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Geospatial assessment of agricultural land expansion and its impact on biodiversity: A systematic review

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Agricultural land expansion remains one of the most significant drivers of biodiversity loss globally. Geospatial approaches among other tools can support researchers in understanding the complex impacts of this loss. This systematic review critically analyzes recent scientific advancements in remote sensing, land-use transitions, climate-smart agriculture, and policy frameworks to assess the relationship between agricultural expansion and biodiversity. Remote sensing technologies – particularly the integration of Sentinel-1 SAR data with deep learning algorithms have shown promises in detecting tropical dry forest disturbances, enhancing near real-time data processing for monitoring land encroachments, though caution is warranted due to limited interpretability and linear assumptions inherent in most of deep learning models, which may not fully capture the complexity of natural ecosystems as fixed deep learning models typically lack the ability to adapt in real-time to new or unforeseen data conditions. Agro ecological systems such as cocoa-based agroforestry emerge as vital buffers against biodiversity erosion by enhancing ecosystem resilience and species richness. However, rewilding efforts, while ecologically beneficial, have revealed unintended conflicts with farming communities, necessitating adaptive management strategies. Globally, agricultural trade and land-use transitions, notably in regions such as Brazil and Ghana, have led to significant habitat fragmentation and biodiversity intactness loss, exposing urgent trade-offs between conservation and food production. Furthermore, climate-smart innovations like digital twin technologies and nitrogen budgeting have improved agricultural efficiency and reduced environmental impacts, although challenges in adoption persist in smallholder systems. Sustainable agriculture, underpinned by land-use and land cover (LULC) monitoring, policy integration, and restoration strategies, offers a pathway for harmonizing productivity with ecological integrity. The review concludes by emphasizing the role of geospatial tools in guiding evidence-based policymaking, advancing sustainable land management, and reconciling biodiversity conservation with food security in an era of global environmental challenges.

Key words: Biodiversity loss, remote sensing, sustainable agriculture, sentinel-1 SAR, land use change, climate-smart agriculture.

INTRODUCTION

The expansion of agricultural land is a key factor of environmental change; this significantly affects biodiversity in various dimensions. Due to the rising global demand for food, fiber, and biofuels driven by population pressure, the intensification of agriculture and land conversion has resulted in habitat fragmentation, endangering species, and ecosystem destruction (Cross et al., 2020). Understanding the nexus between the expansion of agricultural land and biodiversity is crucial for developing sustainable land-use policies that balance ecosystem management and food security. Therefore, integrating geospatial techniques such as satellite remote sensing, GIS-based modelling, and spatial data analysis emerges as a significant tool to analyze these dynamics and provide high-resolution data on land use changes, loss of habitat, and alterations of environmental services (Ai et al., 2024). This review expands upon existing literature, such as Ortiz et al. (2021), by integrating geospatial methods with emerging practices like climate-smart agriculture and rewilding to assess both technological applications and conservation trade-offs. Despite the attempt of many research efforts, understanding the long-term impacts of land expansion on biodiversity remains a gap, especially in areas such as tropical and subtropical regions that experience high rates of deforestation and agricultural encroachment (Andrews et al., 2024). Therefore, future studies should prioritize lasting ecological monitoring, integrate high-resolution remote sensing data, and develop a predictive model which incorporate ecological, technical, and socio-economic variables to assess biodiversity loss and habitat fragmentation more effectively.

The interrelationships among biodiversity, agriculture, climate change, trade, and policy need an approach that is systemic and integrative to efficiently address trade-offs and synergies (Ortiz et al., 2021). Despite the mechanisms of climate-smart agriculture technologies to scale up food security, minimize consumption of resources, and improve the profitability of the farm, their adoption of climate-smart agriculture remains uneven across regions as a result of technological, financial, and policy barriers (Erekalo et al., 2024). Further, several studies show that agroforestry systems such as planting cocoa highly support biodiversity unlike monoculture practices but yet fall short of conserving the Indigenous forest biodiversity (Carlier et al., 2023). However, the efforts of rewilding aiming to restore biodiversity initiate trade-offs for small-scale farmers who often face competing priorities between conservation needs and livelihood sustenance (Pandian et al., 2024). Grazing mechanisms also significantly contribute to biodiversity management, with studies indicating traditional grazing techniques enhance plant diversity while mitigating the accumulation of biomass (Pereira et al., 2023).

