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Modeling coastal land use scenario impacts on ecosystem services restoration in Southwest Ghana, West Africa

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Urbanization significantly degrades coastal habitats in West Africa, necessitating habitat restoration. However, application of land use scenarios to investigate coastal habitat restoration outcomes in West Africa is still lacking in the scientific literature. We developed four land use scenarios for Southwest Ghana—Urbanization Scenario (UBS), Urban Greening Scenario (UGS), Plantation Agriculture Scenario (PLAS), and Landscape Restoration Scenario (LRS). The impacts of these scenarios on land use patterns and ecosystem services (ES), namely, food, fuelwood, carbon sequestration, and recreation benefit were assessed and visualized by integrating benefits transfer data and experts' knowledge in a spatially explicit modeling platform. UBS decreased all ES supplies, while LRS showed negative synergies between food and carbon sequestration, turning positive with increased restoration. LRS also led to mixed swamp forests' expansion, unchanged palm swamp forests, and declining mangrove swamps. The study recommends planning regulations to protect and restore swamp forests to safeguard these critical habitats from urbanization impacts.

Coastal ecosystems are integral components of landscapes and seascapes and provide the requisite biophysical and ecological conditions in which marine and terrestrial species thrive[1,2]. Across the land-sea continuum, multiple coastal ecosystems and their associated habitats interact to co-create ecological functions and enable interconnectivity between terrestrial, nearshore and marine ecosystems[3–5]. Ocean currents, nutrient transport, and feeding patterns of marine organisms across different habitats drive these habitat interactions[6]. Moreover, environmental gradients such as salinity, temperature, and elevation in coastal environments have effects on the spatial distribution of interconnected coastal and marine habitats. For instance, mangrove forests are limited in their range by coastal geomorphological features and estuarine tidal dynamics[7,8]. Similarly, variations in coastal microenvironments create the ecological conditions which enable some fish species to live their juvenile stages in nearshore areas and adult life in marine environments[2,9]. These interconnections underpin ecological functions and the supply of ES in coastal regions[10]. Maintaining the spatial connectivity and heterogeneity of coastal habitats and their functions is fundamental to conserving biodiversity[5].

However, coastal habitats are predisposed to urbanization threats as human population and activities are concentrated on the narrow zone between land and ocean interfaces along coastal areas[11]. Such threats are pronounced in estuarine environments where the interaction between migration flows, land use/land cover (LULC) changes, coastal erosion, and flooding reinforce habitat fragmentation and biodiversity loss[12]. Coastal urbanization is characterized by land use changes which convert natural areas into built infrastructure such as settlements, roads, wharfs and breakwaters[13]. Such land use pressures distort the spatial connectivity between coastal habitats and lead to the loss of ecosystem services (ES)[13].

At the international, national and local levels, ecosystem restoration has been proposed as a policy and pragmatic response to the degradation of natural resources[14,15]. The Kunming-Montreal Global Biodiversity Framework (GBF) acknowledges the need for Parties to the Convention on Biological Diversity (CBD) to undertake urgent actions to maintain and restore ecological connectivity in marine and coastal ecosystems. Consequently, restoration of 30% of degraded coastal and marine ecosystems by 2030 is recommended under the GBF's action-oriented Target 2[16]. Coastal and marine ecosystem restoration also advances climate action as enunciated by

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the Sustainable Development Goal 13. The UN Decade on Ecosystem Restoration acknowledges the centrality of actor-oriented land use planning to the attainment of global and local restoration goals and targets linked to the 2030 Agenda for Sustainable Development[17]. Land use planning focused on restoration is gradually developing towards the application of frameworks and tools for the participation of a broad range of stakeholders in restoration decision-making, including the determination of socio-economic objectives and benefits of restoration[18]. Goal-setting in landscape restoration becomes effective with the engagement of various land use actors as it allows to identify different interests, values, and preferences for sustainable landscape planning[19,20]. Hence, a socio-ecological perspective integrating both biophysical and social components and their spatial and temporal interactions is a prerequisite for effective coastal landscape planning and restoration[21]. Understanding the role of human agency, as a beneficiary of natural resources, in coastal habitat restoration planning paves the way for integrating ES supply into restoration goals[22]. Incorporating ES into restoration decisions increases the chances for successful outcomes by addressing human values and wellbeing dimensions[23–25]. Consideration of human values also reduces the risk of political and community backlash against restoration actions while promoting public support for restoration goals[23,26].

Participatory scenario development and assessment have increasingly proven to be valuable heuristic tools for engaging ecosystem restoration actors in goal-setting processes and the collective development of plausible ES provision futures in West Africa[27–29]. Integration of local knowledge into scenarios revealed that future urbanization and deforestation land use patterns will reduce ES provision in West African agricultural landscapes[27,30]. Furthermore, in Ghana's forest-plantation mosaic landscapes, preferences for segregated rather than integrated land use scenarios provoked trade-offs between multiple ES supply[28]. Effective scenarios can be those appropriate for performing three interrelated functions of modeling, planning, and making effective future-oriented decisions[31]. Different types of scenarios have been advanced in literature to create narratives and to characterize diverse coastal and marine socio-ecological contexts[32–34]. Exploratory scenarios are increasingly utilized by scientists to describe plausible future states of ES supply under different driving forces and environmental conditions[35–37]. Whereas exploratory scenarios investigate a range of plausible futures considering key drivers of change, normative scenarios on the other hand, define the vision of a preferred future and identify the goals and strategies required to achieve that vision[34,36,38].

Coastal areas in West Africa are characterized by heavy reliance of the population on natural resources for their livelihoods, hence, the conditions of the region's coastal habitats are interlinked with ES supply and human wellbeing[39]. Driven by the accelerating pace of urbanization in coastal West Africa, rapid land use changes poses threats to the sustainability of coastal ecosystems in the region[40,41]. Restoration of the region's critical biodiversity habitats such as mangroves, peatlands, lagoons, estuaries, rocky reefs, and benthic ecosystems can mitigate marine biodiversity loss and recover such ecosystems and the functions and services they provide. Particularly, in the coastal landscapes of Southwest Ghana, different restoration initiatives are underway and aim to advance the protection of pristine coastal habitats and restore degraded ecosystems to enhance ES supply[29,42]. However, research on land use scenario planning in West Africa has focused attention on ES provision potentials due to land use changes in agricultural and production landscapes[28,30,43]. Similar studies conducted in Southwest Ghana confined land use scenario impact assessment to ES provision in perennial tree crop-dominated landscapes[44,45]. Other studies analyzed scenarios in the context of cultural ES supply and of site evaluation to assess suitability for establishing nearshore marine protected areas[29,46]. There has been less attempt at scenario applications in landscape restoration planning and for evaluating trade-offs in restoration outcomes[47]. Furthermore, few studies have applied participatory scenarios in the coastal and marine contexts to understand spatial changes in habitats and ES supply dynamics[48]. This study addresses the foregoing knowledge gap by integrating remote sensing, benefits transfer and participatory land use scenario modeling to deepen understanding of future urbanization and coastal landscape restoration outcomes on ES recovery in Southwest Ghana.

The spatial dynamics of habitats and land use patterns according to urbanization and landscape restoration outcomes can be analyzed using remote sensing data[49,50]. Benefits transfer is a proxy-based technique for ES assessment, utilized especially in data scarce contexts for extrapolating biophysical values from one site to another[51–53]. Application of the foregoing analytical techniques in a spatially explicit scenario modeling approach is useful to identify risks and opportunities associated with the articulation of land use actors' visions and values for landscape restoration. Furthermore, understanding and generation of such information and knowledge is necessary to inform multi-habitat restoration and strategic planning to mitigate risks posed by urbanization to the functionality of coastal habitats. We hypothesize that scenarios in favor of landscape restoration will lead to an increase in multiple ES supply and the spatial extent of habitats in coastal areas undergoing urbanization. This study aims to address the following research questions in the context of Southwest Ghana; (i) how will local experts' perspectives on land use transitions influence future land use decisions in coastal landscapes undergoing urbanization? (ii) what are the impacts of future land use scenarios on the spatial extent of critical coastal habitats and supply of ES in Southwest Ghana? (iii) what potential trade-offs and synergies could result between multiple ES due to future land use scenarios in Southwest Ghana? Given the influence of urbanization and land use transitions on coastal habitat transformation, restoration planning, and practice underpinned by scenario development offer prospects for successful restoration of critical coastal habitats such as mangroves, palm swamps, mixed swamps, and their interconnected estuaries and lagoons in Southwest Ghana. Specifically, this research illustrates the utility of participatory land use scenario modeling and spatially explicit simulation techniques in planning and restoring multiple coastal habitats and related ES in the context of rapid coastal urbanization.

