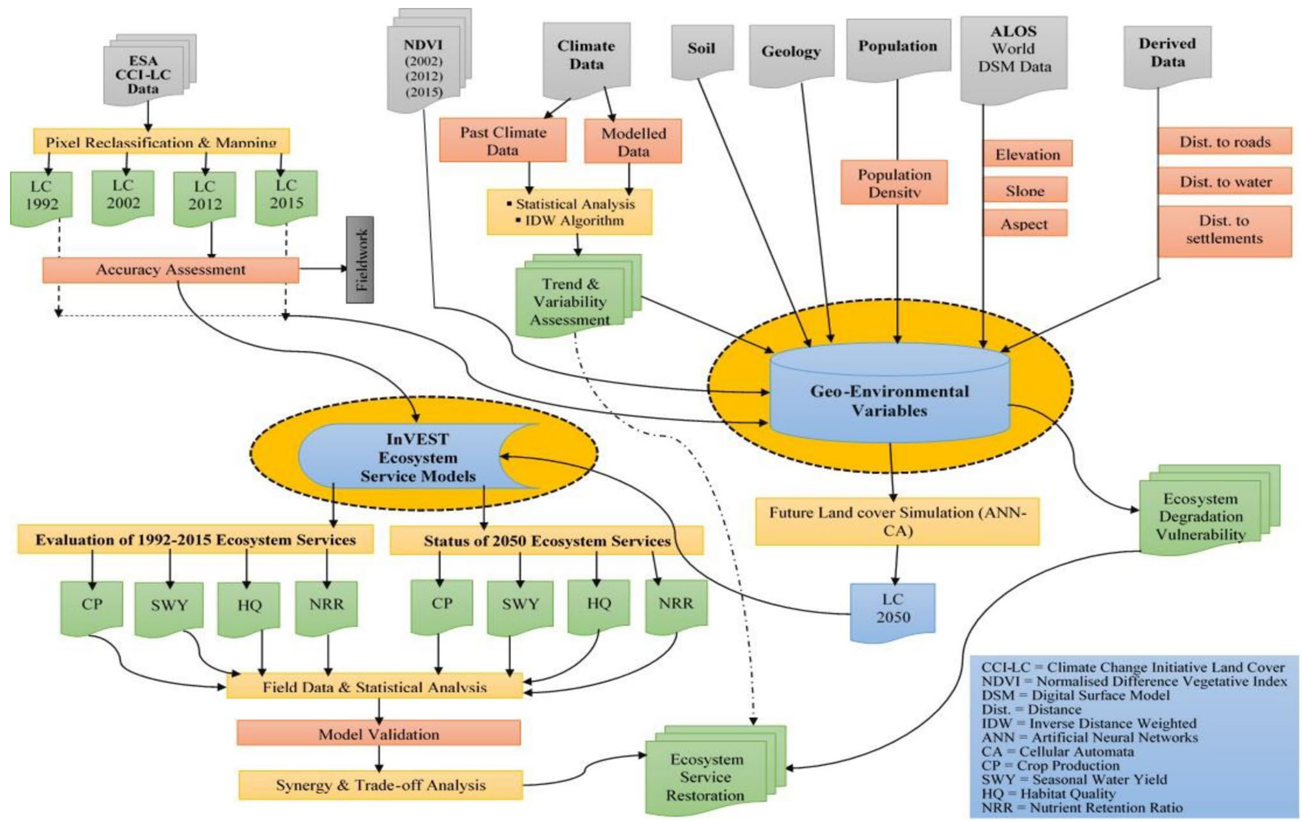


Fig. 2 Methodological framework adopted for the study

spatialised using inverse distance weighted (IDW), which is a spatially explicit numerical algorithm in ArcGIS software. NDVI was extracted for the years 2002, 2012, and 2015. Data on soil, geology, and population density were generated from their respective data layers to GIS specified formats. Derived data on roads, water, and settlements were generated from data sourced from the archives of the Laboratory of Remote Sensing and Geographic Information System (GIS), University of Lagos. This pool of data, denoted as geo-environmental variables database, was used to simulate future LC (2050) data and ascertain the basin's vulnerability to ecosystem degradation.

Data from terrain (elevation, slope, and aspect), LC data for 1992 and 2015, soil, geology, past and future climates, NDVI (2002, 2012 and 2015), and derived data were used as proximate and underlying drivers to simulate LC (2050) data using ANN-CA (Artificial Neural Networks–Cellular Automata) on QGIS software package. The performance appraisal of the CA-ANN approach, which was based on 5,000 iterations, yielded a 75.88% accuracy of validation is appropriate for future landcover simulation. The LC (2050) data were used to generate ESs for the year 2050 using InVEST. This approach was based on the argument by Lambin (2003) and Fasona et al. (2007) that diverse environmental and climatic factors are responsible for progressive risks of degradation of terrestrial ESs within the West African semi-arid zone. Sequel to quantifying the future ESs, spatiotemporal ecosystem interactions (synergy and trade-off) were statistically measured using Pearson's correlation coefficients. These ecosystem interactions, alongside future ESs, landcover, and climate change, were used as the basis for the development of ES-based restoration mechanism for the Sokoto-Rima basin.

Quantifying ecosystem services

Anthropogenic activities in the Sokoto-Rima basin mainly cluster around floodplains, wetlands, riverbanks, lakes, oases and other water bodies. These water bodies were fed continuously by surficial and underground hydrological processes aided by precipitation and other natural resources flow complexes. At the same time, agricultural practices are essentially climate-dependent, and the expansion of this poses a significant threat to biodiversity. Since ESs are connected to these human–nature interactions, it is vital to assess their nexus using quantification. In this study, four ESs, specifically crop production (CP), seasonal water yield (SWY), habitat quality (HQ), and nutrient retention ratio (NRR), were computed using InVEST 3.6.0 software. InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) is an open-source freeware spatially explicit software package used for mapping, modelling and quantifying ecosystem services using biophysical and spatial variables (Sharp et al. 2018). It is a fallout of the Natural Capital Project, which is a collaboration of ecosystem science community between Stanford University, University of Minnesota, The Nature Conservancy, and World Wildlife Fund. The software available for download at www.naturalcapitalproject.org/invest/. The selected ESs have representative models programmed within the InVEST suite and are described in the subsequent subsections.

Crop production

The Sokoto-Rima basin is agrarian, and most of its landscape has been subjected to a series of agricultural practices, mainly the cultivation of cereals, spices, and livestock production. InVEST Crop Production Model (regression) was used for this study because it suitably simulates this semi-arid zone's nature better than other models (Mueller et al. 2012). The model is mathematically expressed as:

$$\begin{aligned} Y_{\mathrm{mod}\,GC} = \min\big(&Y_{\max}\left(1 - b_{NP}\exp\left(-c_N N_{GC}\right)\right),\\ &Y_{\max}\left(1 - b_{NP}\exp\left(-c_P P_{GC}\right)\right),\\ &Y_{\max}\left(1 - b_K\exp\left(-c_K K_{GC}\right)\right)\big), \end{aligned} \tag{1}$$

where $Y_{\mathrm{mod}\,GC}$ is the yield for a particular crop (tonnes/ha); $Y_{\max}$ is maximum yield; b_{NP} and b_K are the y-intercepts for each nutrient-yield response curve; c_N, c_P, and c_K are response coefficients that describe the percent of $Y_{\max}$ achieved at a given nutrient level; $N_{GC}\,P_{GC}\,K_{GC}$ are the crop-based fertilisation rates which were extracted from Raji et al. (2020a).

Seasonal water yield

This is important to ascertain the average amount of seasonal water available in the study area and its flow dynamics. The InVEST Seasonal Water Yield (SWY) model was adopted as stated by Sharp et al. (2018). The model's core algorithm calculates the SWY based on the water balance concept with climate, topography, soil, and landcover as data parameters. The model is quantitatively expressed in Eq. (2) as:

$$\begin{aligned} QF_{i,m} = n_m * \Bigg(&\left(a_{i,m} - S_i\right)\exp\left(-\frac{0.2S_i}{a_{i,m}}\right)\\ &+\frac{S_i^2}{a_{i,m}}\exp\left(\frac{0.8S_i}{a_{i,m}}\right)E_1\left(\frac{S_i}{a_{i,m}}\right)\Bigg) * \left(25.4\left[\frac{mm}{in}\right]\right). \end{aligned} \tag{2}$$

Given that $QF_{i,m}$ is monthly quick flow per multispectral space, the annual $QF_{i,}$ is thus computed as:

$$QF_i = \sum_{m=1}^{12} QF_{i,m}, \tag{3}$$

where $S_i = \frac{100}{CN_i} - 10[in]$, $\mathrm{CN_i}$ is the curve number for pixel i, a function of the local landcover and soil type; $a_{i,m}$ is the mean rain depth on a rainy day at pixel i on month m, and E_1 is the exponential integral function, $E_1(t) = \int_1^{\infty} \frac{e^{-t}}{t}dt$ in which t is the time study period. Hence, $QF_{i,}$ is adopted owing to the water scarce nature of the study area.

Habitat quality

The InVEST's Habitat Quality (HQ) model was employed as a measure of biodiversity. The model quantifies ecosystem service by analysing landcover maps in conjunction with spatial threats to biodiversity. This approach was adopted because HQ estimates the extent of habitat health and its spatial degradation across the landscape (Fu et al. 2017; Yang et al. 2018). Two categories of threats sources were set depicting human-dependent (cultivated lands, settlements, railways and main roads) and nature-dependent influences (waterbody). The data required for the model include landcover, threats, and threat's sources. According to Sharp et al. (2018), HQ can be quantified using Eq. (4):

$$Q_{xj} = H_j\left(1 - \left(\frac{D_{xj}^z}{D_{xj}^z + k^z}\right)\right), \tag{4}$$

where Q_{xj} is habitat quality of cell x in landcover j, D_{xj}^z is associated total threat level in the same multispectral space x and j, z (hard coded = 2.5) and k (half-saturation constant was set as 0.5) are scaling parameters.

Nutrient retention ratio

Nutrient retention ratio (NRR) was quantified using InVEST's Nutrient Delivery Ratio Model. This model employs a mass balance approach describing the spatial movement of nutrient mass across the study area. It expresses nutrient flow across the landscape, showcasing the temporal pathway from diffuse sources and, to a great extent, nutrient cycling. This model's data requirement includes DEM, landcover, watershed, nutrient load parameter, retention efficiency, retention length, and nutrient runoff proxy data. Data from Tarfa et al. (2017) on optimisation of fertiliser and integrated soil fertility management in Nigeria were adopted. This model is quantitatively expressed as:

$$NRR = 1 - \frac{NE}{NL}, \tag{5}$$

where *NRR* (nutrient retention ratio) is the portion of nutrients held in at a pixel location. *NE* (nutrient export) is the proportion of nutrient that is exported per pixel position within the multispectral space, *NL* (nutrient load) is the amount of nutrient traversing through the multispectral space to the next. NRR ranges between 0 and 1 indicating no retention and peak retention ratio, respectively.

Assessment of landcover change

In this study, landcover change was assessed using three stepwise procedures. The first step is the development of static images of each of the period of study following the reclassification task. This was followed by the computation of area change and change rate. Finally, change maps were constructed using map differencing algorithm of ArcGIS software to depict the spatial distribution of observed landcover changes in the Sokoto-Rima basin. According to Salata (2017), this methodology is an image differential technique that permits the statistical differences between study periods to be computed.