Additionally, geospatial analyses highlight crucial changes in land use in different regions, such as the Tawi Basin, where the settled population is estimated to rise from 5.29% in 2020 to 13.98% by 2100, resulting in a decrease in agricultural and forested lands (Pereira et al., 2023). The destruction of riparian vegetation in the Black Volta Basin as a result of human interference indicates a pressing need for restoration mechanisms, such as the establishment of buffer zones and mechanisms for sustainable land management(Yahaya et al., 2024). Remote sensing analyses of the Ngorongoro Conservation Area , similarly highlights a marked reduction in in forest cover, inhabited by human settlement and agricultural practices, raising concerns over stability of the long term based ecosystem (Mwabumba et al., 2022). This study used publicly available and open-access platforms like Copernicus Open Access Hub to access up-to-date Sentinel-1 SAR data which remains a critical tool for environmental monitoring. The rise of satellite-based datasets dependence underscores the urgency of improving data accessibility, interoperability, and validation for efficient monitoring of ecosystems(Timmermans and Kissling, 2023).

The use of geospatial techniques from previous studies highlights a crucial view of the effects of agricultural land expansions on biodiversity. The use of Sentinel-1, SAR, and deep learning models indicated high detection of forest encroachment in dry tropical forests compared to traditional Landsat-based GLAD alerts, providing detailed, clear, and on-time feedback to threats of deforestation (Lobert et al., 2021). The application of Sentinel-2 bare soil imagery together with a two-step classification technique similarly maps soil erosion effectively in croplands, accurately differentiating areas with extreme and moderate erosion (Qi et al., 2024). The heterogeneity of habitat, especially canopy height and initial productivity, has been noted as a determinant factor shaping the diversity of birds in agricultural landscapes, insisting on the significance of maintaining landscape complexity for conserving the ecosystem (Anderle et al., 2023). Additionally, the price increase of urea has been projected by studies that could increase deforestation, with an increase of 1% price linked to an approximated 97.65-ha loss of forest, affecting both tropical and subtropical ecosystems disproportionately (Kassouri, 2024).

Several studies aim mainly at species richness, neglecting broader ecological and socio-economic interlinks that influence the outcome of biodiversity (Song et al., 2025). The Sentinel-2 imagery's effectiveness in detecting grazing-induced changes in biomass remains uncertain as a result of its limitations in capturing shifts in sub-tropical vegetation (Li et al., 2021). The capacity of projecting change in land-use models such as CA-Markov remains constrained by their inability to account for external barriers such as industrialization, climate change, and socio-economic factors (Sannigrahi et al., 2020). Also, the challenge of legal restrictions and inconsistent open-data of accessing biodiversity data is another crucial factor limiting innovation and equitable sharing of knowledge (França et al., 2022). Additional

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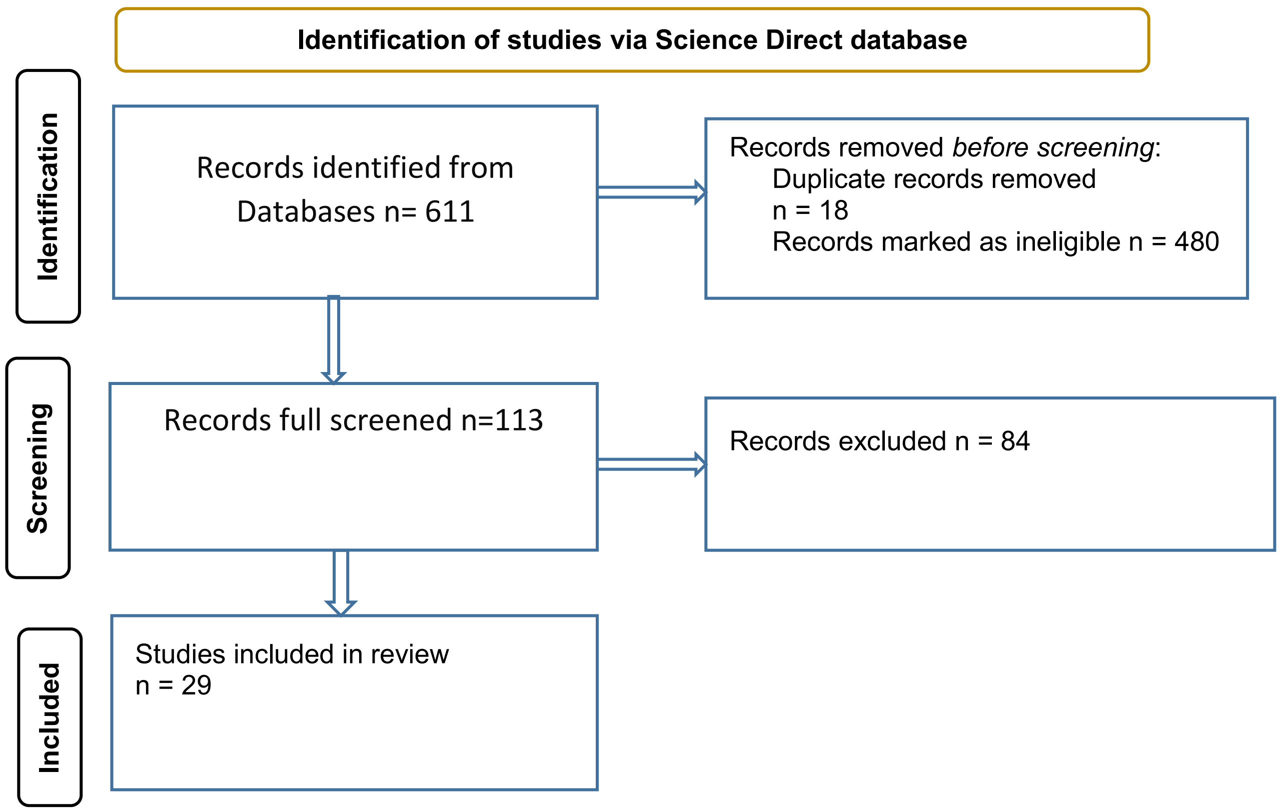