Methods

Description of study area

The study was conducted in the coastal zone of Southwest Ghana, specifically, the Greater *Amanzule* wetlands landscape. Covering ~60,000 hectares, the area lies between the Ankobra river estuary and the Tano river basin on Ghana's Southwest border with Cote d'Ivoire[54] (Fig. 1). The rainfall pattern is characterized by a peak season occurring between May to June and a minor season, spanning October to November of each year. Mean annual precipitation and relative humidity are 1600 mm and 87.5% respectively[55]. The study area is known for its rich and diverse but critical marine and coastal habitats and biodiversity. These critical habitats comprise lagoon-wetland systems, mangroves, estuaries, sandy, and rocky beaches, located in the only coastal area in Ghana, which hosts intact peat swamp forests[1,54].

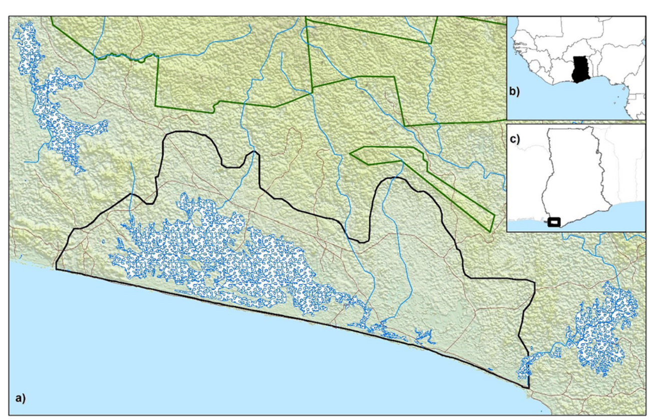


Fig. 1 | Location of study area in the context of Africa and Southwest Ghana. The maps show **a** boundary (black) of the study area and associated coastal habitats, **b** location of Ghana (black) within Africa, and **c** location of the study area (black) within Ghana.

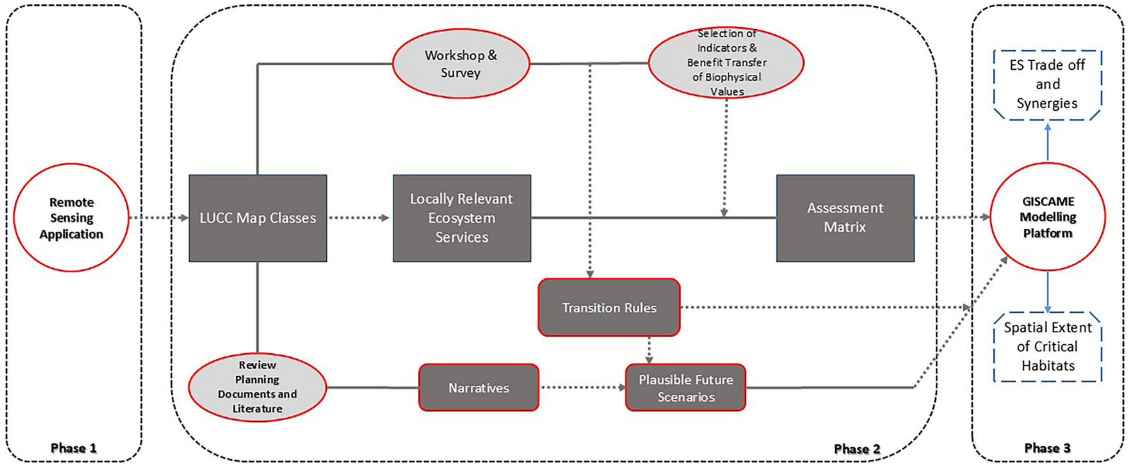


Fig. 2 | Methodological framework for modeling the impacts of coastal land use scenarios on ecosystem. services (ES) supply in Southwest Ghana. The figure illustrates the three phases of the research with the circles denoting the methodology employed during each phase, shaded rectangles and squares denoting outputs derived from application of respective methods and dashed squares denoting the final research outcomes.

These habitats are vulnerable to the mounting threats of population growth, urbanization, industrialization, and climate change[1]. The study area spans three administrative boundaries in Southwest Ghana – Nzema East, Ellembelle, and Jomoro districts.

Socio-economic activities in the study region revolve around fishing and farming. The fishing industry has witnessed a steep decline over the past decades, due primarily to overfishing[56]. Recent land demand in the region is significantly shaped by urbanization, which is a consequence of LULC changes linked to the region's growing oil and gas industry, large scale plantation agriculture development, and population growth[57–59]. Traditional arable land uses are being displaced in favor of mining and in some instances, illegal mining operations[60,61]. Food crop (including cassava, plantain, and cocoyam) farming is undertaken at the subsistence level. Other land use options such as rubber and oil palm plantation development are commercial ventures dominated by land owners and the agro-based private sector[58]. There is high demand for mangrove wood as it is culturally preferred to other wood sources for fish smoking in traditional ovens.

Methodological framework

The study methodology was implemented in three phases, resulting in key research outputs and outcomes (Fig. 2). The first phase involved LULC classification and delineation of critical coastal habitats and interlinked terrestrial LULC types. In the second phase, workshops and questionnaire survey were implemented with selected land management experts. The workshop sessions were framed around the land use situation revealed in the LULC maps, information contained in the relevant municipal and regional spatial plans, and the identification of relevant ES in the study region. Through the workshop and questionnaire survey, locally relevant ES were identified and land use transition rule-sets for simulating plausible future scenarios were co-created with land management experts. The second phase also involved the selection of indicators and extrapolation of biophysical values from existing studies for compilation into an ES assessment matrix. In the final phase, the land use scenarios were simulated, and their impacts on habitat spatial extent and ES supply were evaluated using the GISCAME simulation platform.

Remote sensing

The land cover classification was conducted using the Google Earth Engine (GEE) platform. GEE provides access to free, georeferenced, and atmospherically corrected real-time remote sensing data, comprising a comprehensive catalog spanning over four decades[62]. The classification utilized a blend of optical and radar satellite sensors to address the persistent challenge of cloud cover interference commonly encountered with optical sensors. Sentinel-1 Synthetic Aperture Radar (SAR), Ground Range Detected product, with dual polarization and Landsat 8 OLI (Operational Land Imager) Collection-1 Tier-1 Top-of-Atmosphere Reflectance product, acquired in May 2015 and April 2020 served as the primary datasets. As a further preprocessing step of the SAR dual-polarized data, a speckle filter was applied to denoise the image. Speckle filtering enhances visual quality and improves qualitative parameters like Peak Signal-to-Noise Ratio[63]. Subsequently, Gray Level Co-occurrence Matrix parameters were computed to capture textural information available in the data. Various vegetation indices from Landsat 8 were derived to characterize vegetation properties and later integrated with the SAR bands. In addition, ancillary data, including slope, aspect, hill shade and elevation were derived from the Shuttle Radar Topography Mission data. The three categories of data were merged into a composite image. Training samples were collected over the composite image, representing each land cover class (Fig. 3 and Supplementary Table 5). The samples were grouped into one feature class, and a Random Forest classifier using 100 trees and 2 variables per split was trained with 70% of the samples as the training dataset. To enhance the model's performance, hyperparameter tuning was performed. The parameters evaluated included the number of trees and the number of variables per split. The number of trees refers to the individual decision trees used in the model, with each tree contributing to the final classification. The number of variables per split indicates the number of features considered when splitting a node in each tree; this approach helps to increase the diversity of the trees and improve the model's robustness. For the number of trees, a sequence was established, starting from 50 and increasing to a maximum of 300, with intervals of 50. Although the initial limit was set at 1000 trees, it was ultimately reduced to 300 due to computational limitations in GEE. A similar technique was applied for the number of variables per split, which ranged from 2 to 10. Each combination of parameters was evaluated based on the overall accuracy derived from the classification error matrix on the test dataset. The configuration that yielded the highest accuracy involved 100 trees and 2 variables per split, justifying their use in the final model training (Supplementary Table 6). The classifier was then applied to the entire composite image, and the resulting classified image was evaluated using a 30% validation set to compute accuracy metrics (Supplementary Table 7). The area covered by each land cover class was calculated within the region of interest. As a result, twelve LULC types were derived, following a previous study which utilized multi-source data features for peatland classification in the region[54] (Fig. 3 and Supplementary Table 5). Current land use in the remaining sections of the paper refers to 2020 LULC map illustrated by Fig. 3 below.