Climate change assessment

Detection of climate change is based on the definition expressed by Ojo et al. (2001) and Aguado & Burt (2013) that climate change is any significant long-term change in the expected patterns of average weather of a region (or the whole Earth) mostly exceeding 35 years. On this premise, two climatic parameters–monthly rainfall and maximum air temperature for the past climate (1951–2017) and future climate (2018–2050)–were used to assess climate change as driving mechanisms. Rainfall and maximum temperatures are essential climatic and meteorological variables such that they signify the regulating factors for vegetation growth of the West African semi-arid zone. It has been established that rainfall is very periodic, defining the nature of tropical seasons in the Sokoto-Rima basin (Akinsanola et al., 2017). The maximum temperature is a significant driver of plant phenology changes and a key factor of photosynthesis and evapotranspiration, thus setting a mark for related ecological processes. Trend analysis of each of the two climatic parameters was based on Mann–Kendall's test. Mann–Kendall (M–K)'s test is a measure of a monotonic trend, and it is expressed in Eqs. (6) and (7):

$$S = \sum_{i-1}^{n-1} \sum_{j+i+1}^{n} \sin\left(x_j - x_k\right) \tag{6}$$

$$\sin\left(x_j - x_k\right) = \begin{cases} +1 \ if\left(x_j - x_k\right) > 1 \\ 0 \ if\left(x_j - x_k\right) = 0 \\ -1 \ if\left(x_j - x_k\right) < -1 \end{cases}, \tag{7}$$

where S is the M–K's test statistics; x_i and x_j are the sequential data values of the time series in the years i, and j ($j > i$) and n is the length of the time series. Tau's method was used for trend magnitude.

Spatial ecosystem restoration mechanism

Ecosystem service interactions

Measurement of ecosystem service interactions was determined using spatial correlation among pairs of ecosystem service models. Spatial correlation coefficients were therefore used to ascertain synergies and trade-offs. Synergy in this study indicates the interaction of ecosystem elements that, when pooled, produce a cumulative effect that is better than the entirety of the discrete elements leading to complimentary gains. In this context, synergy means a positive correlation coefficient, which could be either weak ($0 > \mathrm{r} < 0.5$) or strong ($0.5 > \mathrm{r} < 1$). Conversely, the trade-off is a modelling decision that involves losing or trading one quality, quantity or property of a set or design in return for increasing gains in other aspects of a given system. This means that trade-off is measured by a negative correlation coefficient, which could be weak ($-1 > \mathrm{r} < -0.5$) or strong ($-0.5 > \mathrm{r} < 0$).

Before the computation of the ESs interaction, the four ESs' different units were standardised. This becomes vital as the different units could depict false statistical correlations, yielding unrealistic ecosystem service connections. The general standardisation method that normalises units was adopted, and it is expressed in Eq. (8) as:

$$\gamma_{Std} = \frac{\left(\gamma_{obs} - \gamma_{\min}\right)}{\left(\gamma_{\max} - \gamma_{\min}\right)}, \tag{8}$$

where γ_{Std} is the standardised ES value, γ_{obs}, $\gamma_{\max}$ and $\gamma_{\min}$ are the observed ES values at a specific location, maximum and minimum ES values across the entire multispectral space correspondingly. The outcome of the standardised ES value is expected to range from 0 to 1.

Furthermore, indices of cropland and ecosystem service vulnerability index (EVI) (extracted from Raji et al. (2019) were integrated to strengthen further the spatial expression of the ecosystem service interactions for the present (2015) and the future (2050). Gally algorithm enshrined in R was used to statistically depict the ecosystem service interactions, while respective radar charts were generated to depict the dominant ecosystem service. Final ecosystem service interactions were further spatialised down to the local council level using ArcGIS software's zonal statistics tool.

Ecosystem service restoration mechanism

The existing geo-ecology of the Sokoto-Rima basin makes a clear case for spatial outlining of ecosystem restoration. Naturally, there exists a geographic delineation of the study area into eastern uplands, the central Sokoto plains and the southern lowland Niger valley as earlier established in subsection "Study area". These, alongside the outcome of the ecosystem service interactions, main landcover, dominant ecosystem service units, and pattern of climate change, were integrated to produce five ecological restoration indicators with nineteen indicator elements (Table 2). Aggregates of these were utilised as measures of ecosystem restoration mechanism for the study area.

Results

Dynamics of landcover and climate change of the Sokoto-Rima basin

Landcover change

From 1992 to 2015, the study area's landcover experienced spatiotemporal inter-conversions across the different categories mapped. Specifically, cropland, waterbody, settlement and bare surface experienced enlargements, while shrubland, grassland, and woodland decimated. Meanwhile, agroforestry had fluctuating spatiotemporal dimensions with initial expansion and further decimated. It gained 26.83 km^2 within the decade 1992–2002, while it shrank by 32.13 km^2 and 16.27 km^2 within the periods 2002–2012 and 2012–2015, respectively. This led to a cumulative agroforestry loss of 21.57 km^2 within the study period (Fig. 3). The urban expansion was detected as settlement expanded with an annual rate of 136 km^2 (a cumulative 199.04% compared to 1992) within the 23 years of study.

Similarly, the bare surface expanded annually with 129.9 km^2, an indication of progressive degradation of the ecosystem, especially with encroachment of the Sahara Desert within the northern fringes of the study area. Waterbody also expanded annually at 3.1 km^2, which showed possible traces of inundation. Cropland, however, had the highest impact with a 6-km^2 average annual expansion from a baseline of 67,851.46 km^2, which represents roughly two-thirds of the study area. This shows that over time, crop cultivation stretched spatially. These increases occurred at the expense of natural landcover categories, mainly shrubland, grassland and woodland, which yearly lost 62.7 km^2, 38.45 km^2 and 31.42 km^2, respectively, within the period of the study. The shrinkage of these natural landcover categories, which substantially aid the provisioning and regulating ESs of the Sokoto-Rima basin, can be examined further at the decadal level. For instance, the decade 1992–2002 showed that grassland, shrubland and woodland lost 200.62 km^2, equivalent to the spatial increases in the land area and proportion of settlement, cropland and bare surface. The sharp decimation of woodland, evidence of deforestation, is well presented as 14.57 km^2 was lost over the 23 years of study.

Table 2 Ecosystem service restoration indicators

s/N	Ecosystem service restoration indicators	Indicator elements
1	Spatial location descriptors	1. Locational setting 2. Local councils/major settlements 3. Nature of communities
2	Main landcover	4. Rain-fed cropland 5. Agroforestry 6. Woodland 7. Grassland 8. Bare surface 9. Water body
3	Pattern of climate change	10. Past precipitation 11. Future precipitation 12. Past temperature 13. Future temperature
4	Dominant ecosystem services	14. Crop production 15. Seasonal water yield 16. Habitat quality 17. Nutrient retention ratio
5	Mean ecosystem service interaction	18. Synergy status 19. Trade-off status

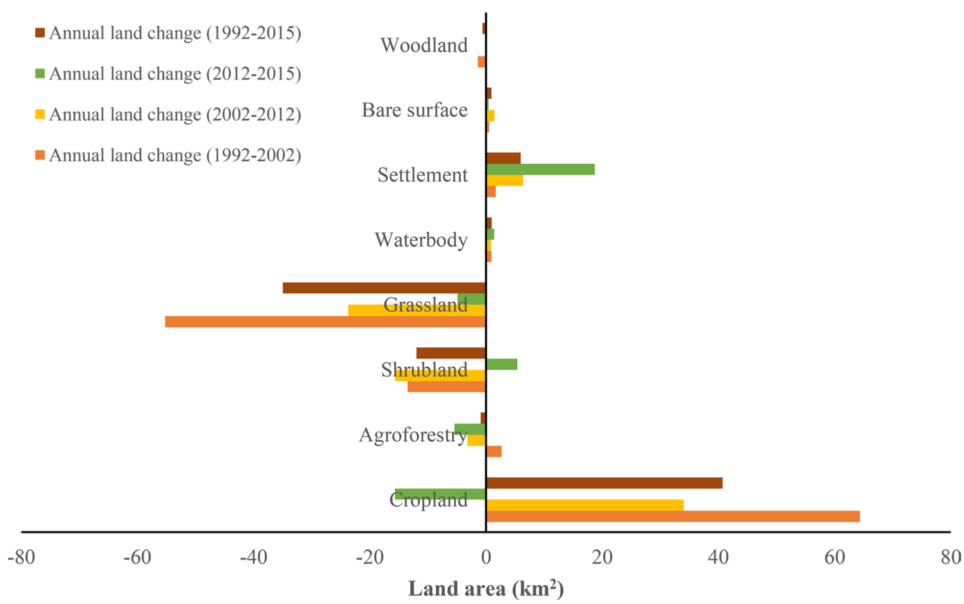


Fig. 3 Net rate of change of specific landcover categories 1992–2015

Changes in the spatial distribution of landcover for that decade (2002–2012) and the entire study period (1992–2015) showed that cropland, agroforestry, shrubland, and grassland recorded substantial spatial inter-conversions (Fig. 4). Other landcover classes had minute inter-conversions, which are spatially negligible. During 2002–2012, the Gwadabawa–Gada axis experienced substantial shrubland losses, spreading to adjoining areas such as Kware, parts of Goronyo, and Wurno. Similar shrubland losses were also observed in Wamako, Silame, Yabo, Shinkafi, Maradun, and Zurmi. Grassland losses were recorded majorly in the western and eastern axis of the study area. These were at the fringes of existing water bodies in Kalgo, Talata Mafara, and Bungudu. Agroforestry loss was recorded in Shanga, Sakaba, and some southern parts of the study area. Cropland gains were the most obvious in the northern areas owing to expansion in cultivation activities. Gains in agroforestry, shrubland, and grassland were detected in some parts of Maru, which were initially woodlands. This depicts the evidence of forest decimation and degradation as this was also a period when Nigeria experienced a significant rate of deforestation (FAO 2016).

In comparison with the entire study period (1992–2015), significant landcover changes were related to gains in cropland, shrubland, agroforestry, grassland, and waterbody, respectively, in addition to gains in waterbody. Cropland gains were visible in some parts of Maru woodland, which were converted to crop cultivation. Shrubland gains were detected in Arewa Dandi, Augie, and Gudu areas. Agroforestry gains were detected in Illeila and parts of Gudu. Grassland gains were observed in wet areas of Birnin Kebbi and previous woodland areas of Maru. Traces of inundation were detected in some parts of the Sokoto–Wamako–Shuni axis as water bodies were found to have expanded beyond their spatial boundaries. Hence, the study area experienced substantial anthropogenic influences on landcover, such that some natural landcover shrank. The influence of climatic processes on landcover led to the expansion of water bodies. These interchanges have implications on the delivery of ESs, given that human settlement was also observed to have expanded geometrically in the study area.