Figure 1. Illustration of PRISMA 2020 flow diagram for articles analysis criteria.

studies are needed to refine geospatial data for assessing loss of biodiversity, especially through integration of LiDAR and multispectral data to capture heterogeneity in habitats at finer scales (Comesaña-Cebral et al., 2024). Moreover, limited research has been conducted on the long-term effect of armed conflicts on ecosystems especially in areas vulnerable to deforestation and land degradation (Fernandes-Tavares et al., 2024). Deeper investigations also required in the urban land conversion for ecosystem restoration, especially pertaining the role of energy crops in reducing maintenance costs while enhancing ecosystem (Sikorska et al., 2020). Finally, despite nanotechnology holding promises for improving agricultural sustainability through precision agriculture and targeted agrochemical delivery, its large-scale field use remains limited, demanding further demonstrations and regulatory framework (Arko et al., 2024).

METHODOLOGY

This study followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Page et al., 2021) to ensure transparent and reproducible production of existing studies. The methodology comprises four key stages in this study: search strategy for the literature, study selection, extraction of data, and synthesis and quality assessment.

Search strategy

The study used a Science Direct and Google Scholar databases due to institutional access limitations to Scopus for literature search mainly focusing on review and research articles published between 2020 and 2024. A preliminary scan showed significant overlap between Google Scholar results and Science Direct-indexed articles, justifying their combined use for comprehensive coverage. The search strategy used both Boolean operators (AND, OR) and keywords ensuring a detailed coverage of relevant studies (Page et al., 2021). The search string used includes; (:("remote sensing "AND "biodiversity loss") AND ("farming "OR "agriculture") and ("satellite imagery "OR "earth observation") AND ("habitat degradation "AND "land use change")). The criteria of inclusion used in this study consisted of studies published in peer-reviewed journals, research focusing on the use of geospatial techniques in assessing biodiversity impacts, studies that included land use change, biodiversity indicators, thematic categories, farming activities, metrics used, remote sensing effectiveness, impact on biodiversity, and the remote sensing methods. The exclusion criteria comprised studies not directly addressing biodiversity loss as a result of agricultural expansion, articles without empirical validation, and policy briefs. Grey literature and studies not published in English were excluded to ensure peer-reviewed, high-quality, and language-consistent sources.

Study selection process

The selection process of this study followed the PRISMA 2020 flow diagram as shown in (Figure 1) for systematic screening. The study identified 611 articles initially, 18 duplicates were removed using

Mendeley Desktop, a reference management tool used for organizing and screening bibliographic data, resulting in 593 unique records which were exported to excel sheet for further screening. Using Excel filters, 480 records were automatically excluded based on keywords in titles and abstracts that did not align with our inclusion criteria (such as studies unrelated to biodiversity, agriculture, or geospatial tools). This step streamlined the selection process, narrowing to 113 articles. After full-text screening, 29 articles were retained for inclusion based on the defined inclusion and exclusion criteria.

Data extraction and coding

The study used Excel for data extraction structure, extracting key information from the articles selected. The data extracted consists of; study metadata, thematic categories, biodiversity indicators, farming activities, geospatial techniques, impact on biodiversity, and remote sensing effectiveness as summarized in Table 1.

Quality assessment of studies

The research applied the use of the Mixed-Method Appraisal Tool (Hong et al., 2018), to ensure methodological rigor for assessing the quality of the study based on the relevance of the objectives of the research, reliability of data and transparency, robustness of methods (use of geospatial tools, indicators of biodiversity) and the clarity of the conclusion. Each research was rated on a scale ranging from low (1) to high (5) of methodological rigor as shown in Table 2.

