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Research article

Designing mosaic landscapes for sustainable outcome: Evaluating land-use options on ecosystem service provisioning in southwestern Ghana

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ABSTRACT

The landscape in southwestern Ghana faces rampant modification due to socio-economic activities, posing threats to ecosystem service provision and environmental sustainability. Addressing these threats involves empowering land-use actors to design landscapes that offer multiple benefits concurrently. This study employs a geodesign framework, integrating participatory ecosystem service assessment and spatial simulations. This geodesign framework aims to design the landscape in a collaborative manner in a way that supports multiple benefits concurrently, mitigating the threats posed by landscape modification. Reflecting on local land-use perceptions during a workshop, we developed land-use options and land management strategies based on selected land-cover types. We identified urban greens, open space restoration, rubber mixed-stands, mangrove restoration, selective-cutting land preparation, soil conservation, and relay cropping as land-use options to target selected land-cover types of shrubland, cropland, smallholder rubber, smallholder palm, wetland, and settlement. The land management strategies translated into landscape scenarios based on local need conditions. We generated the local need conditions which translated into the landscape scenarios by reflecting on the location of land-cover types, 'change-effect' conditions within rubber, settlement, and cropland, and 'no-change' conditions within cropland. Results indicate synergies between the created landscape scenarios and ecosystem service provisioning, with 'no-change' within cropland providing the highest synergy and 'change-effect' within rubber providing the least synergy. Spatial modeling of local perceptions forms the novelty of this study, as the fusion of participatory assessments and spatial modeling allows for a more holistic understanding of the landscape, its services, and the potential implications of different management strategies. The geodesign framework facilitated the design of the complex heterogeneous landscape to visualize possibilities of maximizing multiple benefits and can be used for future planning on the landscape.

1. Introduction

In southwestern Ghana, land-use/land-cover changes (LULCC) of the mosaic landscape[2] are consequences of plantation agriculture developments, activities of the oil and gas industry, sandwining and illegal mining, and population growth mainly through in-migration and urbanization (Abdul-Kareem et al., 2021; Asante-Yeboah et al., 2022; Bugri and Yeboah, 2017; Page, 2013). Increasing land losses and switch in crop choices within cropland, shrubland, and palm favor tree-crop plantations and settlement expansion within the landscape (Benefoh et al., 2018; Bugri and Yeboah, 2017; Kleemann et al., 2017). Oil discovery in Ghana since 2007, especially in the marine and coastal areas, along with rubber out-grower schemes, have triggered land-use competition among agriculture, industry, and residential land-uses (Acheampong et al., 2018; Asante-Yeboah et al., 2022; Bugri and Yeboah, 2017). This competition results in the loss of farmlands and fallow lands to prioritize rubber establishment and settlement expansions. These changes occur either through landowners' decisions, as

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[2] Mosaic landscape' in this paper is defined as structurally complex heterogeneous area that consist of spatially interacting land-cover types and governance regime and providing multiple benefits (Clough et al., 2016).

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seen in out-grower schemes and land deals, or through state land acquisition under Article 21 of 1992 Ghana's constitution (Bugri and Yeboah, 2017; Larbi, 2008). For instance, In Ahanta West Municipal Assembly (AWMA), land under rubber cultivation expanded more than threefold between 1986 and 2020 (Asante-Yeboah et al., 2022). This change indicates a substantial increase in rubber plantation from cropland, shrubland, and palm. Similarly, settlement areas quadrupled in size during the same period (Asante-Yeboah et al., 2022). Another study by Kankam et al. (2022) observed a more than fivefold increase in rubber cultivated areas between 2000 and 2018. Other assessment-studies also acknowledged the encroachment on sensitive landscapes from the oil and gas discovery, causing habitat fragmentation and endangering biodiversity (deGraft-Johnson et al., 2010; Otchere-Darko and Ovadia, 2020; Sagoe et al., 2021).

Land-use changes have a profound impact on ecosystem service provisioning. The interactions between humans and their environment have a significant impact on ecological processes and ecosystem services, ranging from biodiversity to climate change (Sintayehu, 2018; Smale et al., 2019; Weiskopf et al., 2020). The extent of the alteration in ecosystem service provision varies depending on the specific land-use practices adopted (Felipe-Lucia et al., 2014; Wang et al., 2017). In southwestern Ghana, land losses in favor of rubber and settlement have affected the provision of local ecosystem services such as food fuelwood, species diversity, cultural values, carbon sequestration, and the regulation of soil quality (Asante-Yeboah et al., 2024; Kankam et al., 2021, 2022). Land-use changes significantly impact ecosystem services, as evidenced by various studies (Cord et al., 2017; Fu et al., 2013; Haines-Young and Potschin, 2010). Human activities play a bigger role in these changes than environmental factors (Han et al., 2017; Song et al., 2018). Interestingly, while LULCC can disrupt ecosystems, these changes also offer opportunities for enhancing multifunctionality in landscapes (Bretagnolle et al., 2018; Comberti et al., 2015). Properly managed land-use changes can support various services like food production and climate regulation (Keesstra et al., 2018), potentially reversing the decline in ecosystem functions.

Sustainable multifunctional landscapes are landscapes that are created and managed to enhance the service flow of critical ecosystem services by integrating human activities and landscape usage into the ecological fabric of the ecosystem (Helming and Wiggering, 2013). The concept of landscape multifunctionality is intrinsically linked to the concept of ecosystem services. When ecosystem services are structurally integrated into landscape management planning to advance multifunctionality, there are several opportunities for improving landscape sustainability and resilience (Kremen and Merenlender, 2018; Kremer et al., 2016). In the past, landscapes were often managed using sectoral approaches, which meant different sectors or industries (e.g., agriculture, forestry, urban development) would focus on their specific goals instead of fully considering ecosystems' interconnectedness and multifunctional nature of patches or ecosystems within the landscape system (Freeman et al., 2015; Wiggering et al., 2006). This approach often led to unintended consequences and neglected numerous benefits provided by ecosystems, beyond each sector's immediate objectives (Bennett et al., 2015; Schirpke et al., 2019). Regarding such issues, current sustainable landscape development thinking emphasizes the importance of the design of landscapes that offer multiple benefits simultaneously (Dronova, 2019; Fagerholm et al., 2019).

While the idea of designing landscapes for multiple benefits is globally acknowledged, challenges arise in implementing this concept in landscape management and planning. This difficulty stems from a gap between the theoretical understanding and practical application of multifunctional landscapes. (Lähde et al., 2019; Lin and Doyog, 2023). The gap emerges because landscape planning effectiveness increases significantly in a particular geographical area when there's greater local involvement. (Di Lucia et al., 2018). Lack of context-specific local knowledge and local perspective hinders the adoption and applicability of designed future landscape scenarios which have the goal to advance multifunctionality. Additionally, understanding ecosystem services is crucial in promoting multifunctional landscapes. The integration of these concepts often demands diverse data and models, necessitating expert guidance to help locals interpret and grasp these complexities (MacKinnon et al., 2019; Sandifer et al., 2015). Involving local participation and iterative collaboration are vital processes for effective landscape planning and scenario development aimed at designing multifunctional landscapes (Lin and Doyog, 2023; Tran et al., 2020). Land-use strategies that are practical and likely to be adopted by farmers and local land users can be developed when land-use actors are involved in designing multifunctional landscapes (Nigussie et al., 2017; Shahpari et al., 2021).