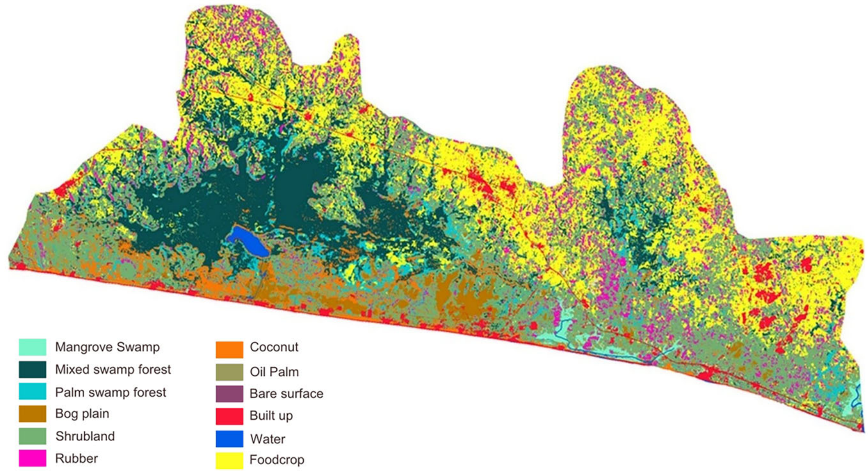


Fig. 3 | 2020 Land use/cover classes in the study area.

Table 1 | Data generation methods for locally relevant ES and their proxy indicators

Relevant Ecosystem Services	Proxy indicators	Data Generation
Provisioning		
Food	Yield in Tonnes/ha	Benefits transfer, remote sensing
Fuel wood	Biomass in Kg/ha	Benefits transfer, remote sensing
Regulating		
Carbon sequestration	Above-ground carbon in MgC/ha	Benefits transfer, remote sensing
Cultural		
Recreation benefits	Benefits derived from recreational activities in open and green spaces	Questionnaire survey, workshop

Selection of ES and indicators

Coastal and interconnected marine ecosystems supply an array of ES for the wellbeing of the dependent coastal population in Ghana[64]. Based on the results of prior studies on ES supply in the study region, locally relevant ES were identified and selected for impact assessment of land use scenarios on ES restoration[29,42]. Cultural ES are generally created through human perception of ecosystems and the biophysical environment[65]. In this study, we utilized land management experts' judgements to obtain estimates of recreation benefits based on a ranking criterion. Recreation benefits were selected as the coastal landscape and adjoining seascape have unique tourist attractions including scenic beaches (bare surfaces), water bodies, pristine mangrove forests, and green spaces (shrublands) that offer recreation opportunities[29]. Among potentially relevant provisioning and regulating ES in the study context, a specific set of ES were determined according to data availability. As provisioning ES, we selected food and fuel wood supply. In addition to staple food supply by cropland, oil palm and coconut plantations are sources of vegetable oils in the region while mangroves, swamp forests, and waterbodies such as estuaries and lagoons are critical to meet the local population's fish food needs. Mangroves, shrublands and rubber plantations are also important sources of fuelwood supply to the local population. For regulating ES, carbon sequestration was determined. This ES is supplied by all vegetation types in the study region, albeit at different magnitudes (Table 1).

Considering data availability, indicators that quantitatively depict ES supply were derived in relation to the characteristics of the LULC types (Fig. 3 and Supplementary Table 5). Specifically, food and fuelwood supply were respectively measured in Tonnes/ha and Kg/ha while carbon sequestration was quantified in MgC/ha[42,66]. Finally, all the ES indicator values derived through benefits transfer, remote sensing, and experts' consultation were standardized to a relative scale (0–100 value points)[67]. Standardization of the different indicator values was necessary to allow subsequent comparison of ES supply potentials across the different LULC classes with the same unit value[67].

Selection of land management experts

Experts in this study were defined as knowledge holders about land use system dynamics of the study region by virtue of their training, research, skills, and practical experience[68]. We selected land management experts across academic institutions, government agencies, private sector, non-governmental organizations, and heads of land-owning clans in the study region. Through this representation, we elicited knowledge held at the local scale by land owners with non-professional interests as well as insights from professional knowledge holders at the regional scale[69]. The experts were identified through snowball sampling, in which those selected experts identified other potential experts[70]. This sampling technique was suitable for this study as it allowed identification and recruitment of experts based on their availability, influence on regional land management decisions, and long-standing experience in land system research and practice in the study region. In total, twenty-four land management experts comprising 4 coastal ecologists, 10 land use and development planners, 4 environmentalists, 2 rubber and oil palm plantation managers, and 4 land owners were identified and recruited for the scenario co-creation workshops and questionnaire survey.

Future scenarios development workshop and questionnaire survey

A workshop with land management experts was utilized to facilitate development of land use scenarios. As preparation for the workshop, relevant regional land use planning and policy documents were screened (see Supplementary Table 4). Literature on the drivers of land use changes and their influences on coastal ecosystems within the study region were also reviewed to enable contextual understanding of the LULC classification.

Table 2 | Narratives of coastal land use scenarios for Southwest Ghana

Scenario	Description
Urbanization Scenario (UBS)	The urbanization scenario is characterized by unfettered settlement expansion and encroachment of built-up infrastructure on natural areas[91]. Drivers of these land use changes are population growth and implementation of transportation infrastructure development plans, notably for road network expansion and establishing railway line connections between Ghana and neighboring Cote D'Ivoire along the coastal corridor[83]. Built-up infrastructure expansion is also related to coastal tourism development to enhance recreation experience in tourist destinations along the coast[29].
Plantation Agriculture Scenario (PLAS)	The plantation agriculture scenario represents future land use trends dominated by rubber and oil palm plantations[92]. Forests, shrublands, and food crop areas are substituted for plantations as landowners and farmers realize higher returns from rubber and oil palm cultivation[44,93]. Plantation agriculture also expands in response to the increasing global demand for agricultural commodities such as natural rubber latex and palm oil[94,95].
Landscape Restoration Scenario (LRS)	The landscape restoration scenario prioritizes strict protection of swamp forests using planning and zoning regulations, community-based conservation norms, and active restoration of degraded mangrove ecosystems and shrublands to create habitats for biodiversity[96]. Abandoned illegal gold mining sites are reforested[97].
Urban Greening Scenario (UGS)	The UGS targets future coastal land uses characterized by developed urban core zones and sprawl along the urban peripheries[59,91]. Within this urban development context, green spaces are introduced into the built-up areas such as along road medians, around compounds of homes, schools and within recreational parks, in line with the government's reforestation program[98].

UBS urbanization scenario, *PLAS* plantation agriculture scenario, *LRS* landscape restoration scenario, *UGS* urban greening scenario.

This literature served as the basis for spatially explicit simulation of four land use scenarios, namely, Urbanization Scenario (UBS), Plantation Agriculture Scenario (PLAS), Landscape Restoration Scenario (LRS), and Urban Greening Scenario (UGS) using the GISCAME software. It also informed the development of scenario narratives (Table 2), which framed and contextualized the workshop discourses together with the baseline simulation results.

At the commencement of the workshop, the LULC information in the region was presented alongside spatially explicit representations of the land use scenarios. As ES is an unfamiliar concept to the experts, an overview of the potential ES supplied by the LULC types was also presented[29]. Subsequently, the experts were randomly assigned to one of three groups (comprising 8 experts per group) and asked to discuss the following questions: (1) which land use transitions, for instance, conversion from mangrove to built-up areas, neighborhood, and environmental conditions align with urbanization, plantation agriculture, landscape restoration and UGSs in the region? (2) what are the timescales for the identified land use transitions to express in the region? Outputs of the workshop were plausible land use transition rule-sets which align with the land use scenarios (Supplementary Table 2).

A post-workshop questionnaire survey was implemented with the same group of experts. The questionnaires were composed of two parts. The first part focused on the potential supply of cultural ES by the respective LULC types. Related to this aspect, the experts were firstly, invited to rank from a pre-identified list, the top three cultural ES supplied by the landscape. Secondly, an evaluation was performed on the prioritized cultural ES according to the following criteria: (a) on a scale of 1(very low) to 5 (very high), and (b) the relative potential of the twelve LULC types to supply cultural ES. The second part of the questionnaire elicited information on the transition probabilities of the LULC transitions identified at the workshop stage. Concerning this aspect, the experts were invited to rank the probability of occurrence of each LULC transition on a scale between 0 and 100%, given certain neighborhood effects and environmental conditions[30,67].