Dynamics of climate of the Sokoto-Rima basin

This study essentially exemplified precipitation and temperature dynamics, which account for a relatively substantial proportion of climate factors stimulating ecosystem service within the West African semi-arid zone in general and Sokoto-Rima basin in particular (Oguntunde et al. 2011; Sylla et al. 2016a). The defining characteristics and trend of these elements concisely provide a good synoptic view of the climate pattern and its influence on ESs. The precipitation trend showed that mean annual precipitation decreased at a rate of 2.19 mm per annum with an aggregate mean of 893.24 mm for 67 years. The corresponding M–K test value of − 2.598 depicted a decreasing monotonic trend (Fig. 5). This shows that the study area had experienced a low rainfall spell, a pointer to a possible drought event. Precipitation during the future climate will possibly return a mean of 770.02 mm with an increasing rate of 3.30 mm per year. The M–K test value of 1.627 is also expected for the future climate. Compared to the past climate, the future climate is anticipated to increase precipitation, leading to progressive wetting (Fig. 6). By implication, the possible occurrence of flood events (river and urban) should be expected. In areas with pre-existing flood challenges, frequent summer flood

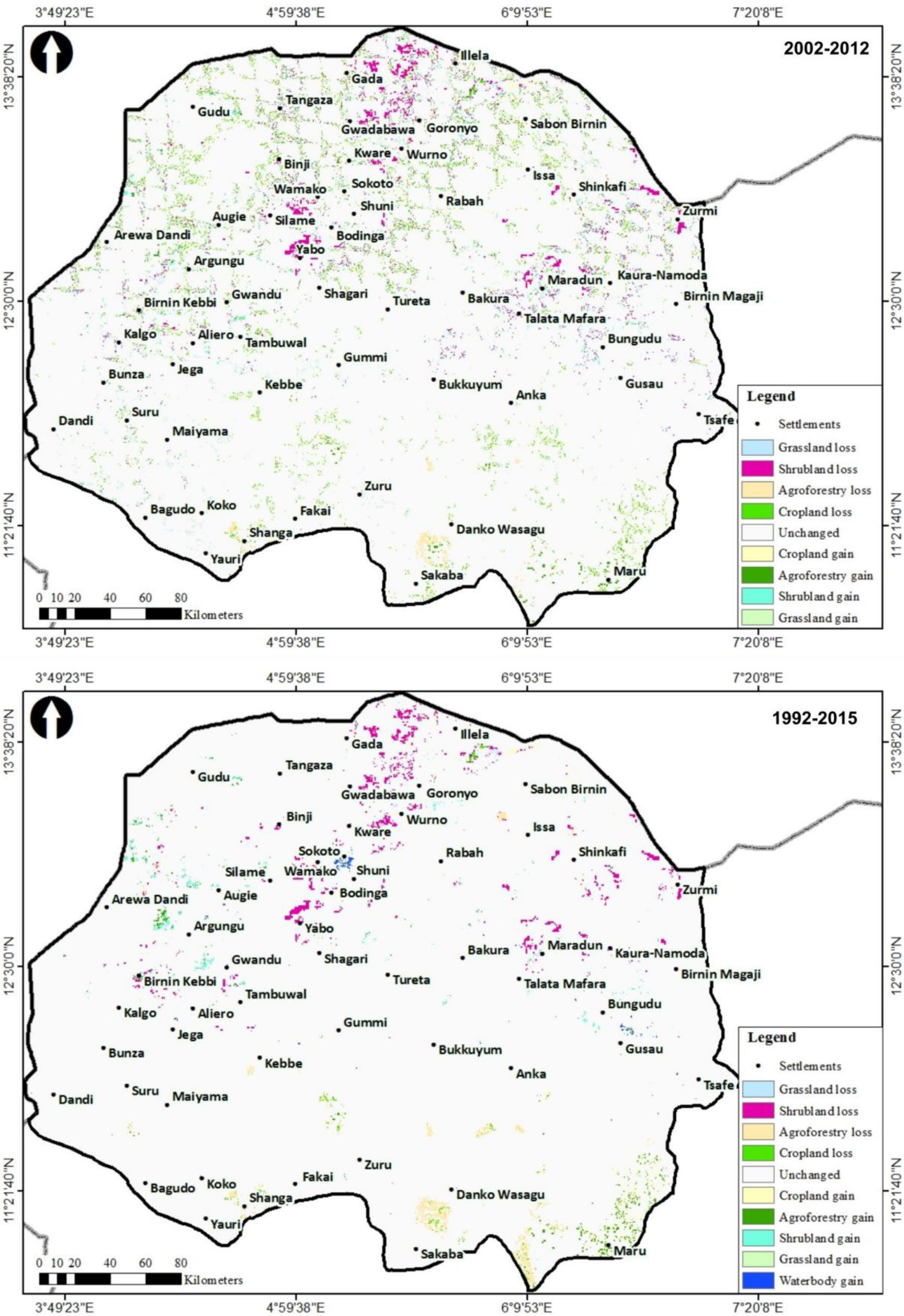


Fig. 4 Spatial distribution of landcover change during 2002–2012 and the entire period of study (1992–2015)

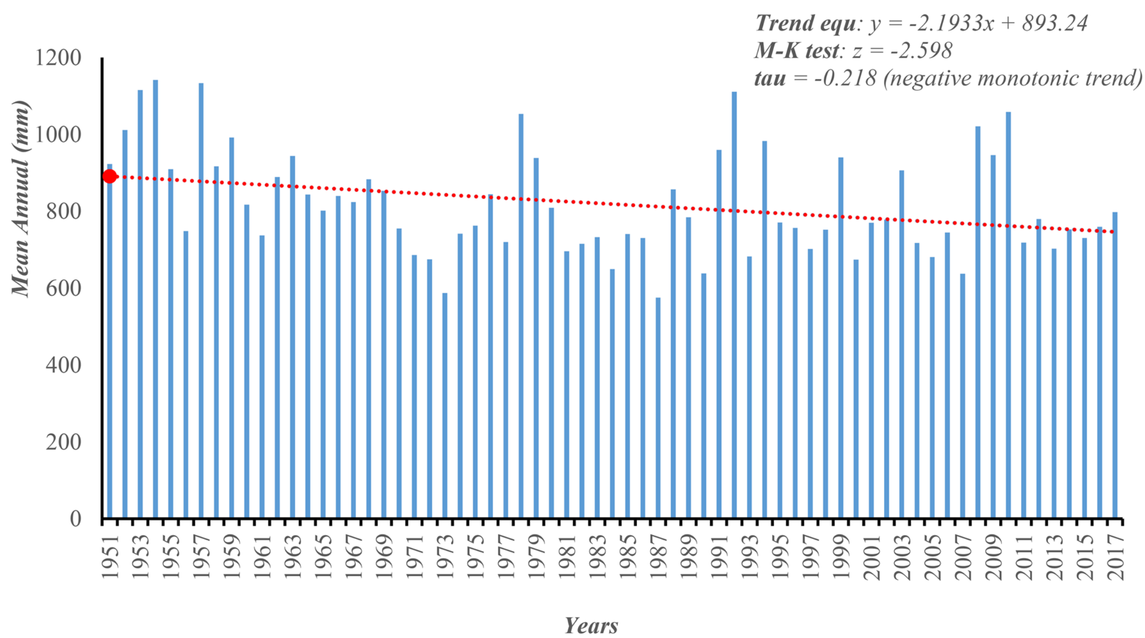


Fig. 5 Temporal rainfall variation and trend for the period 1951–2017

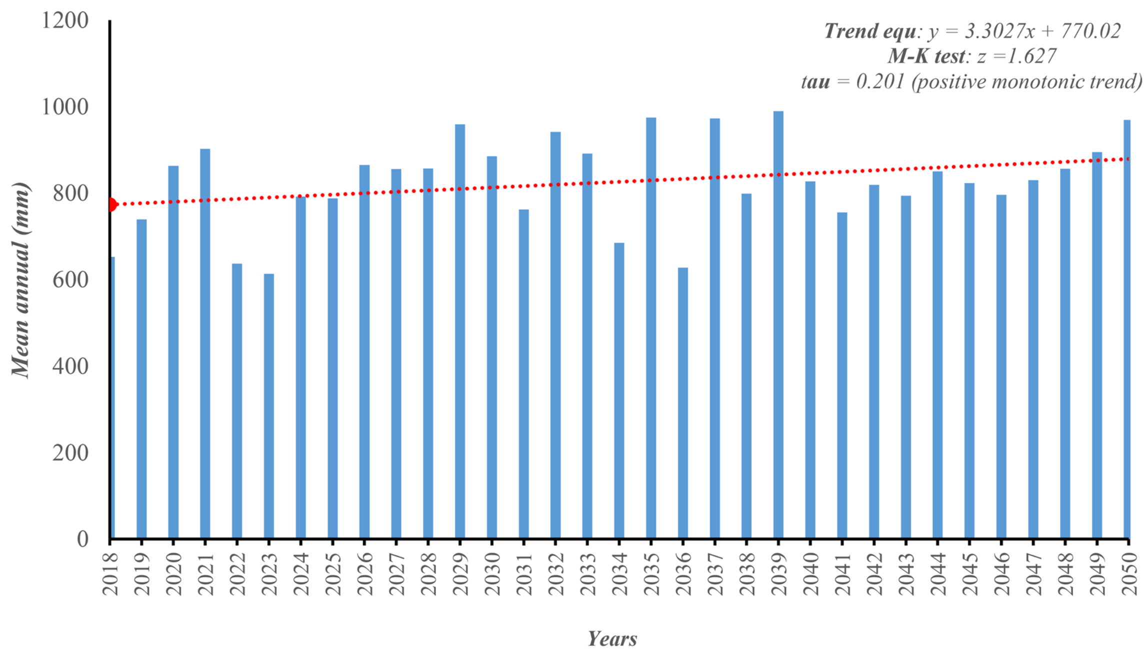


Fig. 6 Temporal rainfall variation and trend for the period 2018–2050

should be expected. Thus existing regulating and provisioning ESs will likely be disrupted.

The temperature trend of the past climate revealed that annual maximum temperature increased at the rate of 0.0093 ºC with a mean temperature of 34.22 ºC in 67 years. The resultant M–K test value of 3.284 was generated, indicating an increasing monotonic trend (Fig. 7), showing that a warming spell was experienced in the study area. The corresponding future climate also showed that temperature would have a mean maximum value of 34.54 ºC with an increasing rate of 0.013 ºC (Fig. 8). Its associated M–K test value of 2.154 is expected, specifying that an increasing monotonic trend should be expected for this period. This suggests clearly that the temperature warming spell over the