Synthesis and analysis of data

The data extracted in this research were synthesized both qualitatively and quantitatively to identify main patterns in agricultural land expansion and biodiversity impacts. The descriptive statistics were applied for analyses of the frequencies of the biodiversity indicators, remote sensing techniques, and the thematic trends across all research. The effectiveness of geospatial was evaluated based on the sensor's resolution, accuracy of classification, and capabilities of detection of different remote sensing datasets (Fortin et al., 2020). The study also integrated a narrative synthesis for findings across studies, highlighting similar titles, abstracts, key findings, limitations, research gaps, and future directions for studies to improve the monitoring of biodiversity using geospatial techniques (Timmermans and Kissling, 2023).

RESULTS

Detection of tropical dry forest disturbance using Sentinel-1 SAR data combined with deep learning models

Remote sensing technology has emerged as an important tool for conserving biodiversity in monitoring tropical dry forests (Mullissa et al., 2023). Integrating Sentinel-1 SAR data with deep learning models highlights finely detailed accuracy in detecting forest disturbances compared to optical-based systems mainly affected by cloud cover (Blickensdörfer et al., 2022). This technology enhances continuous and near-real-time monitoring significant for evaluating encroachment impacts on forest ecosystems (Boron et al., 2023). Figure 2, adapted from (Mullissa et al., 2023), illustrates seasonal variation using a combination of Sentinel-1 SAR and Sentinel-2 data from the Miombo woodland in Zambia, highlighting the strengths of this integrated geospatial approach.

Cocoa-Based agroforestry and biodiversity

The practice of cocoa-based agroforestry systems contributes to conserving biodiversity by supporting pollinators, fostering ecosystem resilience, and maintaining crucial shade cover for retaining species (Maney et al., 2022). The existing studies highlight that the diversification of agroforestry systems shows increased plant and avian species richness than practicing cocoa monocultures, which results in loss of biodiversity through habitat simplification (Tschumi et al., 2020). These findings underscore why the integration of ecological principles into the production of cocoa is needed to facilitate sustainability. To demonstrate how biodiversity, particularly pollinator richness, respond to landscape structure-a key element in agroforestry, Figure 3 presents data on bee diversity across heterogeneous landscapes in Europe, offering insights relevant to broader agro ecological contexts.

Rewilding and its impacts on farming practices

Rewilding mechanisms have been linked to both negative and positive agricultural outcomes. The introduction of new species such as sea eagles has resulted in the recovery of the population but has also intensified predation pressure on agricultural biodiversity, leading to conflicts between conservationists and farmers (Elphick et al., 2024). The approaches to effective rewilding should include adaptive management to balance ecological benefits with agricultural productivity.

Impacts of trade on ecosystems

Trade-offs between conservation and food production

The global trade expansion has driven extensive land-use changes, mainly at the expense of biodiversity and ecosystem services (Kastner et al., 2021). Several studies highlight that an increase in agricultural exports has increased habitat loss and deforestation, requiring policy interventions to balance economic gains with ecological sustainability (Escobar et al., 2020). The challenge in this exists in the designing of trade policies that promote sustainable production while reducing the loss of biodiversity. To demonstrate the complex links between international trade and land-use pressure, Figure 4 visualizes the life cycle stage of Brazilian soy exports between 2010 and 2015, which emphasizes the supply chain`s spatial of and ecological footprint.

Table 1. Data extraction categories.

Category	Description	Variable example
Study metadata	Information about the source and details of the study	Authors, Year, Title, Journal, DOI, Study location, Data collection period
Thematic category	The title under which the study belongs	Conservation of biodiversity in agricultural systems, climate change and food security, policies and sustainable agriculture, smart farming, RS in biodiversity assessments, circular bioeconomy
Biodiversity indicator	Measures used to assess biodiversity	Species Richness, pollinators presence, quality of habitat, Degradation of the forest, biodiversity intactness index (BII), ecosystem services, vegetation diversity, Diversity of bird indices, restoration of riparian vegetation, Emissions of Ammonia
Farming activities	Agricultural practices analyzed in the study	Sustainable farming, agroforestry, conventional farming, nitrogen fertilization management, optimization of crop yield, cocoa monoculture, grazing, management, precision agriculture, pastoral livestock production, Fertilizer and pesticide application
Land use change	Examined land use transformation types	Deforestation, urbanization, agricultural expansion, land abandonment, cultivation of crop energy, Forest to agricultural land conversion, intensification of sustainable agriculture, transitions of land use
Metrics used	Methods and indicators for measuring study outcomes	Emissions of Greenhouse Gases (GHG), Normalized Difference Vegetation Index (NDVI), land use change, water scarcity, biodiversity impact, remote sensing metrics (Sentinel-1, SAR Data, NDVI, Enhanced Vegetation Index(EVI)), rate of soil erosion, Food production and conversion trade-offs, genetic vulnerability.
Remote sensing effectiveness	Methods of evaluating RS in assessing biodiversity and land use	Sentinel-1 SAR Data, NDVI Analysis, LiDAR Rao`s Q Indices, measurements of canopy heights, classifications of land cover time-series, Black Marble HD Nighttime Lights Dataset, Space-for-Time substitution
Impacts on biodiversity	Land use and agricultural practices impacts on biodiversity	Forest loss, changes in species richness, fragmentations of habitat, emissions of Ammonia, nanomaterials effects, rewilding impacts on farming, natural forest decline
Remote sensing methods	Biodiversity assessment and land monitoring techniques	Analysis of satellite imagery, Accurate classification of Land Use and Land Cover (LULC), Error of proportionate metrics, Probability of transitional matrix, NDVI Thresholding, Unmanned Aerial Vehicle (UAV) Remote Sensing, Thermal Imaging