To develop future landscapes, different models and processes must be integrated into a practical framework (Cohen-Shacham et al., 2019). It is also essential to create a framework that facilitates collaboration between different stakeholders to develop a comprehensive land-use plan for the area (Arciniegas et al., 2019; Karrasch et al., 2014). In recent years, one instrument that has emerged as an innovative, effective, and efficient approach to implementing sustainable landscape planning is the concept of geodesign (Gottwald et al., 2021; Huang et al., 2019; Slotterback et al., 2016).

Geodesign framework is a process that involves the application of a variety of methods and techniques to plan sustainable development in an integrated manner, including conceptualization, analysis, simulation and evaluation, scenario planning, impact assessment, and a decision-making process that includes stakeholder participation and collaboration (Gottwald et al., 2021; Slotterback et al., 2016). The geodesign framework has proven very useful in enhancing geographic information systems and the design of landscapes. Among the valuable roles of geodesign, the key is the ability to acknowledge complex socio-ecological systems by improving communication and participation of different groups, including local people, scientists, landscape planners, and other land-use actors (Gu et al., 2018; Tran et al., 2020). Nevertheless, geodesign has been implemented primarily at urban and catchment scales. The application of a geodesign framework following landscape design for sustainable outcomes in mosaic landscapes is rare (Wu, 2021).

This study aims to advance multifunctionality on the study landscape and minimize the trade-offs of land-use practices driven by rubber expansions and oil discovery-related activities. The study adopts the geodesign framework to bridge the gap between theory and practice in landscape multifunctionality planning and collectively and iteratively, identify and simulate the impacts of alternative land-use options on the provision of ES on the study landscape. This paper addresses four questions i) What land-use options are perceived as locally feasible to minimize ecosystem service threats and advance multifunctionality on the study landscape? ii) How should the identified land-use options be translated into landscape scenarios for implementation? iii) What impact will the landscape scenarios have on the provision of ES, and iv) What guidelines are needed for effective implementation of land-use options and landscape scenarios?

2. Materials and methods

2.1. Study site

The study was conducted in Ahanta West Municipal Assembly (AWMA), located in the southwestern part of Ghana (Fig. 1). The geographical location is between latitude 4°45′00″ N and 4°57′00″N and longitude 1°45′00″ W and 2°13′00″W. The study area covers an area of approximately 591 km^2 and has a population of 138,192 (GSS, 2019). The study area lies within the high rainforest vegetation zone, largely characterized by flat lands and among the wettest places in Ghana. The study area is bounded by other municipalities such as Sekendi-Takoradi Municipal Assembly to the east, Tarkwa-Nsuaem, and Mpohor-Wassa Municipal Assemblies to the north, Nzema-East Municipal Assembly to

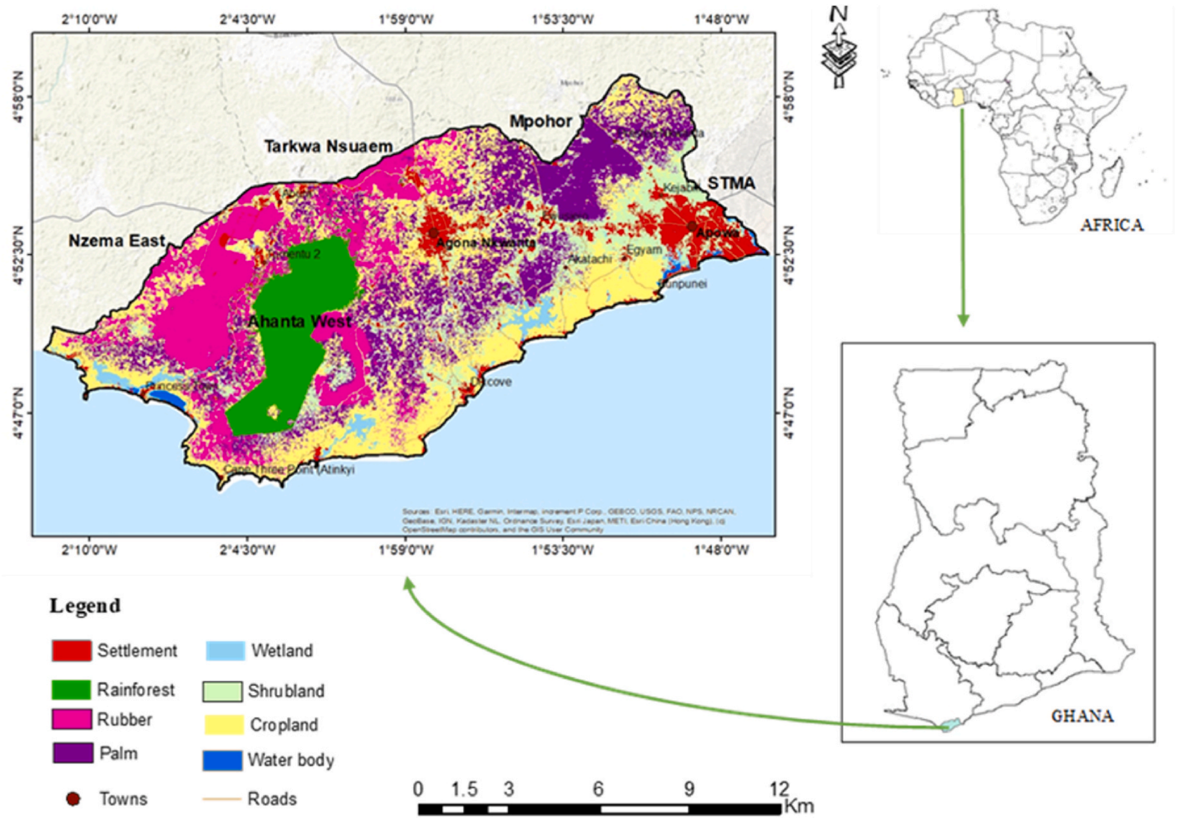

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Fig. 1. Land-use/land-cover types and location of the study area in southwestern Ghana. The land-cover map is based on the maximum-likelihood supervised classification (MLC) of Landsat image 2020 (Asante-Yeboah, et al., 2022).

the west and the Gulf-of-Guinea to the south.

The study district is characterized by a dendritic drainage pattern. It experiences relative humidity of between 75 % and 80 % and a double maxima rainfall (UNDP, 2007). The soils are fertile and thus support on agriculture and other local nature-based livelihood activities (AWMA, 2018; Bessah et al., 2021). The district is noted as a rural landscape (AWMA, 2018), however, expansions in rubber plantations and the birth of the oil exploration industry have led to in-migration, population increase, land rush, land speculation, and infrastructural developments causing all forms of unsustainable land-use and ecosystem degradation (Bugri and Yeboah, 2017). Rubber expansions are rapid and dominating the western part of the study landscape, while rapid expansions in the settlement are dominating the eastern part of the study landscape (Asante-Yeboah et al., 2022). Land preparation for rubber expansions is mainly clear felling, where all woody features and shrubs are cleared (Blagodatsky et al., 2016; Verheye, 2010). The initial establishment of rubber farms is highly fertilizer-dependent (Clough et al., 2016; Vrignon-Brenas et al., 2019). Settlement establishment and expansions are equally known to involve the removal of natural ecosystems. These practices are known to contribute to species diversity declines, habitat degradation, climate change, and overall degradation in ecosystem functions (Kassouri, 2021; Saghir and Santoro, 2018).