Spatially explicit simulation and impact assessment

In order to simulate future land use patterns, transition rule-sets determined by the experts for each of the scenarios were iteratively applied on the current land use map using the cellular automata (CA) module in GISCAME. CA comprises an array of cells which can change their state simultaneously at any given time as a function of their own state and the states of cells in their neighborhood[28]. An iteration in a CA model is dimensionless, however, a timescale can be assigned to an iteration in GISCAME based on the expected period of land use changes[30]. Following the questionnaire survey, realistic land use changes were determined by the experts to occur within 10-year cycles. CA simultaneously reassigns land use types to all raster cells in a land use map according to the defined transition rule-sets, thereby creating new land use patterns affected by future scenarios[30,71,72]. Using the 10-year period as the basis for regional land use transitions, one application of the transition probabilities simulated a change in 10 years, thus a five-time iterative application of the transition rule-sets represented impacts of land use changes on land use patterns for a period of 50 years. Environmental attributes of a landscape influence a region's potential to supply ES, as well as perform as a control factor for individual conversions[73]. In this study, environmental attributes and neighboring land use types were defined for each of the land use scenarios and reflected in the simulations of future land use patterns. For instance, elevation and tidal influences were considered to influence the ranges of mangrove swamps, mixed swamp forests, and palm swamp forests. Relatively high elevations on coastal landscapes inhibit mangrove propagule dispersal and impede mangrove forest growth[74]. Consequently, elevations above and below 14 meters were defined as environmental attributes and iteratively applied to the scenario simulation related to the conversion of mangrove swamp. Similarly, the neighboring cells were defined in order to reflect the proximity effect to the initial land use type as a driver of the land use changes. For instance, based on experts' opinions, under a LRS, water body (brackish water) can be converted to mangrove swamp with 75% probability if the water body has mangroves as a neighboring land use type, whereas the probability of mangroves conversion to built-up areas is 80% under UBS if the mangroves are located adjacent to built-up areas.

The simulated land use patterns were coupled with the ES assessment matrix (Table 3) in GISCAME to display potential ES supply by the study region. The potential of the study region to provide ES was calculated as mean values for the ES supplied by each land use cell. Consequently, the final assessment score reflected the mean potential ES supply of the study region influenced by each of the scenarios. The assessed ES values for land use scenarios were presented in spider charts, provisioning maps, and ES balance tables. The influence of land use scenarios on the spatial extent of critical coastal habitats were interpreted as the percentage change in habitat extent based on original and simulated land use patterns. Similarly, the scenarios' influence on ES supply were derived as the difference between ES values based on original and simulated land use patterns. Increase of a certain ES and concurrent decrease of another represented trade-offs in ES while positive and negative synergies typified simultaneous increase or decline of multiple ES respectively[30].

Table 3 | Final assessment matrix showing normalized values for land use types and their potential to supply ecosystem services from 0 (lowest) to 100 (highest)

LULC	Ecosystem Services			
	Food	Fuelwood	Carbon Sequestration	Recreation
Mangrove swamp	100	100	48	100
Mixed swamp forest	33	50	47	27
Palm swamp forest	33	5	50	21
Bog plain	10	1	50	41
Shrubland	5	22	7	95
Rubber	0	8	52	6
Coconut	5	29	28	27
Oil Palm	4	37	28	17
Bare surface	0	0	0	0
Built up	0	0	5	81
Water	9	0	5	87
Food crop	100	11	100	6

Results

Impacts of coastal land use scenarios on future land use patterns and ES supply

The current LULC map represented the present land use pattern/baseline situation and the transition rule-sets (Supplementary Table 2) defined the land use transitions on which basis UBS, UGS, PLAS, and LRS were simulated. Integration of the simulated land use patterns with the ES assessment matrix (Table 3) displayed the potential ES supply of the region, influenced by the scenarios. Simulation results of the impacts of UBS, UGS, PLAS, and LRS were presented as future land use patterns and ES supply in the region (Figs. 4, 5, 6, 7).

The impacts of UBS on future land use patterns and ES supply are presented by comparing with the current land use pattern (Fig. 4). Under urbanization influence, built-up area showed prominent expansion towards the southern edges and mid-east portions of the landscape compared to the current land use pattern. The expansion of built-up area mostly displaced mangroves, palm swamp forests, bog plains, and food crop areas which were neighboring land uses along the same area of the coastal landscape. However, food crop areas located towards the northern edges of the landscape were moderately influenced by intensifying urbanization within a 50-year timescale. Similarly, mixed swamp forests and water bodies located on the mid-west portions of the landscape remained relatively intact and less influenced by urbanization land use patterns.

Considering UBS at decadal timescale, the results revealed decreased potential of the region to supply food, fuelwood, carbon sequestration and recreation benefits compared to the current land use pattern. Except for carbon sequestration which remained constant, the region's potential to supply food, fuelwood and recreation benefits further declined due to intensifying urbanization (Fig. 4).

The simulation results of UGS compared to the current land use pattern are shown in Fig. 5. Both 10-year and 50-year timescales of urban greening showed expanded built-up areas on the southern edges of the landscape. Furthermore, under the influence of UGS, bog plains in the current land use pattern transitioned to shrublands within the vicinity of built-up spaces. In contrast to urbanization, UGS resulted in slight expansion of mixed swamp forests. Except recreation benefits which remained relatively stable between the current land use and 10-year urban greening timescale, the overall ES balance of the region was negatively influenced by UGS as shown in the spider chart (Fig. 5).

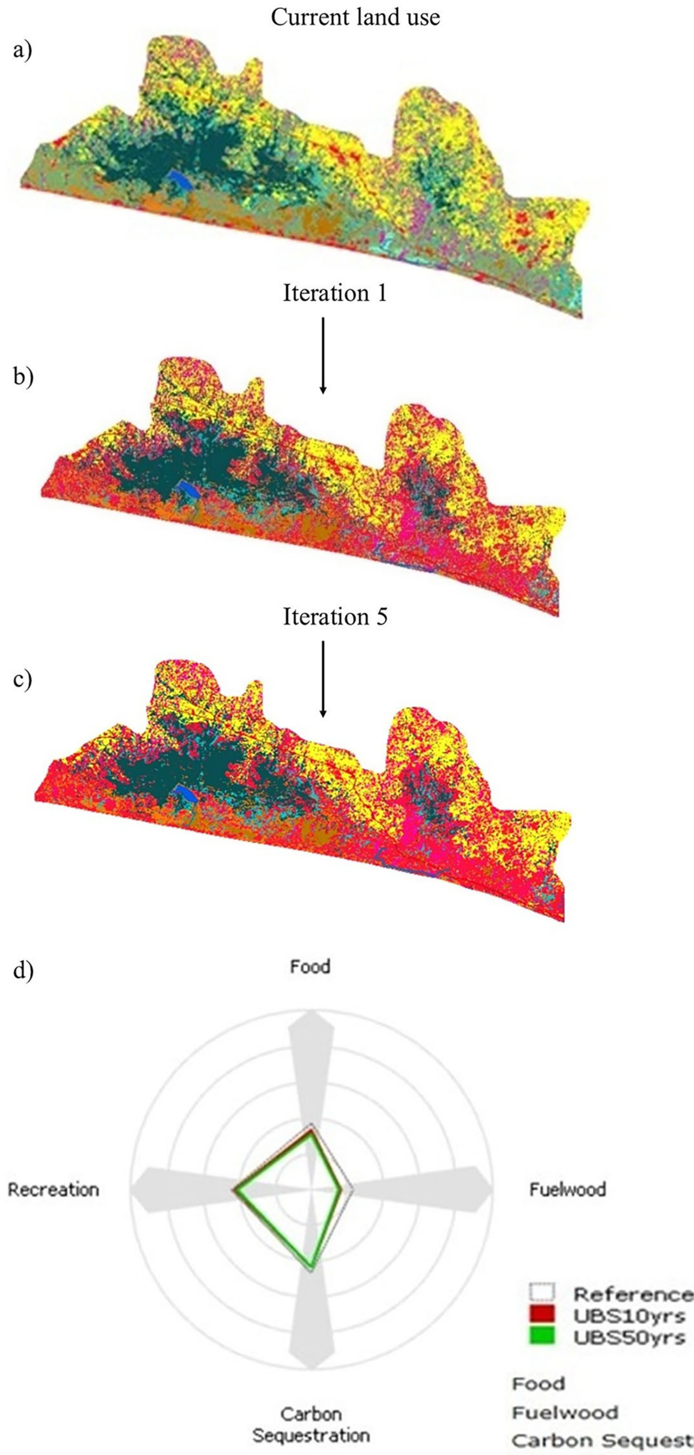
As shown in Fig. 6, the simulation results of PLAS in comparison to the current land use pattern revealed key trends in rubber plantation expansion over the landscape. Bog plains, oil palm, and coconut located along the southern boundary of the landscape transitioned to rubber under the influence of PLAS over 10-year timescale. With the intensification of plantation agriculture over a 50-year timescale, rubber became prominent and dominated land uses along the fringes of mixed swamp forests. The resultant impacts of PLAS on the region's potential to supply ES showed mixed results as depicted in the spider chart. Whereas the region's potential to supply food remained constant between the current land use and PLAS over 10-year timescale, food supply potential decreased with intensification of PLAS over 50-year timescale. Fuelwood supply potential initially increased over 10-year PLAS but later decreased with intensification of PLAS over 50-year timescale. On the other hand, carbon sequestration potential increased progressively from the current land use to PLAS over 10-year and 50-year timescales. On the contrary, the overall influence of PLAS on recreation benefits was negative as depicted by decreasing values in the balance tables.