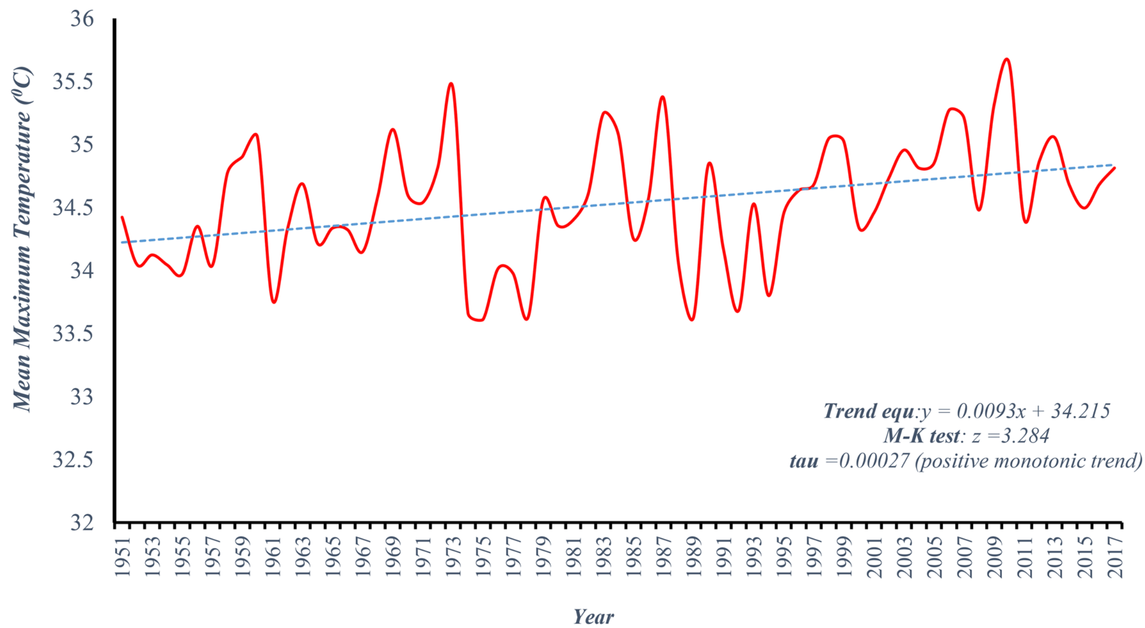


Fig. 7 Temporal maximum temperature variation and trend for the period 1951–2017

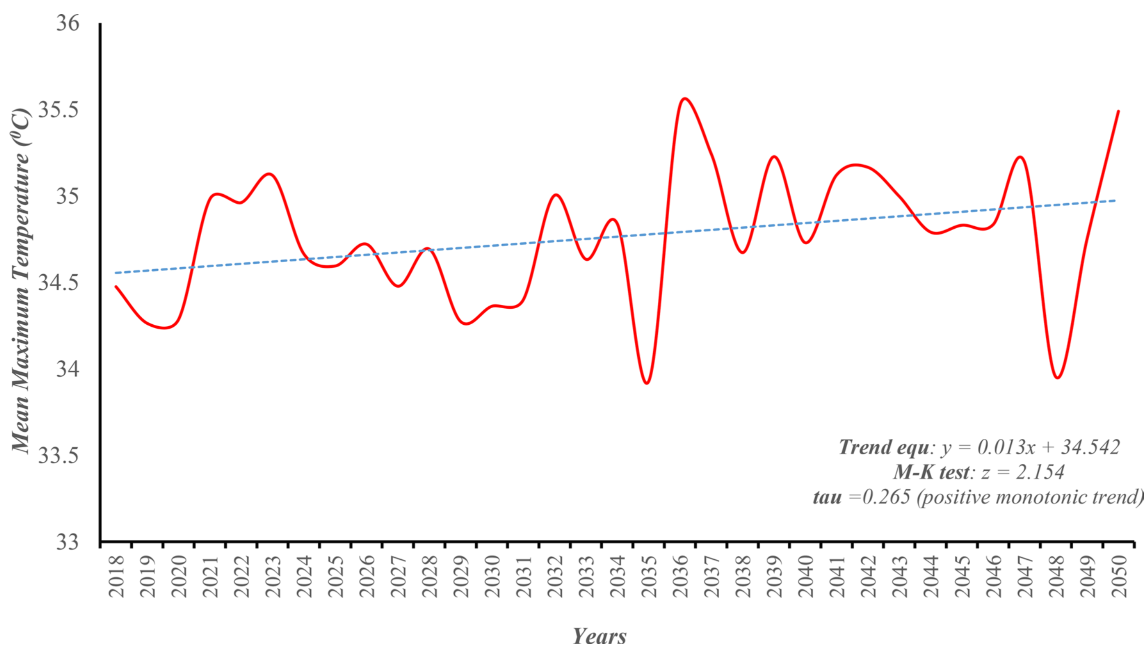


Fig. 8 Temporal maximum temperature variation and trend for the period 2018–2050

Sokoto-Rima basin will persist as it was in the past climate with a tendency to increase slightly. This outcome agrees with 34.8 ºC supplied by Abiodun et al. (2012) for Nigeria's entire north-western axis, where the Sokoto-Rima basin lies with its attendant warming.

The spatial context of these climatic variations depicts some evidence of heterogeneity, which is noteworthy about spatial distribution and dynamics of ESs. This is traceable to the level of the trend observed. Specifically, the cumulative overview of precipitation and temperature over the period of study (1951 to 2050) produced a disproportionate synopsis of climate dynamics. To show the climatic factors' aggregated trend, precipitation and temperature data were overlaid using spatial analysis tools in ArcGIS to show the

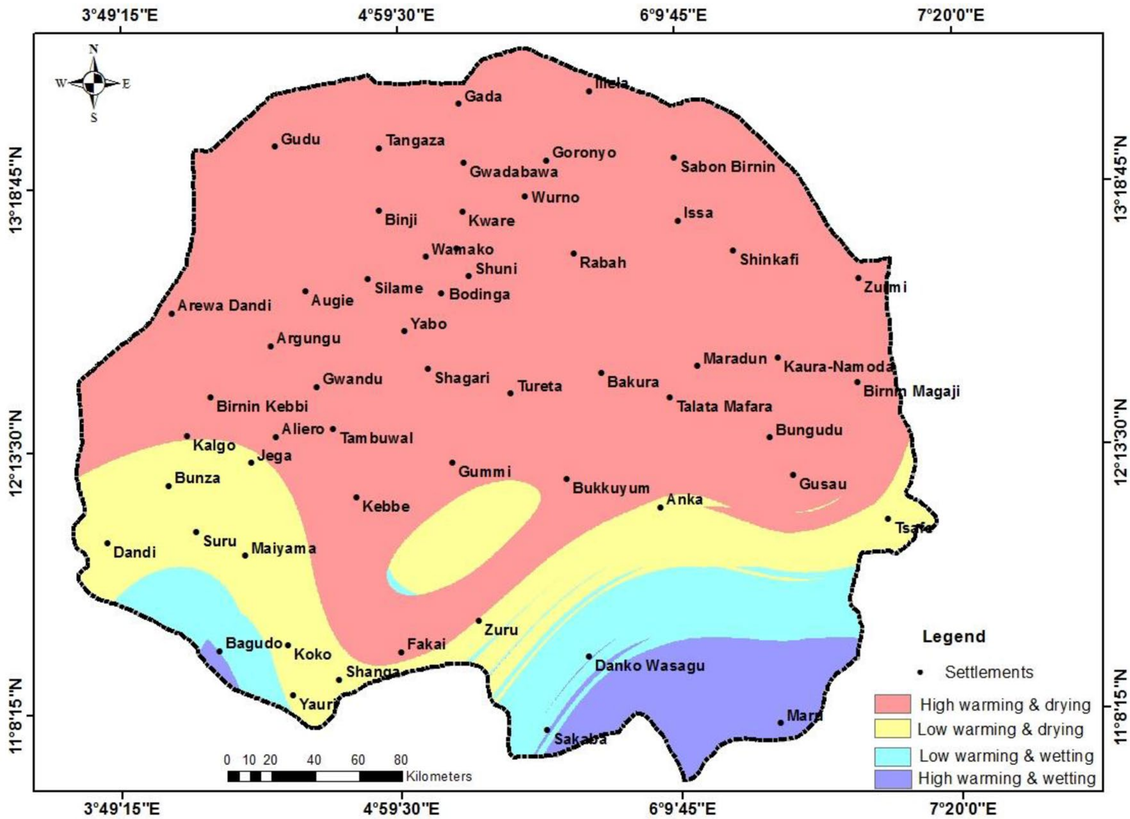


Fig. 9 Spatial distribution of climate change in Sokoto-Rima basin during the period 1951–2017

possible spatial trend and distribution of the two climatic periods. These showed that during the past climate, most of the study area experienced a high level of warming and drying trend (Fig. 9). Obvious exceptions were observed in the southern axis, where a substantial amount of precipitation was recorded. Thus, areas such as Bagudo, Sakaba, and Maru had high warming and wetting spells. The impact of precipitation within the study area's southern axis showed evidence of low warming and wetting. This was extended to some parts of the western axis, especially in Suru, Bunza, Jega, Kalgo, and the Anka-Tsafe axis in the east. Strands of low warming and drying were also detected around Danko Wasagu. The pattern observed for the future climate is a clear regional departure from the past scenario. Due to the increasing amount of precipitation anticipated compared to temperature, there is the possibility of progressive northward expansion of wetting mixed with warming (Fig. 10). Also, southern areas from Bagudo to Danko Wassagu and Maru will experience high wetting with warming events. The hilly areas of the east and the Sokoto plains of the west will also experience low warming and wetting trend, while the drying and wetting trend earlier experienced in the core north will remain unchanged. These climatic transactions are expected to have diverse impacts on ESs.

Ecosystem Service Interactions

Temporal Extent of ecosystem services scenario in 2015 and 2050 Two extents of ES interactions were measured in this study—the past climate scenario (2015) and the future climate scenario (2050). Figure 11 shows that the Sokoto-Rima basin as of 2015 is trade-off oriented (with ten relationships compared to synergies (with five relationships) measured at three significance levels ($p<0.05$, $p<0.01$ and $p<0.001$)). The HQ-EVI relationship reveals the strongest synergy ($r=0.532$, $p<0.001$), suggesting that increasing habitat quality possesses the potential to reduce the vulnerability of the study area to ecosystem degradation. The Cropland-SWY relationship reveals the least synergy with fragile connection ($r=0.115$, $p<0.001$), showing that cropland expansion does not entirely rely on substantial seasonal water availability, not unexpected for a semi-arid zone. Also, the strongest trade-off is depicted by EVI-NRR connections ($r=-0.848$, $p<0.001$), showcasing the extent of nutrient flow in an agrarian region that could be affected by increasing vulnerability to ecosystem degradation. The Sokoto-Rima basin is directly threatened by the southward encroachment of the Sahara Desert suggesting the possibility of this interaction (Olagunju 2015). The least trade-off is

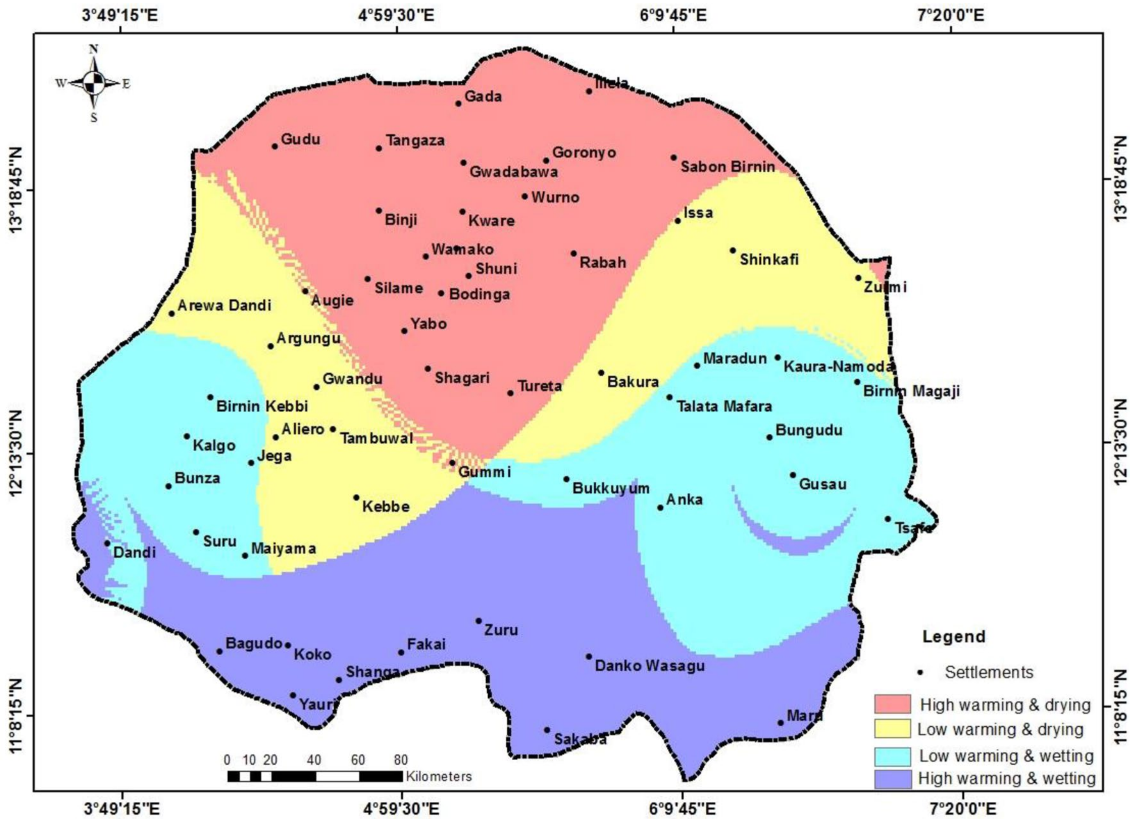
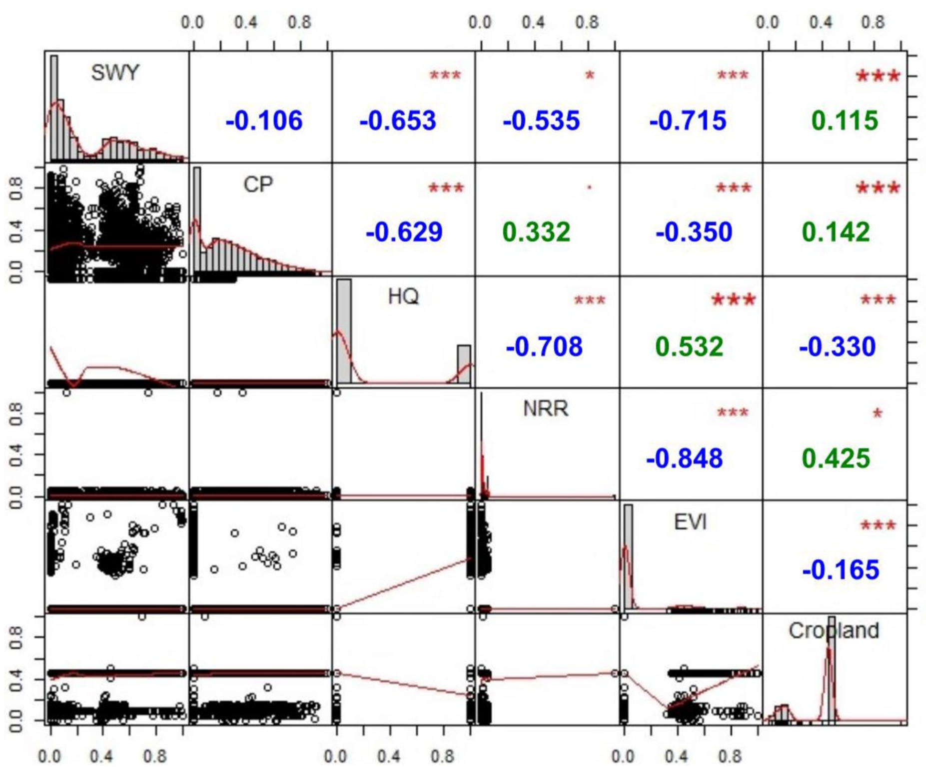