2.2. Geodesign framework

Using the ecosystem-based geodesign framework (Fig. 2), this study elaborated alternative land-use scenarios for the future landscape of the study area. The applied ecosystem-based geodesign framework was adapted from the study of Tran et al. (2020), which captured the concept of multifunctional landscapes according to the proposed geodesign framework by Steinitz (2012). Steinitz (2012) used six models to answer six questions about a target landscape. The first three models/questions are related to the '*assessment phase*', and the last three questions/models are related to the '*intervention phase*'. This paper focuses on the '*intervention phase*'. The '*assessment phase*' is addressed in previous studies and provides the baseline data for this '*intervention phase*' (Asante-Yeboah et al., 2022, 2024).

2.2.1. Assessment phase (stage 1–3)

The first model (representation model) asks the question, '*How should the context be described*'? This deals with defining, describing, and visualizing the study area using Geo-information techniques (McElvaney and Rouse, 2015; Steinitz, 2012). In this study, we applied categorical maps of the study area (see Asante-Yeboah et al., 2022). We generated the categorical land-use/land-cover maps from Landsat images for the years 1986, 2002, 2015, and 2020 coupled with ground truthing, and discussions with key inhabitants who have resided in the study area for over 35years. We used these information to define the composistion and configuration of the study area. From the categoricl maps, eight land-cover types were defined in the land-cover map (Supplementary Material 1).

The second model (process model) asks the question, '*How does the context operate*'? This stage describes the geographic processes and predicts how they might change over time using geospatial data and spatial analysis techniques (McElvaney and Rouse, 2015; Steinitz, 2012). In this study, we relied on locally relevant ES and indicator values which were assessed in a previous study (see (Asante-Yeboah et al., 2024) and Supplementary material 2). The ES and indicator values were assessed based on land-use actors' perceptions, expert opinions and equations. The locally relevant ES were identified reflecting on the environmental, economic, and social changes in the study area. We generated current land-use pattern and a 'business-as-usual' future land-use scenario by reflecting on the drivers of LULUC on the study area established (see Asante-Yeboah et al., 2022). We used a web-based

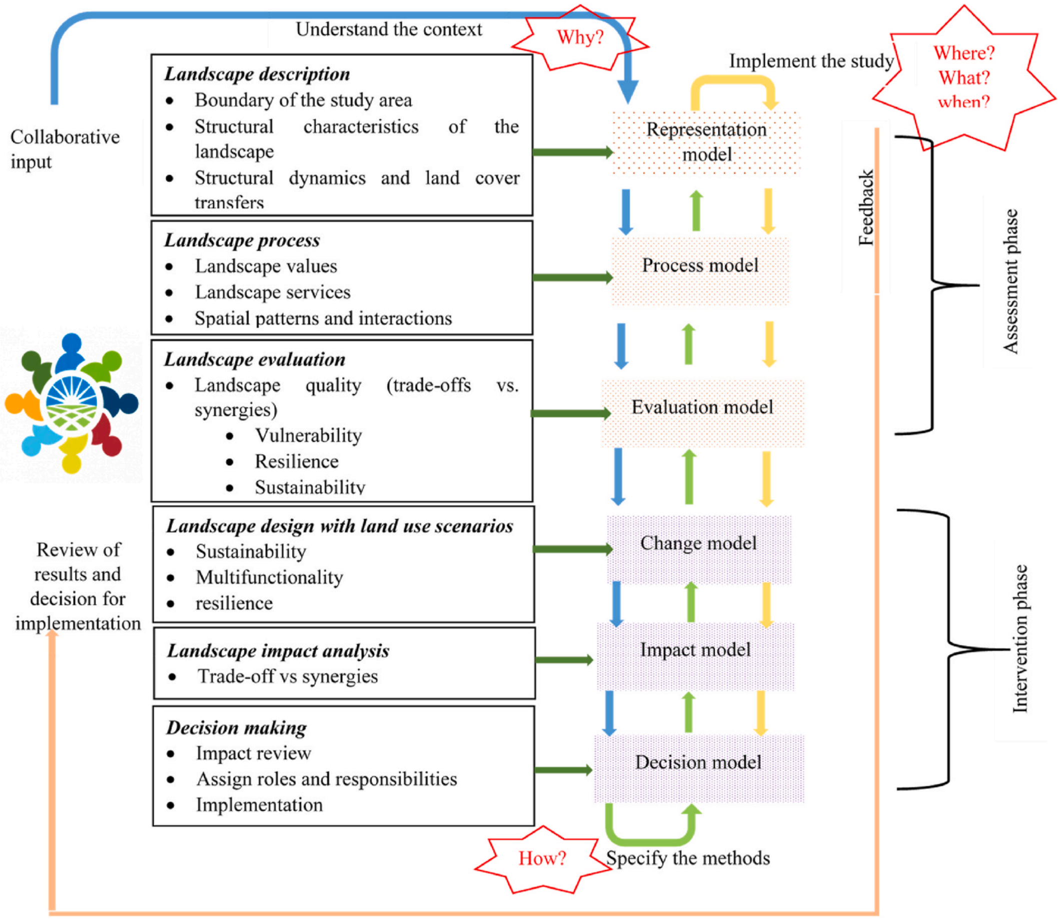


Fig. 2. Geodesign framework integrated with the concept of ecosystem service for generating alternative land-use options (adapted from *(Steinitz, 2012*; *Tran* et al., *2020*)). There are six stages in the geodesign framework: 1) Landscape description, 2) Landscape process, 3) Landscape evaluation 4) Landscape design, 5) Impact assessment, and 6) Decision-making. The arrows show the iterative process answering the questions of 'Why', 'How', and 'Where'. Each arrow colour shows the transition from one iteration to the other.

spatially explicit simulation platform called GISCAME to generate an ES assessment matrix., The ES assessment matrix is a normalization of the ES indicator values for each land-cover type. Finally, we used the GISCAME simulation platform to simulate the capacity of the current and future land-use patterns to provide the identified ES (Asante-Yeboah et al., 2024). The GISCAME is a platform which simulates future land-use scenarios using cellular automata (CA) (Fürst et al., 2013; Koschke et al., 2012, 2013). The CA rearranges land-use patterns based on a transition rule set reflecting locally specific conditions (Fürst et al., 2012). The GISCAME simulation platform was adopted as a means to address the impact of modifying land-use patterns and the corresponding variable characteristics of ES in a spatially explicit manner to visualize the changes in ES provision (Fürst et al., 2012). We validated the results with the land-use actors and adjusted the simulation parameters to reflect local feasibility.

The third model, (the evaluation model), asks the question, '*Is the context working well*? In this study, we delibrated on a previous study which captured discussions on the challenges under the 'BAU' scenario.

2.2.2. *Intervention phase (stage 4–6)*

The intervention phase, the focus of this study, aims to envision a desired future landscape.