In Fig. 7, the simulated results of the impacts of LRS on future land use patterns and ES supply are shown by comparing with the current land use. Mixed swamp forest expanded in the mid-west portions of the landscape under the influence of landscape restoration over a 10-year timescale. Intensification of restoration over a 50-year timescale was accompanied by greater expansion of mixed swamp forest on the mid-west and east portions of the landscape. Similarly, rubber showed progressive expansion, particularly along the fringes of mixed swamp forest considering landscape restoration over a 10-year and 50-year timescales. As shown by decreasing values in the ES balance tables, the overall influence of landscape restoration on the region's potential to supply food and recreation benefits was negative. Conversely, the region's potential to sequester carbon and supply fuelwood increased under the influence of landscape restoration compared to the current land use.

Impacts of coastal land use scenarios on the spatial extent of critical habitats and arable land uses across temporal scales

Differences in the impacts of the scenarios on the spatial extent of critical coastal habitats (mangrove swamp, mixed swamp forest, palm swamp forest, bog plain, and water) and interconnected terrestrial habitat (shrublands) were revealed by comparing scenarios across 10-year and 50-year timescales (Table 4 and Table 5). Regarding 10-year timescale, mangrove swamp decreased slightly in spatial extent and by the same magnitude under the influences of UBS and UGS (−0.9%). Similarly, mangroves decreased in spatial extent under LRS (−0.5%) but remained unchanged under PLAS influence. Furthermore, considering 50-year timescale, mangroves exhibited further decline in spatial extent under UBS (−1.5%) and LRS (−0.8%) respectively, as shown in Table 5. Conversely, mixed swamp forests increased in spatial extent under UGS (0.8%) and LRS (2.6%) and remained stable under UBS and PLAS influences, considering 10-year timescale. In addition, mixed swamp forests recorded 4.3% and 8.3% increase in spatial extent respectively, under the influences of UGS and LRS, considering 50-year timescale, which represent triple and five-fold increase in the spatial extent of mixed swamp forests. Palm swamp forests remained stable under the influences of all the scenarios and their temporal scales. Bog plain declined under the influences of all the scenarios and their temporal scales, except UBS which exhibited zero influence on bog plain. The influence of all the scenarios on water in the region was not significant as its spatial extent remained stable across the respective temporal scales and scenarios.

As shown in Table 4 and Table 5, UBS and UGS significantly and inversely influenced changes in the spatial extent of shrubland and built-up areas. Considering 10-year timescale, shrubland declined in spatial extent under UBS (−24.9%) and UGS (−23.3%), whereas built-up areas simultaneously increased by 28.2% and 30.5% under the respective scenarios. Shrubland further declined in spatial extent under the influences of UBS (−29.3%) and UGS (−26.6%) with concomitant increase in built-up areas



	Reference	UBS10yrs	UBS50yrs
Food	37	33	31
Fuelwood	23	16	15
Carbon Sequestration	46	43	43
Recreation	44	42	41

Fig. 4 | Impacts of UBS on land use patterns and ES supply in Southwest Ghana. Maps show changes in the status of current land use (**a**) compared to urbanization over a 10-year timescale in iteration 1(**b**), and a 50-year timescale in iteration 5 (**c**). The spider chart and balance table (**d**) depict how the current supply of ES (dotted line) can be influenced by urbanization, considering 10-year (red line) and 50-year (green line) timescales.

by 33.6% and 33.3% under the respective scenarios considering 50-year timescale.

Regarding arable land uses, rubber increased under the influence of PLAS (2.6%) and LRS (1.6%), considering 10-year timescale but recorded 11% and 2% respectively under the influence of same scenarios considering 50-year timescale. However, the influences of UBS and UGS on rubber plantation were neutral across all temporal scales. While the influence of PLAS on the spatial extent of food crop remained zero across temporal scales, food crop decreased between 2.3% and 2.6% in spatial extent across UBS, UGS, and LRS considering all temporal scales.

Trade-offs and synergies between potential ES supply

Trade-offs and synergies were evident in the potential supply of ES by the region considering the scenarios and their respective timescales (Table 6). UBS resulted in negative synergies between the potential supply of food, fuelwood, carbon sequestration, and recreation benefits. Similarly, UGS created negative synergies between the potential supply of food, fuelwood, carbon sequestration, and recreation benefits. Synergies and trade-offs associated with PLAS were slightly more nuanced at different temporal scales. PLAS within a 10-year timescale created positive synergies between fuelwood supply and carbon sequestration. Trade-offs resulted between