Fig. 10 Spatial distribution of climate change in Sokoto-Rima basin expected for the period 2018–2050

Fig. 11 Pearson's correlation coefficients between ecosystem service models, EVI and cropland in 2015. (green coefficients denote positive correlation, while blue indicates negative correlation. Symbols *, **, *** specify $p < 0.05$, $p < 0.01$ and $p < 0.001$, correspondingly.)



revealed by the SWY-CP ($r = -0.106$) relationship, which is a pointer to the fact that an increase in the yield of water across the study area could hamper productivity per unit area of land. This is not unexpected as more rainfall often leads to damages to croplands, leading to crop failure and sometimes low farm yield.

The intensity of trade-off relationships in the Sokoto-Rima basin will increase by 2050, as shown in Fig. 12. This means that the synergy relationship will reduce to four from five in 2015. The previous synergy relationship between EVI-HQ will turn negative provided the trend persists. As shown in Fig. 12, the strongest synergy relationship will exist between CP-NRR ($r = 0.816$, $p < 0.001$), indicating that abundant nutrient flow within the ecosystem will trigger more land productivity in terms of crop yield per unit area. Meanwhile, the least synergy is expected to be revealed by the Cropland-SWY relationship ($r = 0.121$, $p < 0.001$), which is a furtherance of the hitherto observed relationship in 2015. Conversely, the trade-off is anticipated to be strongest as defined by the NRR-HQ relationship. This indicates that abundant nutrient that triggers an increase in yield per land area will have a deleterious impact on natural habitat and the biodiversity of the Sokoto-Rima basin. The leanest trade-off is anticipated in HQ-SWY ($r = -0.134$, $p < 0.001$) relationship. This shows that a possible increase in water coupled with a projected increase in rainfall could hamper the fragile natural habitat of the Sokoto-Rima basin.

Spatial extent of ecosystem service scenario in 2015 and 2050 In this section, we assessed pixel-level comparisons of ES interactions at the local community level (based on local councils) to examine their spatial dynamics for the past (2015) and the future (2050). Across these periods, four spatial expressions were detected: low trade-off ($r \leq -0.5 \leq 0$), high trade-off ($r \geq -0.5 \leq -1$), low synergy ($r \leq 0.5 \leq 0$) and high synergy ($r \geq 0.5 \leq 1$) as depicted in Figs. 13 and 14. With respect to the past (2015), the Sokoto-Rima basin is trade-off-dominated with high trade-off relationships having a land area of 37,197.58 km^2 which is as much as four times the size of low trade-offs. As shown in Fig. 13, the distribution of synergy ES interactions on the basis of local councils shows: 14 with high synergy and 17 with low synergy status. Based on trade-off relationships, 21 local councils have high status while 5 returned low status. Spatially, the low trade-offs are confined to the north flanked by the high trade-offs that spread to some parts of the east and west. The central area is particularly dominated by low synergy, while the south and some parts of the east and west are high-synergy-oriented. This outcome is similar to other semi-arid zones, particularly in Asia (Yang et al. 2018; Fu et al. 2018).

The persistence of the ES interactions into the future (2050) will introduce some dynamics to the previously observed. As displayed in Fig. 14, local council areas, such as Anka, Gummi and Gada, which previously exhibited low synergy and low trade-offs in 2015, are expected to advance to high trade-offs. Also, Yabo will transit to high synergy

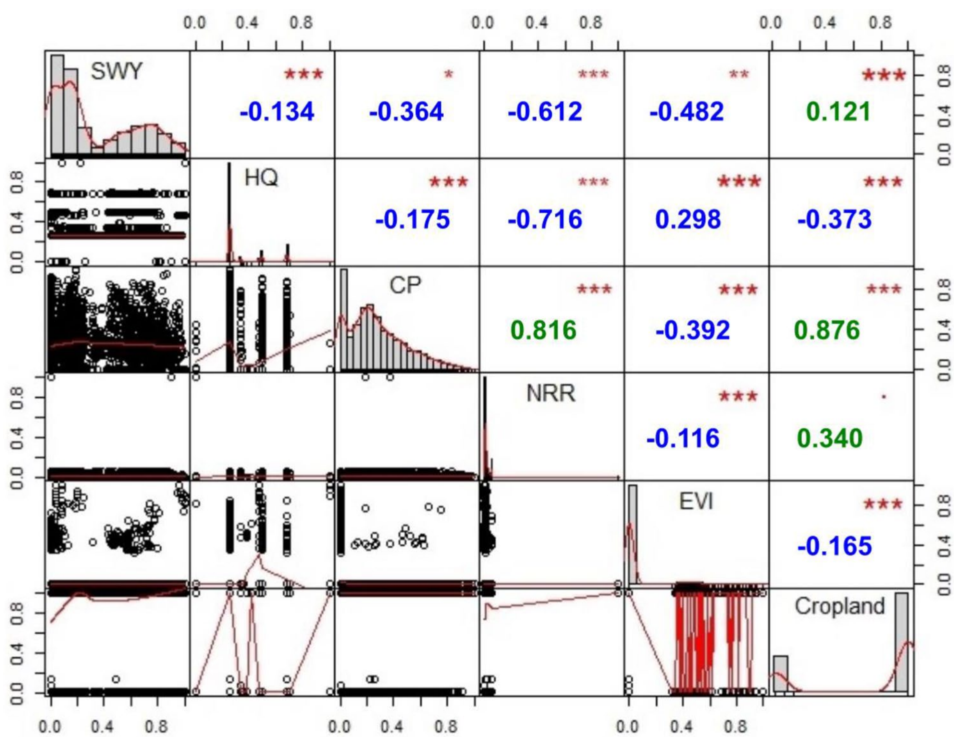


Fig. 12 Pearson's correlation coefficients between ecosystem services models, EVI and cropland in 2050. (green coefficients denote positive correlation, while blue indicates negative correlation. Symbols *, **, *** specify $p < 0.05$, $p < 0.01$ and $p < 0.001$, correspondingly.)

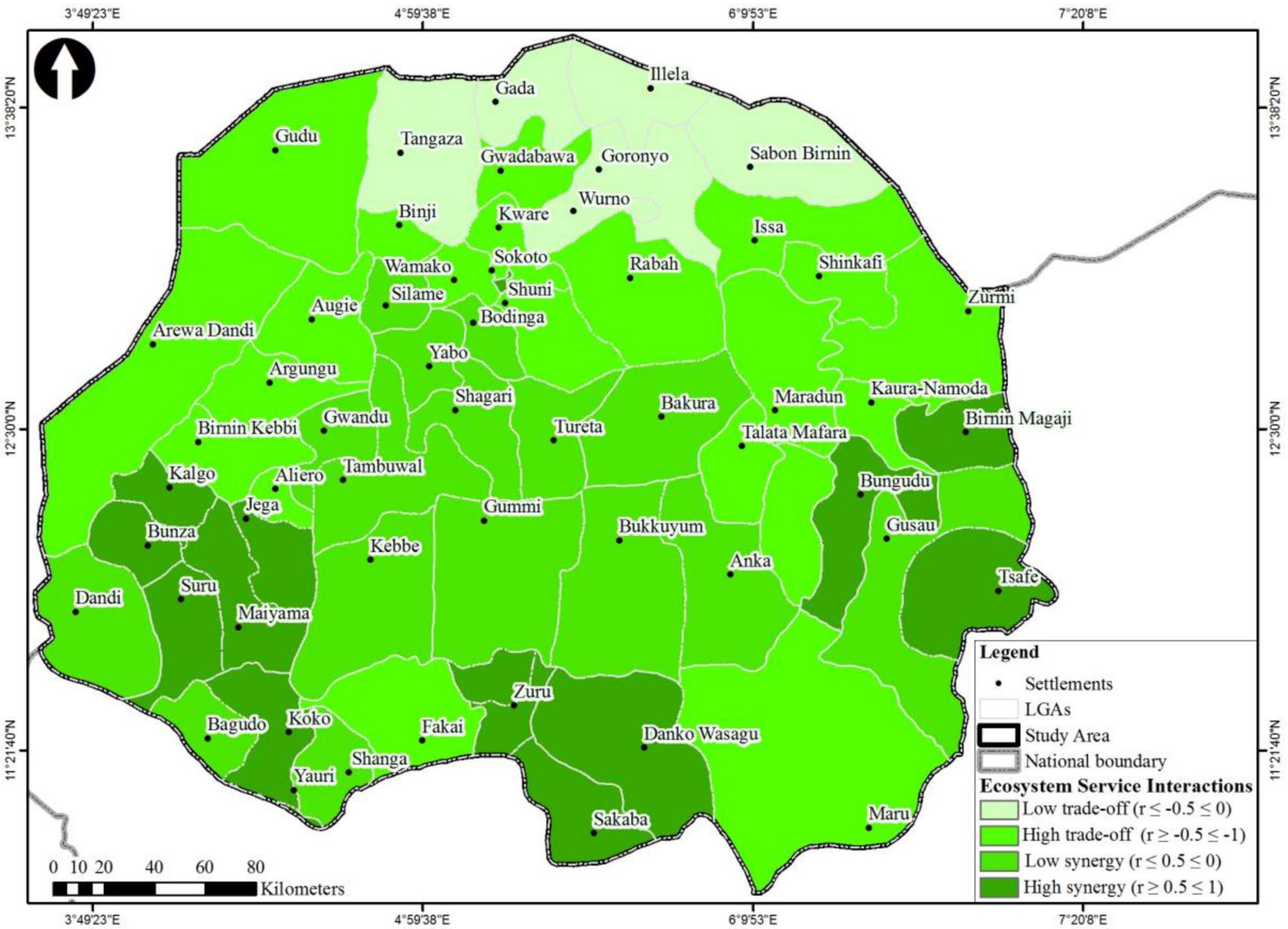


Fig. 13 Spatial distributions of ecosystem interactions in depicting ranges of trade-offs and synergies at local council level in 2015

from low synergy. Thirdly, Gwadabawa and Maradun, which previously exhibited high trade-offs, will transit to low synergy. In summary, high trade-off and high synergy relationships are anticipated in 2050 compared to 2015 (Fig. 15). These spatial transitions and dynamics are anticipated to be driven by the increasing intensity of precipitation, which can yield two positive ESs regulatory merits in terms of available water all-seasons and its yield-boosting impact on small-scale rain-dependent agriculture that is practised in these areas. This will also be normalised by possible alternating cooling and warming spells.