The fourth model, (the change model), asks the question, '*How might the context be altered*'? At this stage, this study employed the deliberate design of the landscape by rearranging land-use patterns directly using a web-based simulation platform. The design process is as follows:

Identifying land-use options. In a workshop, the land-use actors reflected on the challenges perceived to be associated with the 'BAU' scenario. The land-use actors reached a common goal to design the landscape towards an advanced multifunctionality. We engaged the land-use actors to identify the land-use options taken into account the practicability and feasibility to address the challenges discussed under the 'BAU' scenarios. Land-use options are the individual alternative land-cover types that were identified by the land-use actors as alternative land-use practices the study area can adopt to achieve multiple benefits simultaneously. During this exercise, we assisted the land-use actors with examples of suitable alternative land-use practices in

Table 1
Description of locally applicable land-use options identified for the study.

Land-use options	Description
Urban greens	Integrating home gardens, and vertical farming, in residential areas
Open space restoration	Retrieving open spaces for green restoration
Rubber-mixed stands	Conversion of mono-cropping rubber into rubber agroforest, intercropping with other food crops and economically viable crops
Selective-cutting land preparation	Retaining trees and shrubs on land during land preparation for farming and establishing a rubber plantation
Mangrove restoration	Restoration of degraded mangrove sites
Soil conservation	Practicing mulching, compositing, earthworm circulation
Relay Cropping sequence	Practicing relay intercropping

similar regions. We discussed and finanlized on the feasible alternative land-use options (Table 1). One can find the number of participants and workshop protocol in Supplementary Materials 3 & 4 respectively. The land-use actors identified six out of the eight land-cover types that may require manipulation identified alternative land-use options due to thie high conversion rate with the. These six land-cover types are cropland, settlement, shrubland, smallholder rubber, smallholder palm, and wetland. Palm and rubber land-cover types consist of both large-scale plantation sites and smallholder cultivated farms (refer to discription in Supplmentary Material 1). To delineate smallhoder palm and smallholder rubber from palm and rubber land-cover types, in ArcGIS version 10.7, we used the 'earase tool' to identify the plantation sites and we used the 'Merge tool' to merge all plantation sites under one land cover type (either rubber or palm) into one shapefile, and all non-plantation sites for one land cover type (either rubber or palm) into one shapefile. We assigned two different values for the planatiaon and non plantation sites, and in GISCAME we used the values for the plantation site to exclude the plantation site from the simulations. This allowed for only simulations to occur in the non-plantation sites under rubber and palm, which is also referred to as in this manuscript as smallholder rubber and smallholder palm respectively (Supplementary Material 5). Controlled management regimes excluded rubber plantations, oil palm plantations, and forest from the targeted land-cover types.

The capacity of identified land-use options to provide ES. In further steps, we tasked the extension workers and research scientists to facilitate and explain the composition of each identified alternative land-use option so that the land-use actors can assign a a value to represent the provisioning capacity of the land-use options to provide ES. The provisioning capacity is expressed as the difference between the current land-cover type and the alternative land-use option. For instance, the extention workers and research scientiset explained the composistion of rubber-mixed stands as a land-cover type consiting of rubber trees in combination with food and multipurpose tree-crops. We then asked the land-use actors to assign a percentage value to rubber-mixed stand, which will denote its capacity to provide for the identified ES (Supplementary material 6). We repeated this process for all the alternative land-use options., We normalized the final ES values for the alternative land-use options, ranging them between 0 (indicating the lowest capacity to provide ES) and 100 (indicating the highest capacity to provide ES), enabling a consistent unit comparison of land-use options (Fürst et al., 2012). The normalized ES values became the assessment matrix upon which the relationships between ES capacities and land-use options was established.

Development of land-management strategies and landscape scenarios. We paired the identified seven land-use options with the targeted land-cover types to create the land-management strategies. These strategies represent combinations of land-use options with their corresponding targeted land-cover types. For instance, if "urban green" was designated as a land-use option for targeting settlements, we paired "urban green" with "settlement" to establish the specific land-management strategy. Subsequently, we applied these combined land-management strategies as landscape scenarios under specified conditions. The landscape scenarios enabled us to simulate land-management strategies involving the inclusion or exclusion of specific land-cover types. These decisions were based on the desired conditions and the spatial distribution of the targeted land-cover types within the study area.

The fifth stage, (the impact model), asks the question, '*What differences might the land-use change cause*'? The impact model uses simulation models to evaluate the impact of land-use change on ecosystem service provisioning (McElvaney and Rouse, 2015; Steinitz, 2012; Tran et al., 2020). In this study, we utilized GISCAME to simulate and analyze the impact of the newly developed landscape scenarios. The land-use actors formulated 'IF' conditions to create these scenarios, supported by transitional probability rule sets (expressed in percentages) for simulation within the GISCAME platform. For instance, one scenario involved altering the current state of a smallholder rubber land-cover type to a future state of rubber-mixed stands. This change was determined by transition probabilities (%) based on neighboring land-cover types influencing the rubber farm and excluding the rubber farm from the rubber plantation area (defined by a rubber plantation shapefile) (Supplementary Material 7). In further steps, we combined the assessment matrix and the new land-use patterns developed in the CA within the GISCAME platform using the current landscape scenarios. The assessment produced spatially explicit maps presenting ES values through spider charts and an ES balance table. Land-use actors agreed on simulation iterations, equating to a transition probability representing 5 years each. Consequently, simulations extended 10 years (iteration 2) and 50 years (iteration 10) into the future from the current state.

Lastly, the decision model, the sixth stage, asks the question, '*Should the context be changed*'? In this stage, we utilized the information derived from the impact assessment and collaborated with the land-use actors in a workshop to determine implementation strategies (workshop protocol in Supplementary material 4). The discussion prompted a shared responsibility for devising effective implementation pathways. During the discussion, land-use actors deliberated on roles, responsibilities, as well as the challenges and opportunities associated with implementing the land-use scenarios. The insights gathered from these discussions are presented in the results through narratives and figures.

3. Results

3.1. Capacity of land-use options to provide ecosystem services

Table 2 displays the ES values associated with the land-use options. These values were assigned based on replacing the current land-cover types with the respective land-use options. For instance, integrating urban greens, comprising home gardens, vertical farming, and peri-urban gardens, into settlement areas was perceived by participants to enhance the food provisioning compared to the existing settlement. Consequently, incorporating urban greens into settlements would increase the food provisioning capacity from 0 to 50. Moreover, the introduction of urban greens could generate marketable products through sales from peri-urban gardens. Additionally, branches and debris from wood and other crops within urban greens could contribute to fuelwood, while enhancing soil quality regulation through litterfall and decay. Furthermore, introducing different species within urban greens could elevate species diversity compared to the current state of settlements.