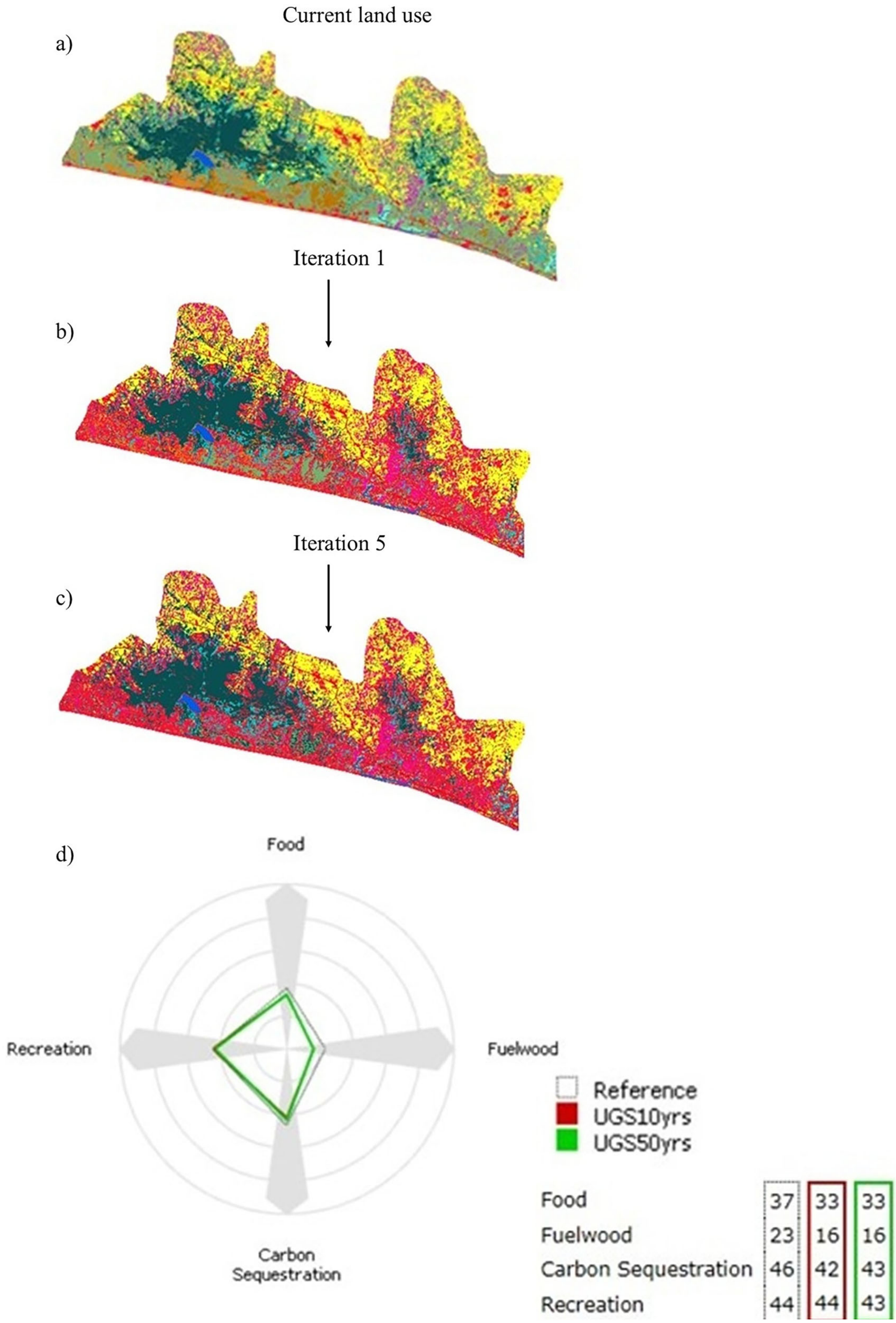


Fig. 5 | Impacts of UGS on land use patterns and ES supply in Southwest Ghana. Maps show changes in the status of current land use (**a**) compared to urban greening over a 10-year timescale in iteration 1(**b**), and a 50-year timescale in iteration 5(**c**) timescales. The spider chart and balance table (**d**) depict how the current supply of ES (dotted line) can be influenced by urban greening, considering 10-year (red line) and 50-year (green line) timescales.

the potential supply of fuelwood, carbon sequestration, and recreation benefits for the same scenario. However, intensifying PLAS within a 50-year timescale resulted in negative synergies between potential supply of food, fuelwood, and recreation benefits and trade-offs between such ES and carbon sequestration. LRS created negative synergies between potential food supply and carbon sequestration considering a 10-year timescale. Furthermore, intensification of LRS at 50-year timescale resulted in negative synergies between food supply and recreation benefits

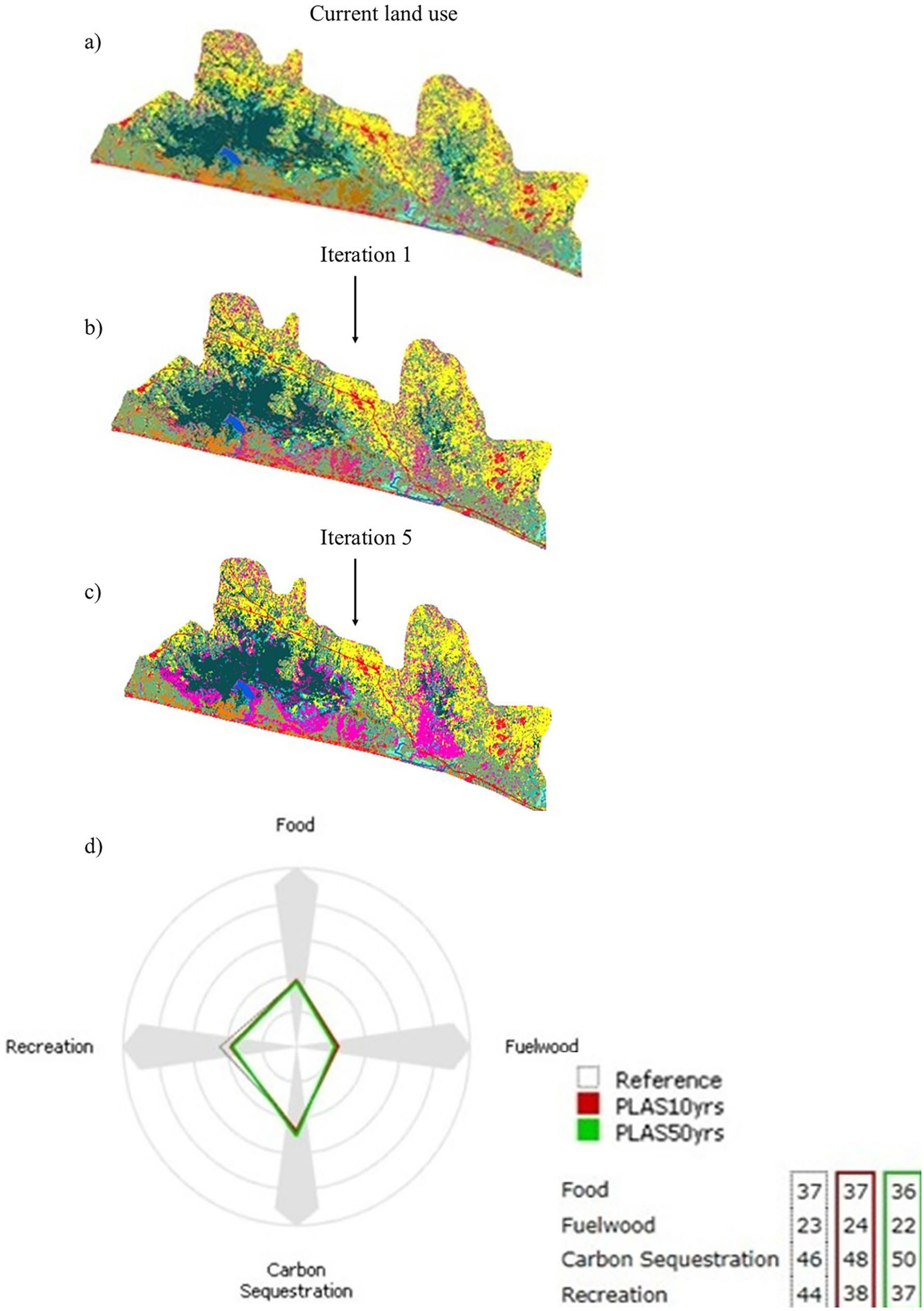


Fig. 6 | Impacts of PLAS on land use patterns and ES supply in Southwest Ghana. Maps show changes in the status of current land use (**a**) compared to plantation agriculture over a 10-year timescale in iteration 1(**b**) and a 50-year timescale in iteration 5(**c**). The spider chart and balance table (**d**) depict how the current supply of ES (dotted line) can be influenced by plantation agriculture, considering 10-year (red line) and 50-year (green line) timescales.

and positive synergies between fuel wood supply and carbon sequestration. Furthermore, LRS was associated with trade-offs between potential fuel wood supply and carbon sequestration and potential food supply and recreation benefits.

Discussion

Studies have utilized expert knowledge to develop participatory land use scenarios and to shape the scenario outcomes based on shared preferences and visions for the future[75,76]. This is because experts are key knowledge