Land-use transitions and their impact on biodiversity

The transitions of land use from agriculture to urban settlements and industrial zones have decreased biodiversity intactness indices (BII) severely, resulting in ecosystem fragmentation (Maney et al., 2022). The application of remote sensing has critically provided insight into these transitions, enhancing policymakers to develop land-use strategies (Wulder et al., 2022). Table 3 presents the changes in land cover (in square kilometers) in the Bosomtwe District, Ashanti Region of Ghana from 2002 to 2022. The data reveals a substantial reduction in forest area from 207.3 km^2 in 2002 to 116.8 km^2 in 2022, while built-up areas increased from 13.9 to 84.2 km^2 –

Table 2. Quality assessment of included studies using the mixed methods appraisal tool (MMAT).

Study ID No.	Study design	Relevance to research objectives (1-5)	Data reliability and transparency (1-5)	Geospatial tools, biodiversity indicators (1-5)	Clarity of conclusion (1-5)	Overall average rating	References
1	Qualitative	4	4	3	4	3.75	Ortiz et al. (2021)
2	Quantitative	4	4	5	5	4.5	Mullissa et al. (2023)
3	Quantitative	5	4	3	4	4	Cesco et al. (2023)
4	Mixed research	4	5	3	4	4	Maney et al. (2022)
5	qualitative	5	4	5	4	4.5	Duckett et al. (2022)
6	Mixed research	4	5	5	4	4.5	Segarra et al. (2023)
7	Quantitative	4	4	5	5	4.5	Taloor et al. (2024)
8	Qualitative	4	4	3	5	4	Gepts (2023)
9	Quantitative	5	5	5	4	4.75	Chamorro-Padial et al. (2024)
10	Qualitative	5	4	5	4	4.5	Qi et al. (2024)
11	Quantitative	4	4	5	5	4.5	Anderle et al. (2023)
12	Mixed research	4	4	5	5	4.5	Negash et al. (2023)
13	Quantitative	4	5	3	5	4.25	Labadessa et al. (2023)
14	Mixed research	3	5	3	5	4	Sikorska et al. (2020)
15	Quantitative	4	4	3	4	3.75	Li and Lei (2023)
16	Mixed Research	4	5	5	4	4.5	Pereira et al. (2023)
17	Quantitative	5	4	5	4	4.5	Kassouri (2024)
18	Mixed research	4	4	5	4	4.25	Yahaya et al. (2024)
19	Quantitative	4	4	5	5	4.5	Akram et al. (2022)
20	Quantitative	4	4	5	5	4.5	Karimi et al. (2020)
21	Quantitative	5	5	5	4	4.75	Mwabumba et al. (2022)
22	Mixed research	4	4	5	4	4.25	Chukalla et al. (2024)
23	Quantitative	4	4	5	5	5.5	Ge et al. (2023)
24	Qualitative	5	4	5	4	4.5	Yadav et al. (2023)
25	Mixed research	4	5	5	5	4.75	Cesco et al. (2023)
26	Qualitative	5	4	5	4	4.5	Safdar et al. (2023)
27	Quantitative	5	4	5	5	4.75	Veisi Nabikandi et al. (2024)
28	Mixed research	4	4	5	4	4.25	Kan et al. (2023)
29	Qualitative	4	4	5	5	4.5	Pettersson et al. (2024)