Aggregate ecosystem service interactions

We consider the fact that aggregate ES interactions as the synoptic response of each ecosystem service to the collection such that the impact of a change in one ecosystem service can be assessed on the whole. This is vital as a single ecosystem service contributes to the overview of the multiple ESs within a landscape. Within the context of environmental restrictions posed by changing EVI and dominant anthropogenic landcover (cropland), the relationship explains the possible reactions of the interconnections between ESs and the environment. The polar charts depicted in Fig. 16 were generated as measured by these multiple ES interactions with aggregate relationships defined by the correlation coefficients from 1992 to 2050—a temporal indication of the dynamic pathway of ESs from the past to the possible future ES interactions in the study area. The dominance of cropland is seen throughout the years, notwithstanding the dynamics detected in other ESs. However, the baseline shows the vital ESs ranging in ascending order CP > SWY > HQ > EVI > NRR. This shows that EVI influences the nutrient cycling and other material flow within the Sokoto-Rima basin directly, while the natural hydrological system influences the expanse of cropland (particularly its associated productivity). Since this relationship is nonlinear, it elucidates the hierarchy of contributory dynamics of a particular ecosystem service to the next within the ecosystem space. At this baseline, the level of biodiversity is greatly influenced by the level of crop production within the Sokoto-Rima basin, which leads to fluctuations in its

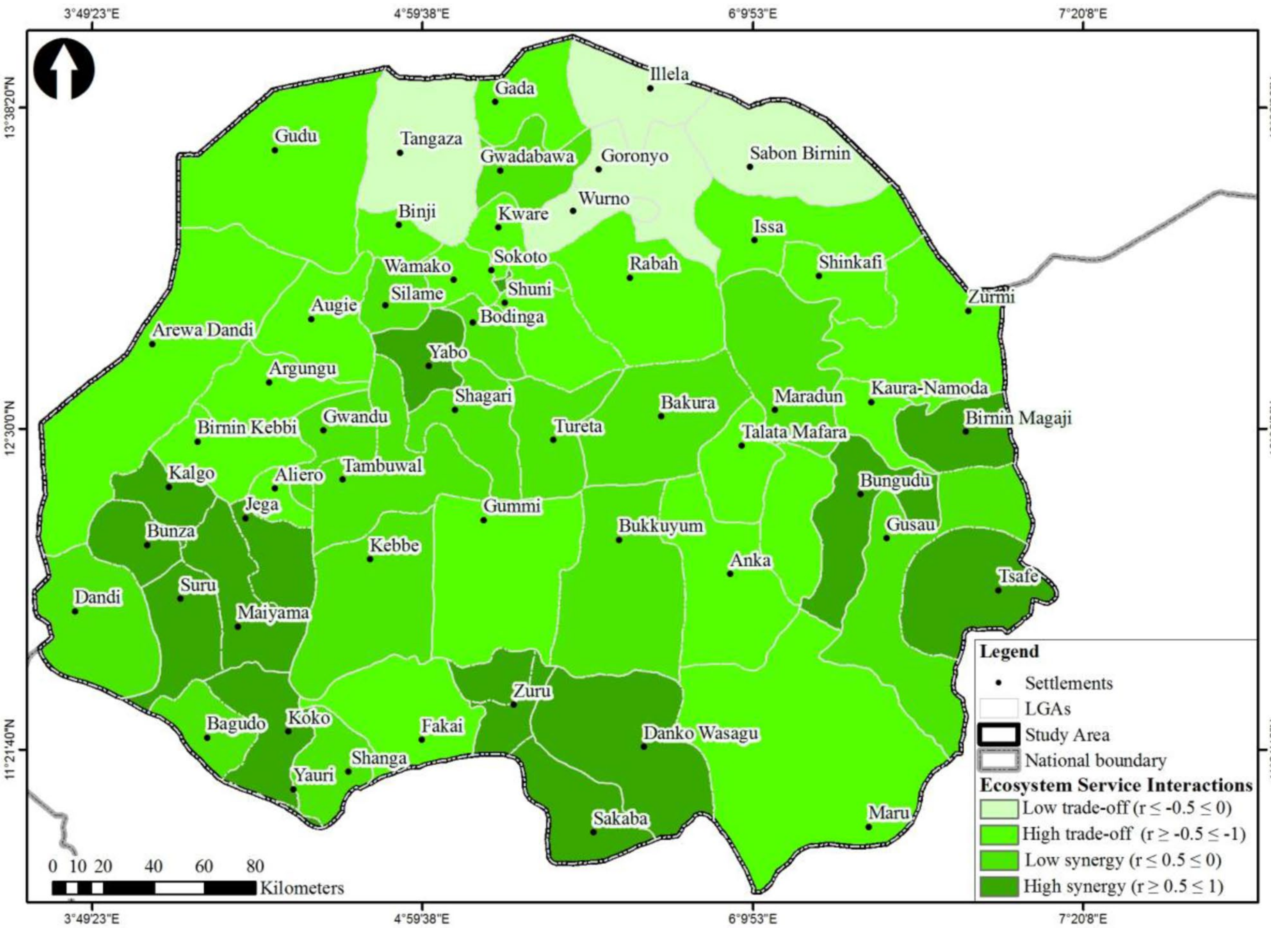
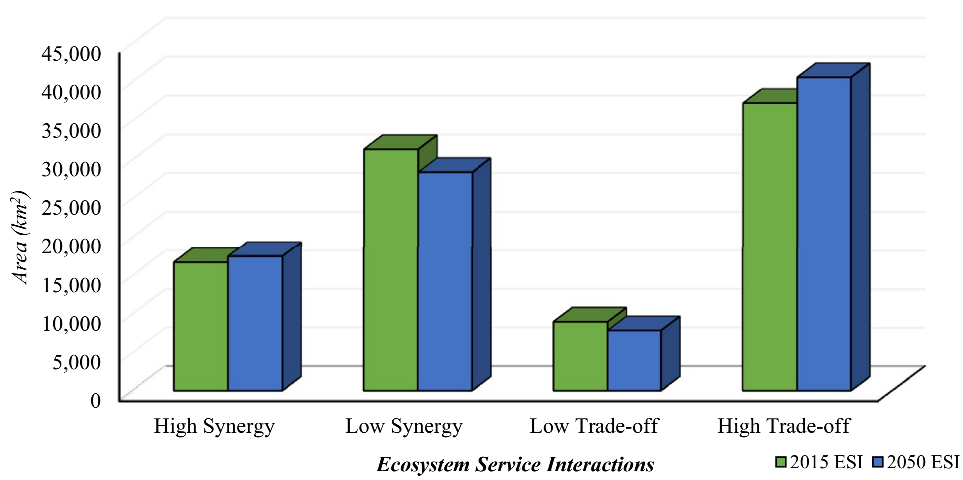


Fig. 14 Spatial distributions of ecosystem interactions in depicting ranges of trade-offs and synergies at local council level in 2050

Fig. 15 Comparative area proportion of ES interactions for the years 2015 and 2050



associated flow of nutrients. Within the period of a decade (1992–2002), anthropogenic cultivation grew at the expense of HQ, NRR, and EVI. Also, EVI shrank faster than other ESs, as Raji et al. (2020a) asserted, while cropland and CP increased within the same proportion signifying an exchange within the ESs spectrum. A slight improvement in NRR was observed in 2012, while NRR shrank further with the increasing CP and cropland rate. This continued in 2015

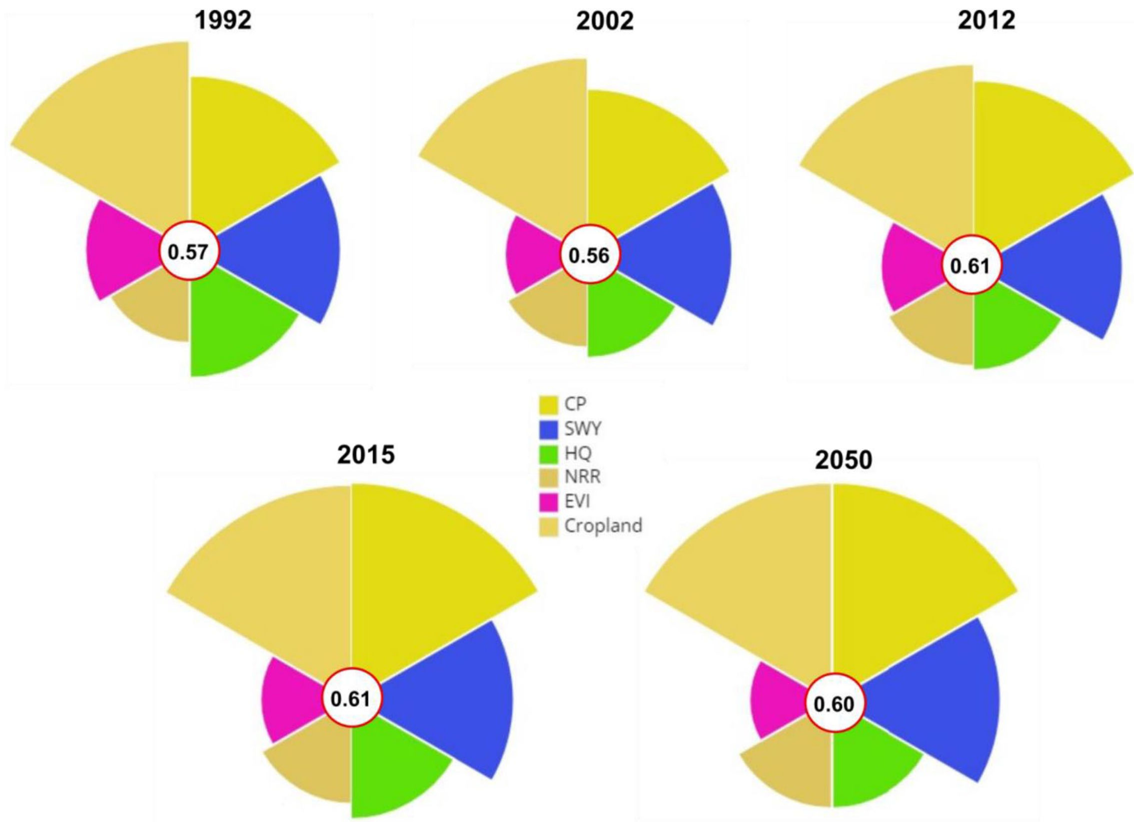


Fig. 16 Historical dynamics of ES interactions with respect to cropland and EVI at the Sokoto-Rima basin for the period 2015–2050 measured at mean Pearson coefficient with $p < 0.05$

with a meagre HQ improvement. It is expected that the array of increase in HQ will persist till 2050. The fluctuations in the correlation coefficient's value from 0.57 to 0.61 could be related to these dynamics of ESs within the study area.

Spatial ecosystem restoration in the Sokoto-Rima basin

This study has shown the nature and trend of ES interactions as influenced by climate change and landcover change and the possibility that ESs might have degraded over time in the Sokoto-Rima basin. It is pertinent, therefore, that sustainable place-based and context-specific measures are designed to address the bourgeoning situation. The description of the suitable ecosystem restorations is based on perceived interactions amongst determinant ESs stated in Table 3, which include five indicators and nineteen elements. The synchronisation of these elements was used to develop the nature of ecosystem response and the respective ecosystem restoration measures expressed in Table 4.