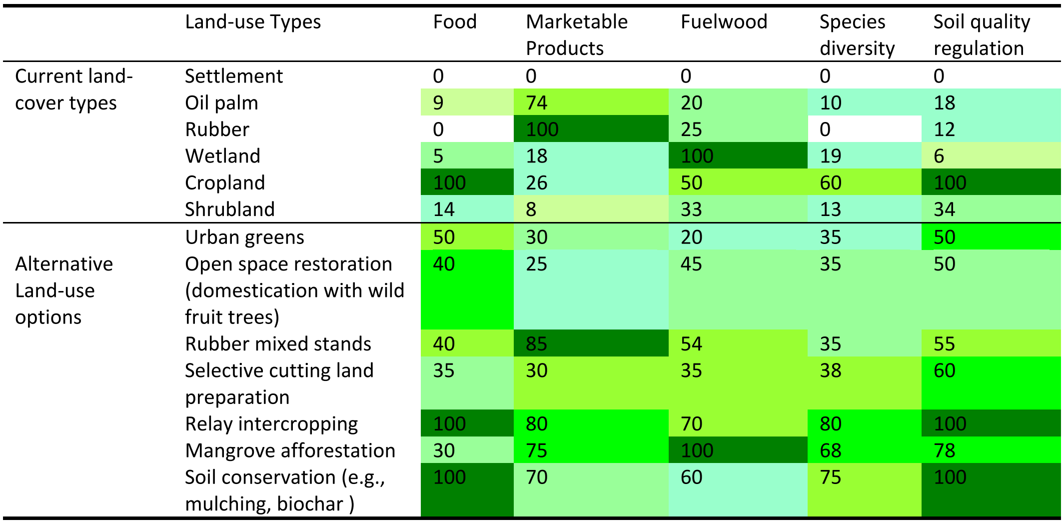
Similarly, the inclusion of rubber-mixed stands featuring food crops and multipurpose trees was acknowledged to augment food production, fuelwood supply, species diversity, and soil quality regulation in contrast to monocropping rubber. However, the perception of local land-use actors indicated a potential decrease in the ES capacity of rubber-mixed stands to provide marketable products.

3.2. Identified land-management strategies and conditions for land-use scenarios

Land-management strategies are detailed in Table 3, outlining how local land-use actors identified potential applications for each land-use option using targeted current land-cover types. For instance, they acknowledged the potential for integrating open space into settlement areas and incorporating shrublands within settlements. Notably, compared to shrublands outside settlement areas, those within settlements showed a higher potential for conversion to settlement. When converting land to rubber, the actors also considered selective-cutting land preparation suitable for smallholder palm and shrubland. It was consensually decided to introduce rubber-mixed stands in already established smallholder rubber farms. Moreover, the agreement encompassed the incorporation of rubber-mixed stands in cropland, shrubland, rubber stands, and palm trees, excluding settlements and wetlands.

Table 2

Ecosystem service assessment matrix for the current land-cover types and the alternative land-use options. The assessment matrix shows the relationship between land-use types and their capacity to provide ES within a range between 0 (lowest capacity to provide ES, in white) and 100 (highest capacity to provide ES, in dark green).



	Land-use Types	Food	Marketable Products	Fuelwood	Species diversity	Soil quality regulation
Current land-cover types	Settlement	0	0	0	0	0
	Oil palm	9	74	20	10	18
	Rubber	0	100	25	0	12
	Wetland	5	18	100	19	6
	Cropland	100	26	50	60	100
	Shrubland	14	8	33	13	34
Alternative Land-use options	Urban greens	50	30	20	35	50
	Open space restoration (domestication with wild fruit trees)	40	25	45	35	50
	Rubber mixed stands	40	85	54	35	55
	Selective cutting land preparation	35	30	35	38	60
	Relay intercropping	100	80	70	80	100
	Mangrove afforestation	30	75	100	68	78
	Soil conservation (e.g., mulching, biochar)	100	70	60	75	100

Table 3

Developed land-management strategies. The management strategies are a combination of the targeted land-cover type and the applicable land-use option. For instance, UGSe is a land-management strategy with urban green as a land-use option to be applied to settlement areas. The abbreviations are a combination of the land-cover type and the land-use option. For instance, ORSe means Open spare restoration on settlement.

Targeted land-cover types		Cropland (C)	Settlement (Se)	Shrubland (Sh)	Smallholder rubber farms (Sr)	Smallholder palm (Sp)	Wetland (W)
Land-use options	Urban greens (UG)		UGSe	UGSh			
	Open space restoration (OR)		ORSe	ORSh			
	Selective land preparation (SP)	SPC		SPSh		SPSp	
	Relay cropping (RC)	RCC					
	Rubber-mixed-stand (RS)	RSC		RSSh	RSSr	RSSp	
	Soil conservation (SC)	SC			SCSr	SCSp	
	Mangrove restoration (MR)						MRW

Land-use actors acknowledged the limited universal applicability of each land management strategy across the study area. As a result, they formulated specific conditions for implementing these strategies as scenarios within the study area (section 3.2.1). Upon analyzing the land-cover map, land-use actors noticed a rapid surge in settlement expansion, particularly concentrated in the eastern part of the study area, indicating potential future growth. Addressing declining ecosystem functions within these expanding settlement areas prompted the recommendation to implement precise and targeted land-use strategies focused on the eastern part of the study area, resulting in the creation of scenario 1 (SC 1).

To address the declining ecosystem functions resulting from rubber expansions, we directed specific land management strategies to the western part of the study area, encompassing scenarios 2 and 3 (SC 2 and SC 3). In SC 2, land-use actors recognized the significance of selective-cuttingland preparation over clear-felling. They emphasized integrating soil conservation methods and establishing mixed rubber stands for cropland, shrubland, and smallholder palm areas. Additionally, they recommended implementing rubber-mixed stands for the already established smallholder rubber areas (SC 3).

In contrast, land-use actors acknowledged the potential of creating a land-use scenario aimed at improving existing croplands to incentivize farmers to maintain their crops and increase productivity levels. They pinpointed a scenario involving relay cropping and soil conservation measures as suitable for sustaining and improving current cropland conditions (SC 4). There was unanimous agreement on the suitability of scenario 5 (SC 5), which proposes converting shrubland and smallholder palm areas into cropland instead of establishing rubber stands.

3.2.1. Conditions and landscape scenarios for spatial simulations

- ❖ Condition 1: Apply land-management strategies under scenario 1 (SC 1) in areas where settlement is expanding because of in-migration and population growth, and where the land-use types are at risk of conversion to settlement (shrubland, smallholder palms, and cropland).
  - ➢ Scenario 1: UGSe + UGSh + ORSh + UGC + UGSp + MRW
- ❖ Condition 2: In areas where the rubber is expanding, apply the land-management strategies in scenarios 2 and 3 (If other land-cover types are been converted to rubber)
  - ✓ In scenario 2 (SC 2),
    - apply selective land preparation to cropland, shrubland, and palm during land preparation to plant rubber
    - after land preparation, apply soil conversation and rubber-mixed stand
      - ➢ Scenario 2: SPSh + SPSp + SPC + SCC + SCSh + SCSp + RSSh + RSC + RSSp
- ✓ In scenario 3 (SC 3),
  - apply rubber-mixed stand to already established smallholder rubber farms

    ➢ Scenario 3: RSSr

❖ Condition 3: If farmers are encouraged to maintain croplands for food production on the entire landscape., apply scenario 4

  ✓ In scenario 4 (SC 4),

    - improve the soil quality of croplands by applying soil conservation and increase crop productivity and diversity by applying relay cropping.