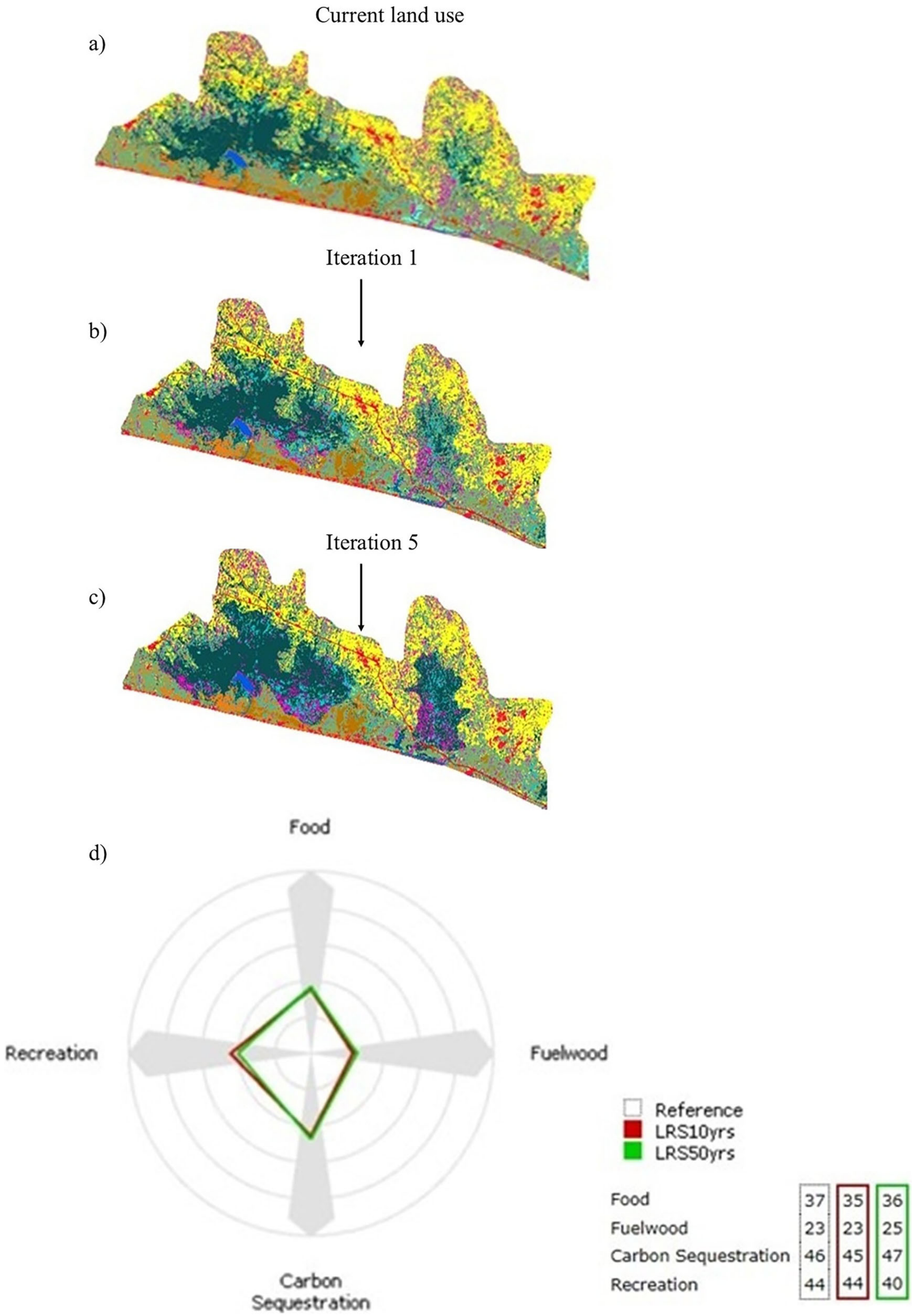


Fig. 7 | Impacts of LRS on land use patterns and ES supply in Southwest Ghana. Maps show changes in the status of current land use (**a**) compared to restoration over a 10-year timescale in iteration 1(**b**), and a 50-year timescale in iteration 5 (**c**). The spider chart and balance table (**d**) depict how the current supply of ES (dotted line) can be influenced by restoration, considering 10-year (red line) and 50-year (green line) timescales.

holders in land use decision making processes, hence their knowledge are valuable in land use planning research to address uncertainties and fill data gaps[68,69]. In this study, we elicited experts' knowledge and perspectives on the drivers of land use changes in coastal environments to complement existing data and develop exploratory scenarios on future sustainable land use pathways. Such knowledge and perspectives underpinned narratives of LULC conversions and their associated transition probabilities in the study region and also influenced the scenario outcomes. For instance, the

Table 4 | Areal change (%) of LULC types under UBS, UGS, PLAS, and LRS over 10-year timescale

LULC Types	Scenarios			
	Change (%) in spatial extent of LULC types			
	UBS	UGS	PLAS	LRS
Mangrove swamp	−0.93	−0.93	0	−0.54
Mixed swamp forest	0	0.82	0	2.6
Palm swamp forest	0	0	0	0
Bog plain	0	−2.44	−1.67	−0.15
Shrub land	−24.9	−23.28	−5.97	0.53
Rubber	0	0	2.58	1.55
Coconut	0	−2.22	−0.68	−1.49
Oil palm	0	0	5.73	−0.05
Bare surface	−0.09	−0.1	0	0
Built-up	28.24	30.46	0	0
Water	0	0	0	−0.06
Food crop	−2.33	−2.33	0	−2.36

The temporal scale signifies the period required for land use transitions to manifest in reality. The values indicate the difference (%) in the areal coverage of LULC types compared to the areal coverage of same LULC types in the current land use map (Fig. 3).

Table 5 | Areal change (%) of LULC types under UBS, UGS, PLAS and LRS over 50-year timescale

LULC Types	Scenarios			
	Change (%) in spatial extent of LULC types			
	UBS	UGS	PLAS	LRS
Mangrove swamp	−1.54	−0.93	0	−0.76
Mixed swamp forest	0	4.31	0	8.32
Palm swamp forest	0	0	0	0
Bog plain	0	−2.6	−2.58	−0.3
Shrub land	−29.29	−26.61	−6.08	−4.59
Rubber	0	0	10.52	2.01
Coconut	0	−5.03	−1.85	−1.92
Oil palm	0	0	0	−0.08
Bare surface	−0.1	−0.1	0	0
Built-up	33.55	33.27	0	0
Water	0	0	0	−0.06
Food crop	−2.62	−2.33	0	−2.61

The temporal scale signifies the period required for land use transitions to manifest in reality. The values indicate the difference (%) in the areal coverage of LULC types compared to the areal coverage of same LULC types in the current land use map (Fig. 3).

transition rule-sets suggest that mangroves rather than mixed swamp forests and water bodies can be converted to built-up land uses under the UBS (Supplementary Table 2). The spatially explicit representation of UBS revealed that mixed swamp forests and water bodies remained resilient against urbanization pressures, consistently maintaining their spatial extents into the future (Fig. 5). This can be explained by the local knowledge of permanent inundated site conditions of mixed swamp forests and water bodies which hamper their conversions to built-up land uses in the study region. Similar studies using participatory approaches also found that understanding of local environmental and biophysical constraints informed the outcomes of future land use scenarios[77,78]. Furthermore, the results

Table 6 | Trade-offs and synergies between potential ES supply values in the study region considering 10 and 50-year timescales

Coastal land use scenario	Ecosystem Services							
	Food		Fuel wood		Carbon sequestration		Recreation	
	10-year	50-year	10-year	50-year	10-year	50-year	10-year	50-year
UBS	−4	−6	−7	−8	−3	−3	−2	−3
UGS	−4	−4	−7	−7	−4	−3	0	−1
PLAS	0	−1	+1	−1	+2	+4	−6	−7
LRS	−2	−1	0	+2	−1	+1	0	−4

Changes in ES values were identified by the differences in ES values of the current land use and ES values of simulations of UBS, UGS, PLAS and LRS (reference values in the balance tables in Figs. 4, 5, 6, 7). Across each scenario, positive values depict positive synergies and negative values illustrate negative synergies. Both positive and negative ES values across each scenario illustrate trade-offs in the supply of the respective ES.

showed that future land uses driven by urbanization, and which manifest in reality, as transitions to built-up areas, became pronounced and intensified over time, within the immediate vicinity of coastal ecosystems along the southern borders of the region (Fig. 6). Such locations experiencing urban expansion were coterminous with the range of mangrove ecosystems, thereby reinforcing perceptions of mangrove forests as particularly vulnerable to urbanization pressures.

The results also showed that experts perspectives on coastal landscape restoration favored transitions from other land uses to mixed swamp forests, mangrove swamps, shrublands, food crop, and rubber (Supplementary Table 2). Such perspectives suggest that experts perceive coastal restoration more broadly, and inclusive of land use transitions that maintain the heterogenous characteristics of the landscape. However, spatially explicit representation of restoration scenario revealed expansion of rubber plantation within the vicinity of mixed swamp forests (Fig. 7). Thus, coupling site-based knowledge of coastal land use transitions with spatially explicit mapping of habitat conditions is essential for multiple habitat restoration planning. By utilizing spatially explicit scenarios to showcase experts' perspectives on future land uses, our approach reveals site-based and temporal risks and opportunities posed by landscape restoration to future ES supply.