In terms of landcover, there is a preponderance of agrarian communities through the study area. This is exceptionally high in areas with high natural resource stocks such as riverine and wetland areas and floodplains. Agriculture, particularly cropland, is almost entirely rain-fed such that there is a high reliance on rainwater storage and irrigation facilities to enhance productivity. Apart from the Sokoto plains and part of Niger valley lowlands, where there are recently revived commercial complexes, seasonal cultivation on a small scale is rampant throughout the study area. Eco-friendly crop management approaches such as shifting current practices towards flood-resistant crop varieties and the deployment of flood warning system against rainfall extremes would come in handy to scale up the current experience seasonal flooding in the study area. Over time, practices of agroforestry have declined acutely in the Sokoto-Rima basin. Woodlots and woodlands that provide shields against windstorm have declined over the years, thus exposing the area to wind erosion, particularly at the northern fringes of eastern plains and Sokoto plains. Within the lowlands of the Niger valley, this phenomenon is gradually becoming intensified. Thus, large-scale re-forestation shields are critical in areas such as Zurmi, Tsafe, Gusau, Birnin Kebbi–Argungu–Gada–Illeila axis, where protection buffers are crucial. A similar development is critical for Suru, Yauri, Shanga to Sakaba within the Niger lowlands to restore the degrading biodiversity to aid ecological productivity. Generally, woodland in the Sokoto-Rima basin's northern axis has declined severely, leading to soil degradation in Yabo, Kebbe, Gusau, Aliero, and Zurmi,

Table 3 Landcover change analysis during 1992–2015

Land-cover	1992	2002	2012	2015	1992–2002			2002–2012			2012–2015			1992–2015		
					Area change (km^2)	Area change as % of 1992	Annual rate of change in %	Area change (km^2)	Area change as % of 2002	Annual rate of change in %	Area change (km^2)	Area change as % of 2012	Annual rate of change in %	Area change (km^2)	Area change as % of 1992	Annual rate of change in %
Crop-land	67,851.46 (72.16%)	68,495.23 (72.85%)	68,835.38 (73.21%)	68,788.24 (73.16%)	643.77	0.95	9.49	340.15	0.50	4.97	−47.14	−0.07	-2.28	936.78	1.38	6.00
Agrofor-estry	11,785.83 (12.53%)	11,812.66 (12.56%)	11,780.53 (12.53%)	11,764.26 (12.51%)	26.83	0.23	2.28	−32.13	−0.27	−2.72	−16.27	−0.14	−4.60	−21.57	−0.18	−0.80
Shrub-land	1,910.49 (2.03%)	1,775.27 (1.89%)	1,618.79 (1.72%)	1,634.97 (1.74%)	−135.22	−7.08	−70.78	−156.48	−8.81	−88.14	16.18	1.00	33.32	−275.52	−14.42	−62.70
Grass-land	9,097 (9.67%)	8,544.47 (9.09%)	8,307.1 (8.83%)	8,292.43 (8.82%)	−552.53	−6.07	−60.74	−237.37	−2.78	−27.78	−14.67	−0.18	−5.89	−804.57	−8.84	−38.45
Water-body	3,041.1 (3.23%)	3,050.28 (3.24%)	3,058.61 (3.25%)	3,062.78 (3.26%)	9.18	0.30	3.02	8.33	0.27	2.73	4.17	0.14	4.54	21.68	0.71	3.10
Settle-ment	68.71 (0.07%)	85.51 (0.09%)	149.25 (0.16%)	205.47 (0.22%)	16.80	24.45	244.51	63.74	74.54	745.41	56.22	37.67	1255.61	136.76	199.04	865.39
Bare surface	70.32 (0.07%)	75.42 (0.08%)	90.01 (0.1%)\	91.33 (0.1%)	5.10	7.25	72.53	14.59	19.35	193.45	1.32	1.47	48.88	21.01	29.88	129.90
Wood-land	201.59 (0.21%)	187.66 (0.2%)	186.83 (0.2%)	187.02 (0.2%)	−13.93	−6.91	−69.10	−0.83	−0.44	−4.42	0.19	0.10	3.39	−14.57	−7.23	−31.42
Total	94,026.5 (100%)	94,026.5 (100%)	94,026.5 (100%)	94,026.5 (100%)												

Table 4 Ecosystem service restoration options

Ecosystem service restoration indicators	S/no.	Ecosystem restoration elements	Possible ecosystem response/ Proposed ecosystem restoration measures	Location-specific ecosystem restoration options		
				Eastern uplands	Sokoto plains	Niger valley lowlands
Main landcover	1	Rain-fed cropland	Nature of ecosystem response	Highly dependent on rain/irrigation, majorly small scale with seasonal distinction	Highly seasonal and rain-dependent, irrigated, small scale with spots of commercial complexes within floodplains	Seasonal cultivation and rain-dependent, small scale with spots of commercial cultivation in the wetland areas and the lowlands
			Proposed ecosystem restoration measures	Better crop management with varied drought and flood-resilient varieties, deploy flood warning systems	Ecosystem-based crop management systems, cultivate flood-resilient varieties, install flood early warning systems	Agriculture management with flood-resilient varieties, crop management to anticipated extreme climate risks, deploy flood warning systems
	2	Agroforestry	Nature of ecosystem response	Ongoing decline of the forest/woodland ecology, dominated by small-scale rain-fed crop cultivation	Gradual debility of the forest/woodland ecology and dire dominated by small-scale rain-fed crop cultivation	Steady decline of the forest/woodland ecology and acutely dominated by small-scale rain-fed crop cultivation
			Proposed ecosystem restoration measures	Better crop management with varied drought and flood-resilient varieties, deploy flood warning systems	Ecosystem-based crop management systems, cultivate flood resilient varieties, install flood early warning systems	Agriculture management with flood resilient varieties, crop management to anticipated extreme climate risks, deploy flood warning systems
	3	Woodland	Nature of ecosystem response	Degraded woodland exposing areas to wind erosion and soil erosion	Exposure to wind erosion and pockets of soil erosion around Yabo, Kebbe extended to Sokoto north	Ample evidence of de-vegetated wetland and woodland trigger seasonal river flooding

Table 4 (continued)

Ecosystem service restoration indicators	S/no.	Ecosystem restoration elements	Possible ecosystem response/ Proposed ecosystem restoration measures	Location-specific ecosystem restoration options		
				Eastern uplands	Sokoto plains	Niger valley lowlands
			Proposed ecosystem restoration measures	Restore degraded woodlands via intensification of Great Green Wall project to the north, revive forest protection systems	Wetland restoration to curtail degraded woodlands, strengthen the Great Green Wall project, intensify local woodlot development projects	Develop tree planting initiatives using localised knowledge systems, encourage wetland protection initiatives including greenbelt buffer zones within de-vegetated areas
	4	Shrubland/grassland	Nature of ecosystem response	~30% projected to become fragmented and reduced	> 20–30% projected to become fragmented and reduced	~20% projected to become fragmented and reduced
			Proposed ecosystem restoration measures	Establish/re-introduce ranching system for cattle herdsmen, encourage research on semi-arid shrub and grass management under climate change scenario	Controlled grazing, established/re-introduce ranching system for cattle herdsmen, encourage large-scale silvopastoralism	Controlled grazing, Establish/re-introduce ranching system for cattle herdsmen, encourage large-scale silvopastoralism
	5	Waterbody	Nature of ecosystem response	Possible expansion ~5–8% of the river limits and severely impact dams and irrigation, rising flood risks along rivers Zamfara, Ka, Gusau and others	Projected to extend to ~5% of the existing river banks and acutely impact existing dams, rising flood hazard and risks along rivers Sokoto, Rima, Gagere, and others	Continued expansion of the river footprints by ~4%, increasing flood risks along the Niger floodplain
			Proposed ecosystem restoration measures	Sustainable climate extreme-based flood monitoring via local systems, flood early warning systems, specific river bank protection measures, dam monitoring and maintenance by the Sokoto Rima River Basin Development Authority (SRRBDA)	Sustainable climate extreme-based flood monitoring via local systems, flood early warning systems, river bank protection measures, systematic review of existing dam monitoring and irrigation sustenance by the SRRBDA	Sustainable climate extreme-based flood monitoring via local systems, flood early warning systems, river bank protection measures, promote inter-basin connections with Niger Basin Development Authority (NBDA) and collaborate with Federal Ministry of Forestry and Water Resources on river basin management to forestall large-scale flooding

Table 4 (continued)

Ecosystem service restoration indicators	S/no.	Ecosystem restoration elements	Possible ecosystem response/ Proposed ecosystem restoration measures	Location-specific ecosystem restoration options		
				Eastern uplands	Sokoto plains	Niger valley lowlands
Pattern of climate change	6	Past precipitation	Nature of ecosystem response	Localised wetting expected around Anka, Saka, Maradun areas	Increasing rain to trigger flood within wetlands and destruction of farmlands	Moderate-to-low flood possibility with normal water input
			Proposed ecosystem restoration measures	Sustainable flood management such as flood early warning measures, cultivate flood-resistant crops, research on climate change in this axis	Deployment of flood early warning system, better crop water management system, introduce flood-resistant crops,	Flood early warning system to be integrated to basin management, seasonal weather forecasting, encourage integrated climate research with NBDA and SRRBDA
	7	Future precipitation	Nature of ecosystem response	Short-duration high-intensity rainfall to increase by 5–10%	Short-duration high-intensity rainfall to increase by ~ 8%	Short-duration high-intensity rainfall to increase by ~ 7% with localised impact of West African Niger River
			Proposed ecosystem restoration measures	Build resiliency through seasonal climate flood warning system, prepare urban flood risk assessment, damage assessment agriculture, using local knowledge systems	Build resiliency through seasonal climate flood warning system, prepare urban flood risk assessment, damage assessment agriculture, using local knowledge systems	Build resiliency through seasonal climate flood warning system, prepare urban flood risk assessment, damage assessment agriculture, using local knowledge systems
	8	Past temperature	Nature of ecosystem response	Substantial cooling from the hilly areas of Anka, Bungudu and Gusua	Normal to warming spells around Yabo–Jega–Gada axis	Normal to warming spells around Sakaba–Suru–Zuru–Bagudo axis
			Proposed ecosystem restoration measures	Intensify the building climate resiliency measures such as flood-resistant crops, local levees around farmlands can be encouraged	Building resiliency measures, set up seasonal weather monitoring	Building resiliency measures, set up seasonal weather monitoring
	9	Future temperature	Nature of ecosystem response	Mild seasonal cooling expected around Bungudu, Gusua and Tsafe with drying around Zurmi and Shinkafi	Warm spells expected around Gada, Argungu, Yabo, Shagari with cooling around Kalgo and Jega	Cooling expected in most of the areas with traces of low warming in the northern axis
			Proposed ecosystem restoration measures	Building climate extremes resiliency via seasonal forecast for farmers within the basin	Basin-scale seasonal forecast is vital, heat-resistant crops should be encouraged	Build climate extreme resiliency through seasonal forecast, heat-resistant crops should be encouraged within the basin

Table 4 (continued)