  ➢ Scenario 4: RCC + MRW + SCC

❖ Condition 4: If farmers are encouraged to convert smallholder palm and shrublands to food/croplands instead of pure rubber stands, apply scenario 5

  ✓ In scenario 5 (SC 5),

    - apply selective land preparation to prepare the land, increase soil fertility with soil conservation, and incorporate relay cropping. ,

  ➢ Scenario 5: SPSh + SPSp + RCSh + RCSp + SCSh + SCSp

3.3. Impact assessment of land-use scenarios

Figs. 3 and 4 present the mean ES values for the five ES in the two iterations (iteration 2 and 10). The variation in ES values between the scenarios in the first iteration (iteration 2) and the current land-cover map indicates that SC 1, integrating food crops and woody vegetation in settlement-dominated areas, increased food (2), marketable products (1), species diversity (2), and soil quality regulation (2). SC 2, involving selective cutting for land preparation and soil conservation practices, led to increased food production (1), fuelwood (2), marketable products (5), species diversity (5), and soil quality regulation (5). SC 3, representing rubber-mixed stands, increased the ES value of food (7), fuelwood (4), species diversity (6), and soil quality (6). SC 4 demonstrated an increase in marketable products (12), fuelwood (6), species diversity (7), and soil quality regulation (1). SC 5 increased the ES value of food (13), marketable products (3), fuelwood (7), species diversity (12), and soil quality regulation (12). There was no change in ES values under SC 1 for fuelwood and SC 4 for food. Additionally, SC 3 showed a reduction in ES value for marketable products. SC 5 resulted in synergies in land-use options and the provision of ES, while SC 3 demonstrated a trade-off by increasing land-use options against marketable products. A similar trend was observed in iteration 10. Food, marketable products, species diversity, fuelwood, and soil quality regulation increased under SC 2 and SC 5. Marketable products decreased with SC 3, and no change in ES values was observed with SC 1 for species diversity and SC 2 for food. Fig. 5 and Figs. S1, S2, S3, and S4 depict the rearrangement of land-use patterns and changes in the spatial distribution of ES in the simulated land-use scenarios.

3.4. Decision-making for future landscape planning

Participants in the decision-making process voiced the following concerns about the food situation on the study landscape:

> 'Agona Nkwanta is a market where I've consistently purchased locally grown food. However, during one visit, I was presented with a choice: whether I wanted locally produced vegetables or those imported from Togo and Burkina Faso. Opting for the locally sourced vegetables meant paying twice the price compared to the imported ones (Institutional actor-AWMA)'.
>
> 'In our district, every farmer utilizes any small plot of land they own to cultivate rubber. Consequently, the production of common cassava, an affordable and easily accessible local staple, has significantly decreased even within households. I find myself preferring to sell my cassava to outsiders rather than local residents. This shift is due to the fact that everyone is converting their land solely for rubber cultivation, leaving no space for growing essential food crops (Farmer-Abra, AWMA)'.
>
> 'Some of the migrants in this village cultivate short seasonal vegetables (e.g., okra, pepper) on communal lands; however, the chiefs have given these communal lands to investors to plant rubber (Farmer-Apimanim, AWMA)'.

Land-use actors stress the importance of multi-stakeholder collaborative planning for the effective implementation of scenarios. They express concern that negotiations regarding land-use changes often involve only chiefs and investors, neglecting input from scientific research bodies, land-use planning departments, and farmers. the land-use actors highlight the significance of allocating a budget within the assembly's medium-term development plans (MTDPs) to support awareness campaigns and implement various land-use options aligned with developed scenarios and their impact on ecosystem services (ES). To ensure transparency and awareness, land-use actors recommended legally supporting land-use plans and making them accessible to the public. They propose disseminating this information through platforms like the National Commission on Civic Education for public sensitization and education. Additionally, land-use actors encouraged non-governmental organizations (NGOs) to assist the Department for Food and Agriculture (DOFA) in establishing demonstration plots showcasing

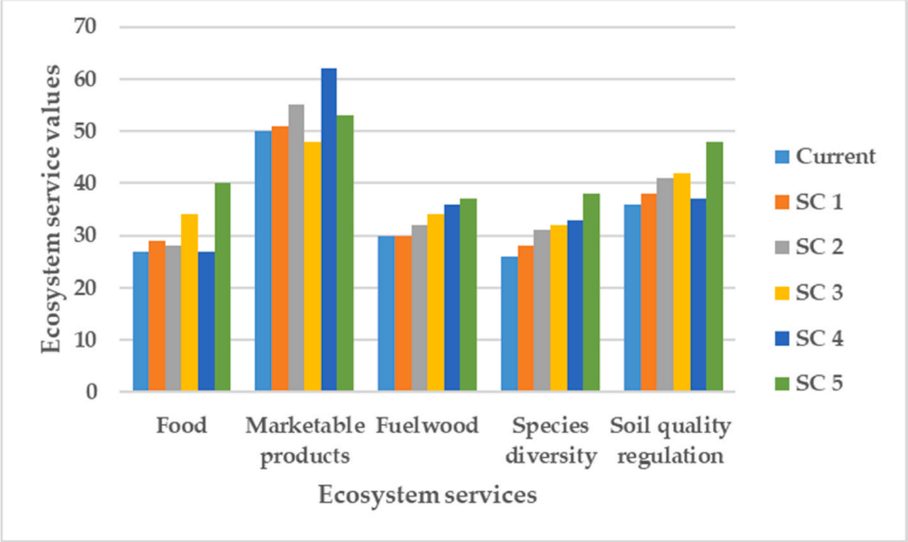


Fig. 3. Provision of ecosystem services under different landscape scenarios for iteration two (10 years from current land cover map).

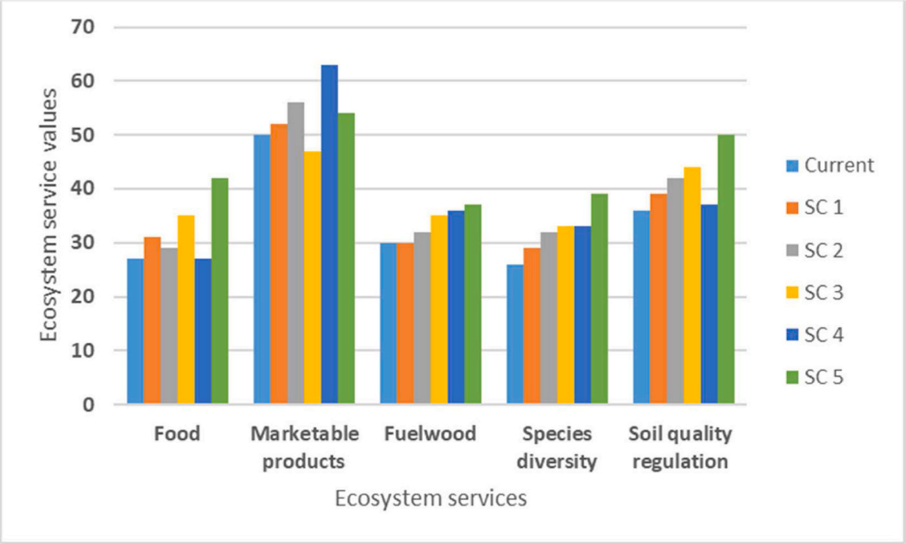
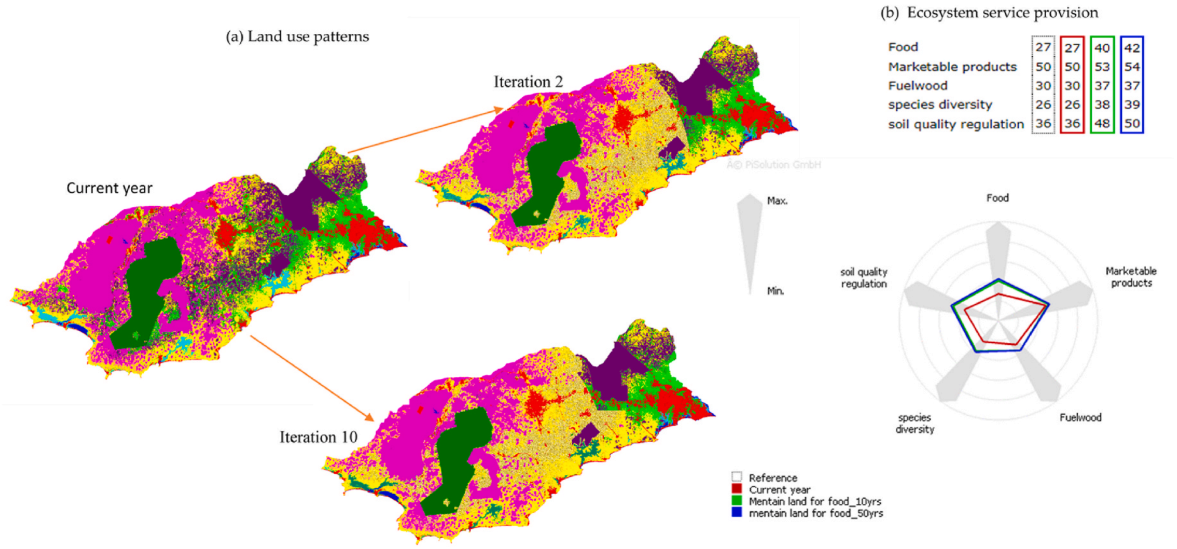