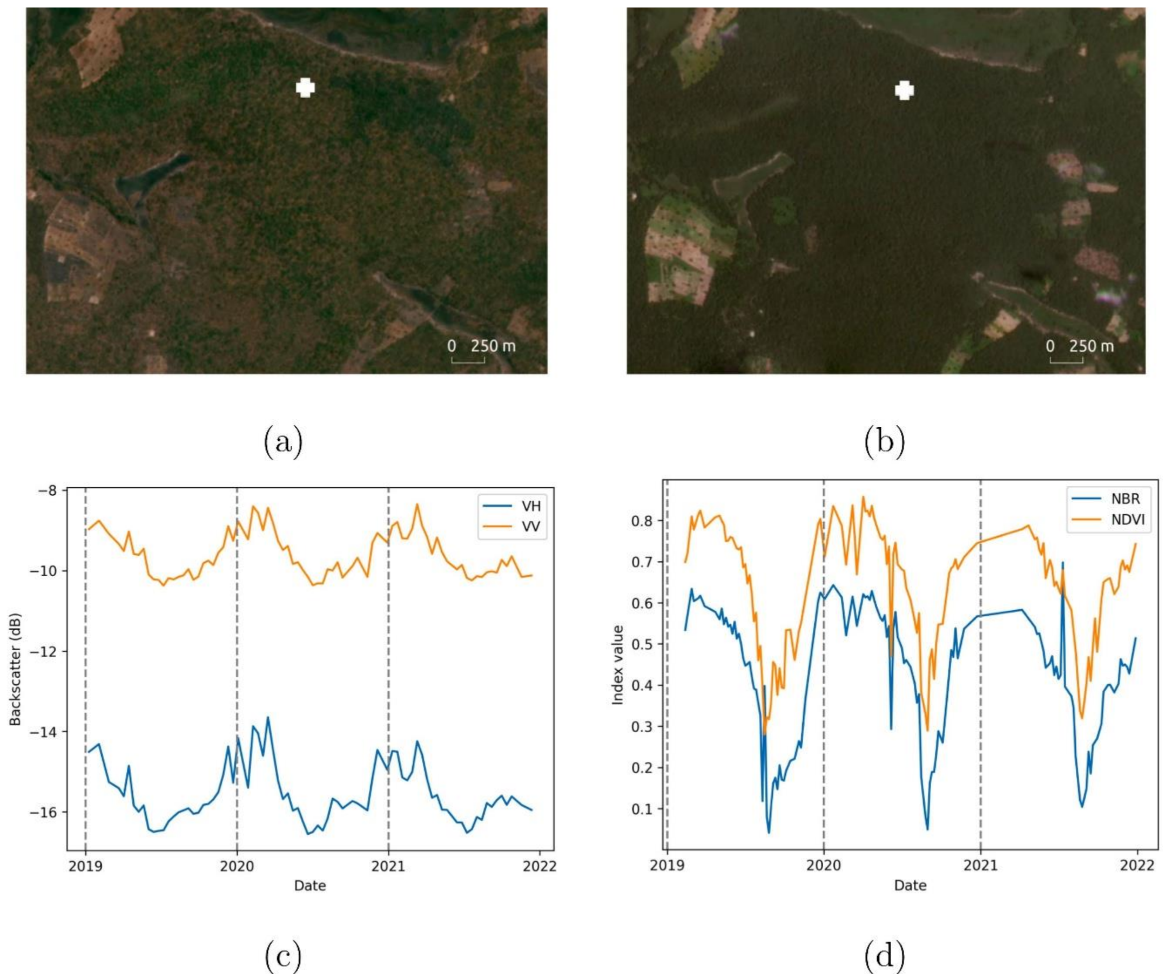

Figure 2. Seasonal comparison of dry forest vegetation using PlanetScope, Sentinel-1 SAR, and Sentinel-2 NDVI/NBR data in Zambia`s Miombo woodland.
Source: Mullissa et al. (2023).

highlighting rapid urban expansion at the expense of natural ecosystems. To project future land use patterns and their impacts for biodiversity, Table 3 indicates a land-use transition probability matrix. These values represent the likelihood of each land class in 2022 transitioning into another class in future time steps as shown in Table 4, for instance, there is a 56.38% chance that agricultural land will remain agricultural, but a 41.24% chance that, this land will transition to built-up land, further stressing ecosystem integrity.

Climate change and food security

Smart agriculture and digital twins for crop nitrogen fertilization

The advancement in climate-smart agriculture through digital twin technology has resulted in the transformation of nitrogen fertilization management. The application of digital twin technology contributes to continuous real-time data updates facilitating dynamic and accurate decision making. The digital twin technology in agriculture integrates with sensor data, machine learning models, and satellite imagery to simulate the growth of crops and nitrogen demand enhancing the efficiency of fertilizer application and sustainability (García-Soria et al., 2024). The significance of using digital twins technology in the management of nitrogen; maximizes the application of nitrogen by predicting nitrogen requirements in crops based on environmental conditions, mitigates nitrogen leaching into groundwater resulting in reduced emission of nitrous oxide (N_2O) a potent greenhouse gas, and improving crop yields and economic returns by enhancing plant health and productivity while decreasing costs of inputs for farmers. To demonstrate the spatial variability in crop yield stability, Figure 5 presents a sub-field scale yield stability map covering 30 million hectares in the U.S. Midwest. This visualization exemplifies how digital agriculture technologies, such as digital twins, enhance