Ecosystem service restoration indicators	S/no.	Ecosystem restoration elements	Possible ecosystem response/ Proposed ecosystem restoration measures	Location-specific ecosystem restoration options		
				Eastern uplands	Sokoto plains	Niger valley lowlands
Dominant Ecosystem systems	10	Crop production	Nature of ecosystem response	Normal yield is expected to reduce by 10–15%	Normal yield is expected to reduce by 5–12%	Normal yield is expected to reduce by 6–8%
			Proposed ecosystem restoration measures	High-yield eco-friendly crops should be introduced, cultivation clusters to be expanded and ensure all-inclusive structure	High-yield eco-friendly crops should be introduced, pro-poor cultivation clusters to be introduced and expand current structure	High-yield eco-friendly crops should be introduced, pro-poor cultivation clusters to be introduced and expand current structure
	11	Seasonal water yield	Nature of ecosystem response	Projected to increase by 10–20%	Projected to increase by 20–30%	Projected to increase by 10–18%
			Proposed ecosystem restoration measures	Encourage large-scale drainage management via sectoral development of the SRRBDA	Encourage large-scale drainage management via sectoral development of the SRRBDA	Encourage large-scale drainage management via sectoral development of the SRRBDA
	12	Habitat quality	Nature of ecosystem response	Estimated to diminish by by 25–30% with minor improvement around Maradun	Estimated to diminish by by 20–25% with slim improvement around the northern axis	Estimated to diminish by by 20–35% with slight improvements around Shanga, Suru and Zuru
			Proposed ecosystem restoration measures	Advance the Great Green Wall (GGW) project at the northern axis, encourage mass tree planting and woodlot projects	Advance the GGW project at the northern axis, encourage mass tree planting and woodlot projects	Advance the GGW project around the affected areas as well as the adjoining locations towards the north, encourage mass tree planting and woodlot projects
	13	Nutrient retention ratio	Nature of ecosystem response	Projected to improve by 1% owing to high water residency time	Projected to improve by 1.5% due to moderate hydrologic residency time	Projected to improve by < 1% due to hydrologic residency time
			Proposed ecosystem restoration measures	Improve existing agroforestry-based crop cultivation clusters towards eco-friendly development	Advance existing agroforestry-based crop cultivation clusters towards eco-friendly development	Develop existing agroforestry-based crop cultivation clusters towards eco-friendly development, build localised systems for management of eutrophication possibilities within streams

Table 4 (continued)

Ecosystem service restoration indicators	S/no.	Ecosystem restoration elements	Possible ecosystem response/Proposed ecosystem restoration measures	Location-specific ecosystem restoration options		
				Eastern uplands	Sokoto plains	Niger valley lowlands
Mean ecosystem service interactions	14	Synergy status	Nature of ecosystem response	More of high synergies and less of low synergies around the south	Averagely unchanged	Averagely unchanged
			Proposed ecosystem restoration measures	Semi-arid intercropping system should be encouraged to boost synergy towards sustainable land management systems	Maintain the current with ecosystem-friendly high-yield crop varieties and ensure sustainable agriculture	Maintain the current with ecosystem-friendly high-yield crop varieties and build eco-friendly sustainable cultivation systems
	15	Trade-off status	Nature of ecosystem response	Less of high trade-offs and more of low trade-offs	More of high trade-off status around the north	Reduced to low trade-off status
			Proposed ecosystem restoration measures	Enhance the current with the use of ecosystem-friendly high-yield crop varieties	Sustain the current system with the use of eco-friendly high-yield crops and cropping systems	Retain and preserve the current with ecosystem-friendly high yield crop varieties

while seasonal river flooding dominates the southern axis during the monsoon (wet) season. Therefore, the ongoing Great Green Wall (GGW) project must be intensified with specific community integration (Goffner et al. 2019). This is essential as it becomes a people-oriented forest restoration drive that will ensure the protection of both the ecosystem and the community. Other measures such as wetland protection systems, greenbelt zone delineation, and re-vitalisation of de-vegetated areas are significant for communities within such zones. Shrubland and grassland are estimated to diminish by ~ 20–30% under the current trend. Community-based measures such as controlled grazing and extensive silvopastoralism are essential. Flooding, along with water footprints and river banks within the study area, is possible in the future with deleterious impacts on anthropogenic activities. Flood prediction measures such as early warning system, riverbank protection measures, and inter-basin collaborations and well linkages with the Federal Ministry of Water Resources are essential. Although details of ecosystem response to climate change have been described earlier, ecosystem restoration measures such as building climate resiliency via the deployment of flood early warning system, drought assessment, urban flood risk assessment based on local knowledge of climatic dynamics remain essential.

The response of quantified ESs depicts some level of coordination to enhance or restore the nature of these natural benefits and preserve natural goods that stimulate the availability of the ecological services when needed. Crop production is inevitable; thus, the projected reduction in intensity from 6 to 15% requires a change in the prevailing systems. Cultivation clusters need to be expanded to gradually up-scale the preponderance of small-scale levels, and high-yield locally adaptable crop varieties should be introduced to expand the current arrangement. Seasonal water availability is expected to increase roughly up to 30% in some areas. Flood-related large-scale damage to lives and livelihoods can be avoided if measures such as sectoral management of the Sokoto Rima River Basin Development Authority (SRRBDA) are ensured. The current management approach of the SRRBDA should be revisited with respect to climate change imprints on the basin's prevailing water systems. Habitat quality is anticipated to further diminish by an average of 25% throughout the study area. The stated intensified GGW project measures, woodland expansion, protected area buffer and community-based woodlot construction and management are very vital. Nutrient flow in the study area is projected to improve slightly by 1.5% (Raji et al. 2020a). The impact of the low flow of hydrological systems within the Niger valley lowland will reduce this proportion to less than one. Thus, it is pertinent to improve agroforestry measures significantly within existing cropping clusters and improve current small-scale dominance. Evidence of eutrophication within areas of low flow using localised management systems is inimical to river ESs. Measures to address this phenomenon and ensure consistent freshwater supplies, particularly for agrarian communities, will be critical to the sustenance of life and livelihood in the areas concerned.

Ecosystem services interaction suggests that trade-offs provide opportunities for ecosystem resource planning. Therefore, synergy must be improved using ecosystem-friendly crop varieties alongside environmentally friendly cultivation systems by avoiding bush burning. In the same vein, agroforestry should be expanded within trade-off contexts to ensure sustainable ecosystem management, a vital component of sustainable development goals.

Discussion

Resource managers, particularly decision-makers saddled with the management and planning of land, require ES interactions to visualise different complementary and competitive interchanges that will shape the choice of the resource allocation, including decisions on the restoration of degraded areas. This study has demonstrated the possibility of combining various environmental components that drive ESs dynamics, their interactions for the present and the future. Thus, quantification of ESs is thus essential for spatial management of ecosystem resources and sustainable support for land-use decisions. In a landscape that is dominated by crop cultivation and increasingly expensing cropland, the pattern of landcover changes explains the direction of anthropogenic controls on the utility of provisioning and ESs on quantification of such relationships. Whereas agroforestry, a better synergy between cropland and woodland management, lost aggregate of 21.57 km^2, cropland had a 6-km^2 yearly expansion. Evidently, this competitive landcover nexus will aid the understanding of such relationships amongst ESs when quantified. The spatiotemporal dynamics of ESs suggests that strong trade-offs between SWY–EVI and NRR–EVI relationships dictate the pace for the ecological functioning of the Sokoto-Rima basin, and in the future, the relationship could change to SWY–NRR. This is a vital pointer to the influence of water, nutrient and quality of biodiversity for the semi-arid ecosystems. Yang et al. (2018) acknowledged that SWY drives the sustainability pattern of the Yanhe watershed in China irrespective of management scenario envisaged. Further, Fu et al. (2018) revealed that spatial heterogeneity of the Altay Prefecture in China is triggered multiple ES relations, which was influenced by the water yield factor. The similarity of these cases with the Sokoto-Rima basin suggests that a greater understanding of the quantified relationships between ESs needs to be explored. This exploration can take the form of additional ESs units with scenario development. Scenario development in this case should recognise local resource allocation discourses and issues. Such scenarios should consider existing landcover laws, regulations, policies and executive orders on land. When these are considered, the most appropriate choice should be weighed vis-à-vis the business-as-usual situation, and the result will be used to make the most environmentally sufficient decision for the area. These scenarios specifically should consider land management with interest in dynamics of landcover, the introduction of new regulations on land allocation, land transactions and decisions, and the impact of environmental dynamics in which climate change is vital. In this study, landcover change and climate change were considered based on-the-ground situation, thus creating the opportunity for multiple scenarios for further studies.

Watershed management of ESs should also be considered vital in shaping the stark spatial coordination absence of the dominant ESs of the Sokoto-Rima basin. A large basin that cut across national boundaries requires integrative governance systems so that upstream decisions will be synergised with downstream implications. The Sokoto-Rima basin is of West African importance with divergent management systems across its watershed countries yet similar cultural linkages. As shown in the nutrient flow study by Raji et al. (2020b), nutrient dispersal at the upstream locations leads to hydrological enrichments downstream with traces of eutrophication. To address such, resource managers need to engage spatial tools such as the InVEST suite to properly monitor spatial variations across watersheds regarding flow and dynamics of nutrients, water yield, carbon fluxes, crop production complexes and productivity. Unlike this study, it is crucial to determine ESs feedback loops between social and environmental factors. Feedback consideration will integrate human decisions with environmental realities and boost or inhibit the general ESs. Models that address such linkages can be adopted to determine the pathway and implications of such feedback on watershed management.

This study is connected to sustainability science as a plethora of sustainable development goals (SDGs) can be attained via optimal ESs delivery. For instance, Wood et al. (2018) claimed that 16 ESs associated with environmental and human well-being are strong enough to achieve United Nation SDG indicators and targets. Consequently, these can be integrated as part of further research such that ESs scenario assessment can track the attainment of SDGs within the Sokoto-Rima basin. When such are applied, and the supply of ESs is enhanced, care must be taken to ensure equity to avoid underprivileged groups' escalation. Therefore, particular attention must be paid to large trade-off situations that could threaten other ES interactions and stifle long-term sustainability intentions. These, when adopted, will drive the expected ecosystem restoration that is critical for the sustenance of the ecosystem.

Conclusion

This study has established that the Sokoto-Rima basin is dominated by provisioning ESs, especially crop production and water yield while regulating ESs such as habitat quality and nutrient retention have either declined or fluctuating. It has also shown that future climate points to progressive wetting, cooling, and warming spells that impact ESs. The entire study area is also highly vulnerable to ecosystem degradation as influenced by factors of climate change. The respective ES interactions have shown that the Sokoto-Rima basin is predominantly trade-off based with spatial differences that depict the north as trade-off-dominated compared to the south, which is more of synergy. These have helped to inform critical spatial ecosystem restoration decisions, which is particularly geographic.

The study has further shown that while cropland area has increased, in the study area, the intensity of the ES interactions within the provisioning and the regulating sphere has decreased progressively, as indicated by the weakening correlation coefficients. Although the Sokoto-Rima basin is trade-off-dominated, the dynamics of synergy will improve slightly in the future as influenced by climate change impacts. The influence of cropland over these manifestation has shown that the ratio of trade-offs to synergies will change in response to the influence of crop cultivation. Thus, landcover management policies that recognise the need to improve crop cultivation practices in line with woodland and protected area development to boost ecosystem management must be adopted. Adopting this will stimulate both the anthropogenic demands, natural supplies and balances for ESs within the semi-arid zone.

The import of concerted ecosystem management will drive the adoption of scenario-based environmental decisions such that policy decisions can be visualised to deliver the most suitable options for resource management. As shown in this study, more opportunities for anthropogenic effects could be integrated as part of a possible scenario building. The impact of ecological development programmes such as the proposed West African Great Green Wall (GGW), the woodlot development programme, and large-scale agricultural development complexes across the study area could be assessed. This will aid the organisation of prime ecological decisions, which could have an impelling impact on the ESs of the Sokoto-Rima basin.

Acknowledgements The authors do appreciate the kind permissions granted by the following organisations for data access: European Space Agency (ESA), Japanese Aerospace Exploration Agency (JAXA), Princeton Climate Analytics (PCA), United States Geological Survey (USGS) and the National Bureau of Statistics of Nigeria (NBS). We also salute the efforts of the three anonymous reviewers for their constructive comments.

Declarations

Conflict of interest No potential conflicts of interest are reported by the authors.

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