Fig. 4. Provision of ecosystem services under different land-use scenarios for iteration two (50 years from current land cover map).



Food	27	27	40	42
Marketable products	50	50	53	54
Fuelwood	30	30	37	37
species diversity	26	26	38	39
soil quality regulation	36	36	48	50

Fig. 5. Potential impact of land-use scenario 5 on the land-use patterns and the ecosystem service provisioning. The application of the land-use strategy results in rearranged land-use patterns (a). The balance table and the spider chart present changes in the provision of ecosystem services (in green and blue boxes) compared to the current state (in grey boxes) (b). The images are captured from GISCAME.

various land-use options aimed at increasing adoption rates Fig. 6.

During the decision-making workshop, a consensus was reached on distributing rubber seedlings alongside versatile agricultural crops. Collaborations were suggested with the rubber industry and the Department for Food and Agriculture (DOFA) for on-farm training. Discussions also focused on incentivizing farmers to maintain secondary or fallow lands. One farmer proposed policy changes involving incentives and recognition. The suggestion includes acknowledging farmers during national events like Farmers' Day celebrations and providing monetary rewards to promote the provision of ecosystem services at the local level.

The land-use actors involved in land-use activities foresaw several potential challenges that might hinder the implementation process. To address these issues, they suggested devising site-specific measures as a viable solution. Specifically, participants acknowledged certain land-use options—such as relay crops, soil conservation techniques, rubber-mixed stands, and urban green initiatives (refer to Fig. 6)—as beneficial for enhancing soil fertility. However, they identified potential obstacles arising from insufficient technical knowledge and low adoption rates concerning these specific land-use alternatives.

4. Discussion

4.1. *Land-use options, land-use scenarios, and ecosystem service provisioning*

In this study, we quantified ES values for the alternative land-use options using local perceptions and landscape characteristics. Urban greens (home gardens, vertical farming), and open space restoration were found to enhance species diversity, contribute to food production and availability, and improve soil health within settlement-expanding areas. Numerous studies have highlighted that urban green spaces and open space restoration bolster urban system resilience, aid in climate regulation, and enhance human life quality (Cameron et al., 2020; Cilliers et al., 2013; Du Toit et al., 2018; Lepczyk et al., 2017). Other studies have also shown how crop and soil management strategies, such as relay

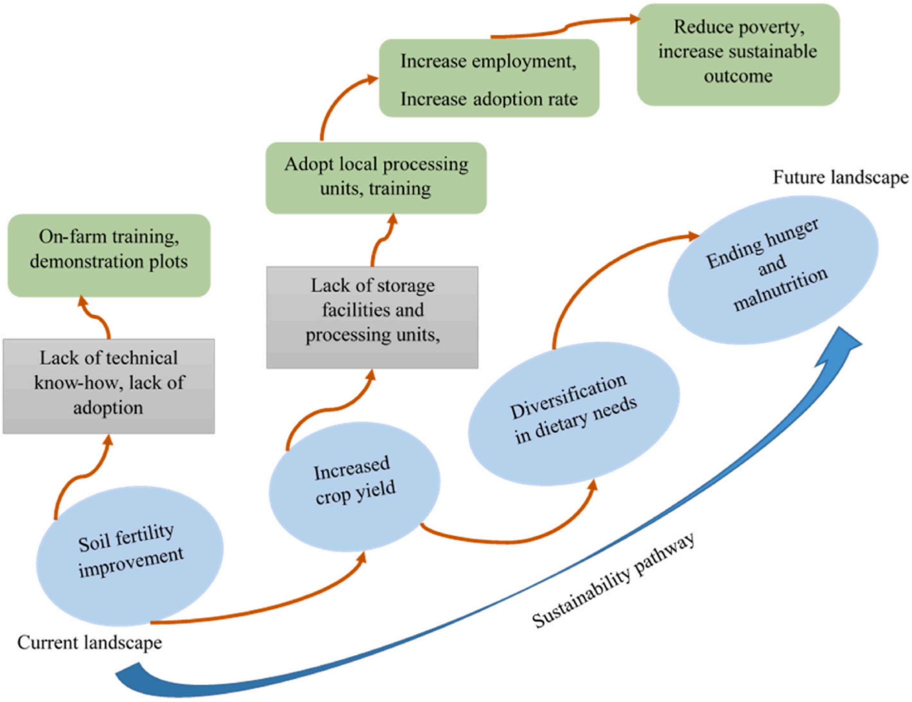


Fig. 6. Pathway to sustainable implementation of land-use scenarios. Blue circles are the anticipated goals a land-use option can achieve. Grey squares are the anticipated obstacles to achieving a goal and green rectangles are the opportunities in practices that can be adopted to overcome the obstacles.

cropping, biochar application, and mulching, can improve soil health, sustain food production, and enhance biodiversity and resilience within croplands (Bertola et al., 2021; El Mujtar et al., 2019; Lal, 2013, 2015; Nielsen et al., 2015; Riaz et al., 2020).

The findings of this study suggest that adopting crop and soil management strategies like relay cropping and soil conservation can enhance ecosystem functioning in future land-cover types compared to the current state. It appears that the landscape's current benefits are insufficient, as indicated by experiences shared by land-use actors from Abra, the district assembly, and Apimanin. Markets have become the primary source of household food availability for inhabitants, yet they fail to meet dietary needs in terms of food quality, sufficiency, and affordability. Otchere-Darko and Ovadia (2020) similarly observed a rise in local food commodities such as cassava, maize, yam, and plantain in this region due to socio-economic activities and population growth.