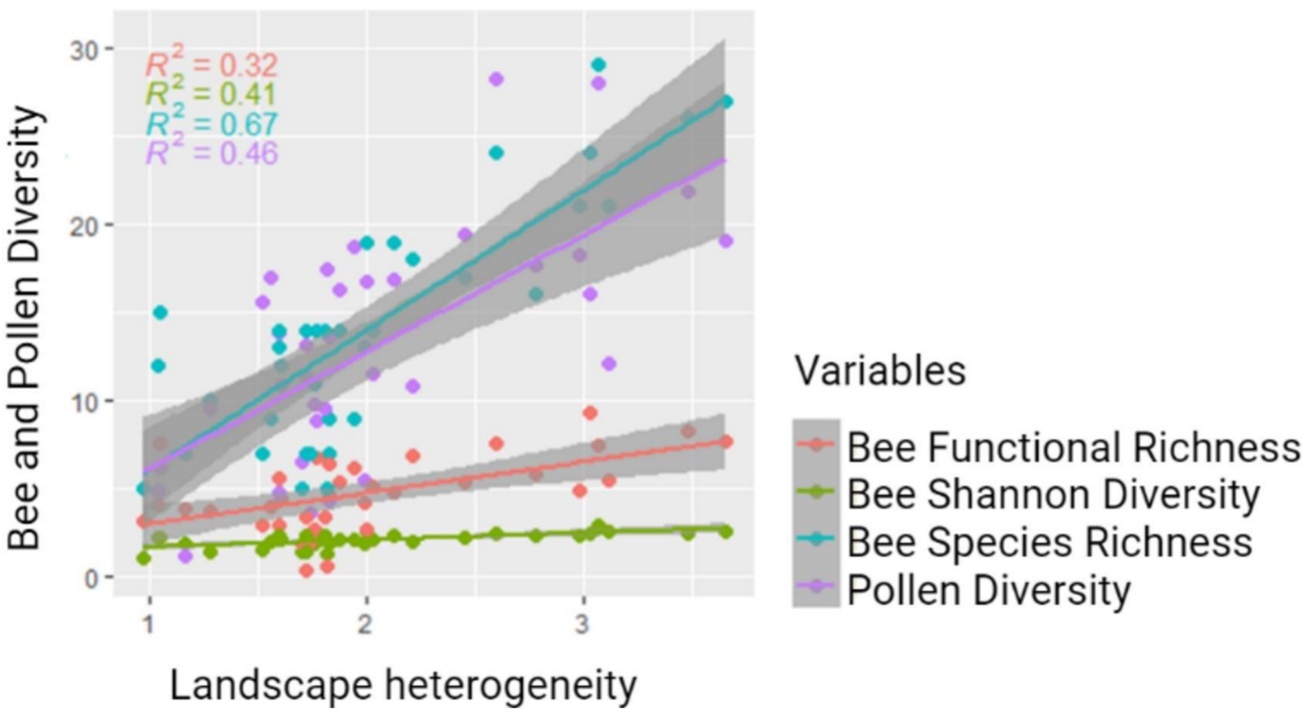

Figure 3. Functional richness, species richness, and Shannon diversity of index bees collected at 36 grassland plots in Germany and Belgium, demonstrating relationships with landscape heterogeneity.
Source: Parreno et al. (2024).

site-specific management and support sustainable intensification.

However, despite these benefits, high implementation costs, the complexity of data integration, and the technological accessibility in smallholder farming systems remain challenges. Therefore, addressing these challenges through government policies, incentives, and public-private partnerships is crucial for high rate of adoption.

Nitrogen budgeting and agricultural productivity

Nitrogen budgeting is a systematic strategy for managing nitrogen inputs and outputs in agricultural systems to facilitate NUE and mitigate nitrogen loss to the environment. This requires nitrogen supply such as from fertilizers, manure, and biological fixation with crop demand, minimizing excess nitrogen does not result in soil degradation, water pollution, or emission of greenhouse gases (Karimi et al., 2020). The key nitrogen budgeting approaches include; Site-Specific Nitrogen Management (SSNM), Integrating Fertilizer Management (IFM), and Cover Crop and Crop Rotation (CCCR).

According to Karimi et al. (2020), nitrogen budgeting efficiency in Canada decreased nitrogen loss by approximately 50% while maintaining or increasing crop productivity. However, challenges remain due to improper budgeting, which results in under-fertilization and yield decreases or over-fertilization and subsequent soil and water contamination.

Therefore, educating farmers, policy support, and real-time data monitoring technologies are crucial for optimizing the benefits of nitrogen budgeting.

Sustainable agriculture and policy

Sustainable agriculture is a key factor in addressing the challenges of climate change, biodiversity loss, and resource depletion while facilitating long-term food security. Efficient policies and creative land management strategies are determinant factors in balancing agricultural productivity with ecosystem conservation. The key components of sustainable agriculture include land use changes, circular bio-economy models, grazing system designs, and riparian vegetation restoration, along with policy integration, technological advancements, and socio-economic considerations.