The analysis of ES supply provides guidance for the planning and implementation of ecological restoration[79,80]. By applying spatially explicit scenarios to inform decisions on the locations for enhancing ES supply in the region through restoration, and where risks to ES supply due to urbanization can be avoided, our approach bridges the gap between the theory and practice of integrating the concept of ES in land use planning[66]. The land use scenarios in this study represented major future land use changes. Potential impacts of the scenarios were illustrated by rearranged land use patterns and their synergistic or trade-off effects between multiple ES. The impact assessments of UBS and UGS (Fig. 4 and Fig. 5) showed temporal decline in the region's potential to supply food, fuelwood, carbon sequestration and recreation benefits. The negative synergies between such ES can be explained by the fact that, according to the UBS, built up areas replaced mangrove swamp (Supplementary Table 2) which are considered to have high potential to provide multiple ES such as food, fuelwood, and recreation benefits (Table 3). Mangroves provide spawning, feeding and resting habitats for a diversity of fish species, hence, are rich sources of fish food[81]. In the artisanal fisheries sector, there is high preference for mangrove wood for smoking fish in traditional ovens[55]. Moreover, mangrove ecosystems serve as important destinations for nature-based recreation and low-impact tourism activities. Similarly, food crop land, including agroforestry systems which have high potential for food supply and carbon sequestration (Table 3) were converted to built-up areas (Supplementary Table 2) which have neither the potential to supply food nor sequester carbon. Although built up areas showed moderate levels of potential to provide recreation benefits (Table 3), this potential was concentrated along the southern portions of the landscape according to the UGS (Fig. 5). With the concentration of recreation benefits to few locations on the landscape, the results showed decline in recreation benefits over time. This implies the creation of green spaces in developed urban areas will not necessarily improve recreation benefits, especially where urban green spaces are not interconnected with other green land uses on the entire landscape.

Impact assessment of PLAS revealed steep declines in recreation benefits alongside positive synergies between fuelwood and carbon sequestration over a decade. However, such positive synergies reversed to trade-offs between fuelwood and carbon sequestration as plantation agriculture intensified over time (Fig. 7). Rubber, oil palm and coconut showed low potential to supply recreation benefits. Land use conversions which favored such plantations explains the decline in recreation benefits according to the PLAS (Fig. 6). It is noteworthy that rubber had a significant influence on the land use configuration and dominated the LULC according to the PLAS (Fig. 6 and Table 5). Although rubber fuelwood is utilized to meet energy demands at the household level, the region showed a low potential to supply rubber fuelwood (Table 3). This can be attributed to the prohibitive costs associated with harvesting rubber trees for fuelwood.

Impacts on potential ES supply of future land use patterns linked to restoration over a decade showed decline in food and carbon sequestration which resulted in negative synergies between such ES. However, food and carbon sequestration potential increased and resulted in positive synergies with the intensification of restoration. This reinforces understanding of the relationships between long-term restoration actions and ES supply[79]. Furthermore, analysis of restoration land use patterns indicates dominance of mixed swamp forest and rubber in future land use patterns. Mangroves showed reduction in extent under the LRS. Yet mangrove swamps in the region have relatively high potential to supply food, fuelwood and recreation benefits. This can explain the low potential supply of food which resulted from the LRS. Given their relatively high potential for multiple ES supply, mangroves require inclusion in future restoration land use patterns through effective land use and habitat restoration planning.

Coastal habitats in developing regions such as the study area, are vulnerable to deforestation and degradation from pressures of urbanization and over-exploitation[11]. Such pressures are underpinned by land use policies that promote industrialization, agriculture expansion and urban development without adequate considerations for the impacts of these policies on biodiversity and ES in marine and coastal environments[39]. Land use policies that favor oil palm and rubber plantation expansion have historically transformed the natural forest cover in the study region and resulted in coastal habitats fragmentation[82]. Spatial development frameworks have been articulated to harmonize land use polices in a manner that reconcile conservation of coastal habitats with economic and social development objectives in the region[83]. Nonetheless, inadequate institutional arrangements and legal tools have hampered effective implementation of spatial development frameworks[84]. Given the urgency to safeguard the rich biodiversity and the benefits of ES to societal wellbeing in the study region, coastal habitats restoration has become an important strategy to balance conservation land use with economic development policies. Coastal habitat restoration is a complex undertaking that involves deployment of a range of passive natural recovery strategies or active human-mediated conservation actions to achieve pre-defined outcomes[85]. In the study area, conservation planning decisions are focused on restoring degraded mangrove swamps without regard for ES considerations or the maintenance of habitat diversity. In this vein, our results are instructive for optimizing the benefits of conservation through multiple habitat restoration planning. Collectively, mangrove swamp, mixed swamp forest and palm swamp forests comprise the peat swamp forests of Southwest Ghana[54]. Peatlands are recognized for their multiple conservation benefits[86]. However, our results show the loss of mangrove swamps considering urbanization and landscape restoration futures (Table 4 and Table 5). Urbanization threats which pose risks to mangrove restoration success are prominent along the southern edges of the coastal landscape (Fig. 4). This implies, in order to pave way for successful mangrove restoration and realize the ES supply potential of mangrove swamps in the region (Table 3), urbanization threats have to be addressed. This can be achieved by applications of planning regulations that restrict conversion of mangroves into built up areas along the intertidal zones of the region. Relatedly, loss of mangroves associated with landscape restoration highlights the need for human-mediated restoration actions to consider habitat complexity and other environmental factors such as elevation and changes in tidal flows which can impede mangrove restoration success[74,87].

The results also highlight the need to re-evaluate conservation planning opportunities in the region as mixed swamp forests showed potential for persistence in the face of urbanization. Mixed swamp forests also expanded in spatial extent considering landscape restoration (Table 4 and Table 5). This finding suggests that, landscape restoration planning in the region should also prioritize mixed swamp forests in order to generate greater ecological benefits from multiple coastal habitats. Activation of planning instruments to guarantee future protection for mixed swamp forests will be necessary to avert their potential conversion to paddy rice fields[88]. Similar landscape protection regulations will be essential for maintaining the stability in the spatial extent of palm swamp forests (Table 4 and Table 5) over time. Results of the study also highlight other risks to successful restoration in the region such as rubber expansion along the fringes of mixed swamp forests (Fig. 7). Additional data and validation processes will be required to assess the potential biodiversity benefits or drawbacks of connectivity between swamp forests and rubber plantations. A similar study reported that, significant decrease in ES resulted from conversion of peat swamps to monoculture crops[86].

Designing four land use scenarios which aligned with urbanization, urban greening, plantation agriculture and landscape restoration futures provides a starting point to re-examine conservation planning decisions and to facilitate multiple coastal habitats and ES restoration in Southwest Ghana. From the theoretical standpoint, this study illustrated the methods for combining literature-based values from benefit transfer with expert knowledge for assessing potential ES supply due to coastal habitats restoration. On the basis of our evidence, which showed future expansion of mixed swamp forests, no change in the spatial extent of palm swamp forests, and decline of mangroves under landscape restoration, we recommend planning regulations and actions to holistically address peat swamp forests in the region to reinforce protection of these ecosystems and avert their future degradation.

Despite its strengths, there are inherent shortcomings which limit the applicability of our approach. Indicator values were unavailable for some LULC classes (Supplementary Table 3). This resulted in possible errors in estimating the maximum and minimum values of the region's potential to supply ES. Thus, the normalized values which represent the potential of each LULC class to supply ES (Table 3) could be lower or higher compared to the reality. Furthermore, the literature values on ES supply potential of the land cover classes were based on benefit transfer estimates. Benefit transfer can introduce errors in the estimation of potential ES supply of land cover classes due to differences between transfer sites and the study site[89]. Consequently, utilization of the scenarios in planning should be approached with caution by embracing underlining uncertainty and ambiguity. Nonetheless, by collating data from studies conducted within Ghana's coastal zone, errors due to benefits transfer were mitigated in our study. Lastly, although the LULC map was validated during the expert workshops, outcomes of scenario impact assessments were not subjected to further expert review and validation.

Consequently, scenarios presented in this study are illustrative of a range of plausible futures, rather than predictions of urbanization and landscape restoration outcomes. The scenarios provide a starting point to shape pragmatic discourses around coastal land uses within the context of regional planning. While this study showcased applications of participatory land use scenarios for impact assessment of ES, future research could identify and apply suitable landscape metrics to assess restoration impacts on the supply of relevant ES in the region. Effects of coastal habitats restoration outcomes on human well-being dimensions such as employment, income, health and food security are also interesting areas that future studies in the region could explore[90].

Data availability

Data is provided within the manuscript or Supplementary Information files.

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Author contributions

S.K. conceptualized the research and wrote the main manuscript text. H.K. supported conceptualization of the research and provided review comments on the draft manuscript. J.N.I. provided review comments. C.F. supervised the research and commented on the final draft manuscript. All authors reviewed the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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