Interestingly, a slight reduction in marketable products occurred with the introduction of rubber-mixed stands into rubber farms (SC 4), which could be attributed to other species occupying space that might have been used by rubber trees. However, rubber-mixed stands can counterbalance the decline in rubber sales by enhancing soil fertility, offering food, boosting species diversity, and providing fuelwood. These stands are recognized for their substantial and continuous litter production throughout the year, which contributes to soil fertility improvement and food production (Michelaki et al., 2019). Rubber-mixed stands offer additional benefits beyond marketable products, serving the livelihood needs of the local population and contributing to the sustainability of the landscape (Singh et al., 2021). Determining that applying scenario 5 (SC 5) would create the greatest synergy between land-use options and ecosystem services was based on a combination of strategies like selective-cutting for land preparation, relay cropping, and soil conservation measures. It's possible that the land share occupied by smallholder palm on the landscape contributes to this high synergy.

Reflecting on the findings of this study, we observe that the coexistence of multiple land-use options or diversification in land uses is likely to contribute more to ES provisioning than simplified landscapes dominated by single land-cover types (de Jong et al., 2021; Jia et al., 2022; Martin et al., 2022). For instance, ES values under the BAU scenario for settlement-expanding areas (Asante-Yeboah et al., under review) were lower compared to ES values simulated under the alternative land-use option scenarios for the same settlement-expanding areas. Simulating settlement under BAU scenarios assumed an urban state where all-natural green spaces are replaced with concrete floors and buildings. According to literature, urbanization and built-up expansions negatively affect ES provisioning by displacing land-cover types that might otherwise contribute to enhancing ES provisioning (Liu et al., 2019; Pickard et al., 2017). However, compared with SC 1 in Supplementary Material 8, simulating land-use options for settlement-expanding areas rather appreciated the ES values and agrees with similar findings on urban green infrastructure studies (eg. Du Toit et al., 2018; Lindley et al., 2018). A similar example illustrates the simulation for rubber expansions under the BAU scenario, showcasing a decrease in all ES values except for marketable products (Asante-Yeboah et al., 2024). However, when compared with scenarios designed to address rubber expanding areas like SC 2 and SC 3, ES values showed an increase.

4.2. *Pathway to implementation of land-use scenarios*

To ensure a sustainable and resilient future landscape design, it must take into account the practical needs and expectations of the local land users (Abah et al., 2015). Participants in this study were tasked with defining the roles and responsibilities required to effectively implement the designed land-use scenarios as well as addressing challenges and opportunities associated with the implementation pathway. One of the implementation pathways is policy changes to capture collaborative and inclusive land-use planning in the district. Land-use planning in Ghana is full of political, economic, and complex socio-cultural factors with limited involvement of beneficiaries inhibiting efforts to attain sustainable landscape development (Poku-Boansi, 2021). The collaboration between industries, land-use planners, and farmers, and the recognition of farmers during national events as means of motivational incentives are also agreed principles under the concept of operationalizing payment for ecosystem service (Capodaglio and Callegari, 2018).

Designing landscapes for sustainable outcomes is a complex task that presents both challenges and opportunities (Schulze et al., 2015; Westerink et al., 2017). Generally, lack of awareness and technical know-how, political change, lack of commitment, financial barriers, and land ownership regimes can affect the implementation of land-use options for sustainable outcomes (Chazdon et al., 2017; Rode et al., 2019). Finding opportunities to address perceived challenges to implementation pathways such as establishing demonstration plots, and setting up local factories for post-harvest processing aligns with national policies in Ghana such as the, 'one district one factory', and 'planting for food and jobs' which seek to boost food production and economic development by establishing and revamping food production and local industries in each district (Ali et al., 2021; Eshun, 2019; Mensah et al., 2021).

4.3. Methodological discussion

Landscape design for multifunctional purposes requires the integration of local knowledge when determining the status of ecosystem services relevant to land-use activities. However, studies of ecosystem service assessment have tended to be scientifically oriented in the West African context. (eg. Elavarasan et al., 2021; Singh et al., 2021). Based on the geodesign framework, this study was able to provide insight into local knowledge and perceptions for predicting how ES provision might be affected by alternatives of land-use options. There is an advantage to this approach over other land-use modeling studies that lack local participation and do not include perceptions about how land-use changes affect ES provision (Xie et al., 2017). Land-use actors' perceptions of numerical values on ES provision are collected in a participatory manner to provide quantitative data that can be used by decision-makers and landholders to change land-use based on social values, cultural values, and/or personal preferences (Martínez-Sastre et al., 2017). By involving local farmers and experts, we can simulate results and evaluate them qualitatively, and we can adjust land-cover patterns based on these results (Tran et al., 2020; Xie et al., 2017).

However, despite the advantages of using a collaborative geodesign framework, there is a drawback to such locally-tailored landscape design: the results may not be transferrable to other landscapes and locations (Koo et al., 2020). The GISCAME model used in this study incorporates stakeholder-generated context-specific information to better understand and assess ecosystem services at local levels. The results obtained from this approach are likely to reflect the perceptions and needs of the local land-use actors who are directly involved in or affected by the use of the ecosystem services in the area under study. Application of the assessment framework and spatially explicit design must therefore be adapted to reflect the local needs of the study context when used in other regions.

4.4. Conclusion

In summary, this study in southwestern Ghana utilizes a geodesign framework to tackle landscape threats arising from socio-economic activities. Engaging local land-use actors and conducting spatially explicit simulations, the study reconfigured the landscape to promote multiple benefits and bolster sustainability. The outcomes encompassed the assessment of land-use options' capacity to provide ES and the spatial distribution of land-use scenarios across the landscape. The geodesign approach and resulting insights are crucial for informed decision-making and future landscape planning.

4.4.1. Supplementary materials

The following materials are available. Supplementary Material 1: Land share and description of land-cover types in the study area. Supplementary Material 2: Description of identified ecosystem services and indicators used for the study. Supplementary Material 3: List of participants for the workshop. Supplementary Material 4: Workshop protocol for landscape design. Supplementary Material 5: Plantation shapefiles for rubber(a) and palm (b). The shapefiles were used to separate the plantation sites from the smallholder farms. Rubber and palm farms outside the plantation shapefiles are considered as the smallholder rubber and smallholder palm. Supplementary Material 6: Assessing the capacity of land-use options to provide ecosystem services. Suplementary material 7: Transitional probability rule set for simulating the landscape scenarios. Suplementary Material 8–11: Potential impact of land-use scenario (SC 1, SC 2, SC 3, SC 4) on the land-use patterns and the ecosystem service provisioning. The application of the land-use strategy results in rearranged land-use patterns (a). The balance table and the spider chart present changes in the provision of ecosystem services (in green and blue boxes) compared to the current state (in grey boxes) (b). The images are captured from GISCAME.

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CRediT authorship contribution statement

Evelyn Asante-Yeboah: Conceptualization, Formal analysis, Methodology, Resources, Validation, Visualization, Writing – original draft, Writing – review & editing. **HongMi Koo:** Conceptualization, Methodology, Validation, Writing – review & editing. **Stefan Sieber:** Writing – review & editing, Supervision. **Christine Fürst:** Conceptualization, Supervision, Writing – review & editing.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2024.120127.

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