Land Use and Land Cover (LULC) change

Changes in land use and land cover have significant impacts on agricultural sustainability, affecting soil health, water resources, carbon sequestration, and biodiversity.

Table 3. Land class area cover (km^2) in the Bosomtwe District-Ghana (2002-2022).

Land use transition (km^2)	2002	2008	2016	2022
Agriculture	144.3	94.4	46.7	168.0
Bare land	8.1	5.1	12.2	5.6
Built up	13.9	27.4	88.0	84.2
Forest	207.3	247.8	227.8	116.8
Water	48.8	47.9	47.9	47.7
Total	422.6	422.6	422.6	422.6

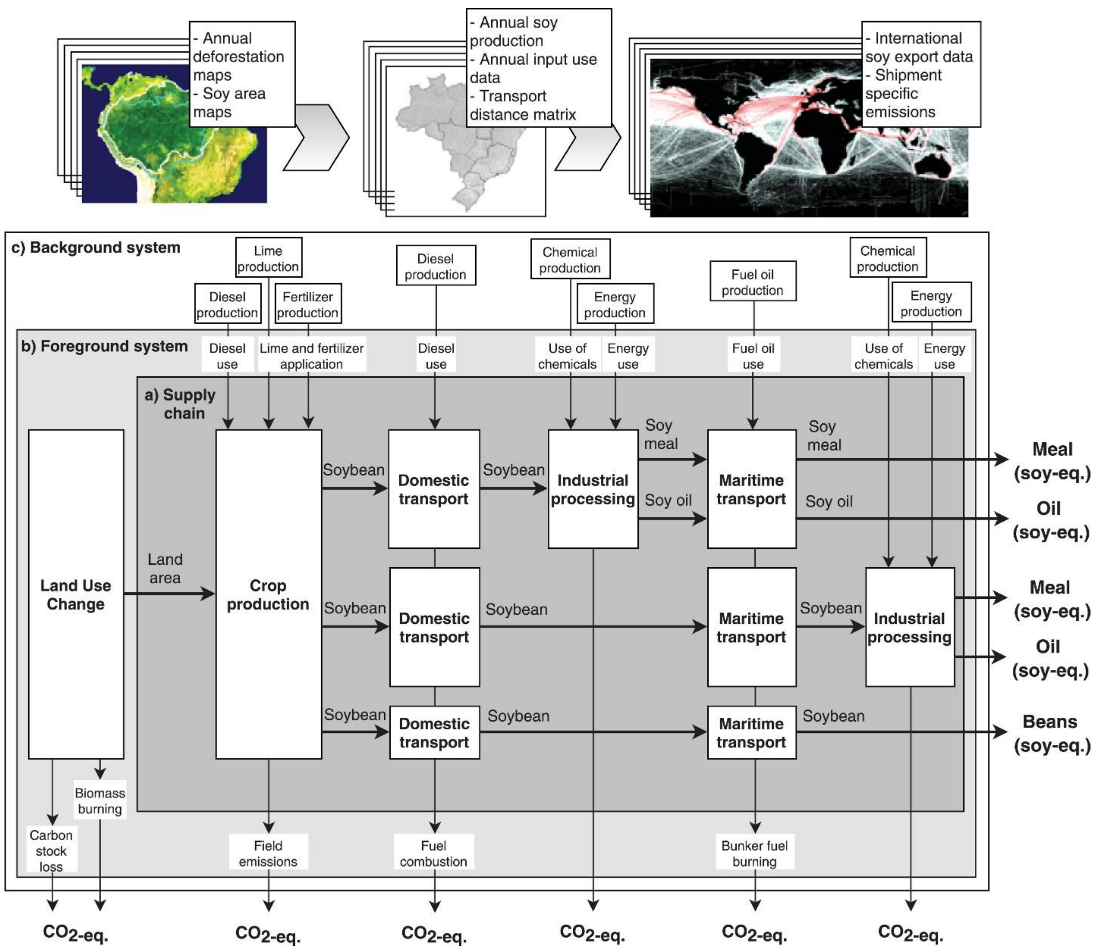

Figure 4. system boundaries and life cycle inventory stages of Brazilian soy for export between 2010-2015, demonstrating land-use impacts across trade-driven agricultural systems.
Source: Escobar et al. (2020).

Expanding croplands, urban sprawl, and deforestation alter ecosystem services, resulting in soil degradation, decreased water availability, and habitat loss (Zvobgo and Tsoka, 2021). Remote sensing technologies, such as satellite imagery and GIS-based models, monitor changes in land use and land cover by providing high-resolution spatial and temporal data for evidence-based policy decisions. Recent studies, for example, Singh et al. (2024), highlight that deforestation for agricultural expansion has resulted in reduced carbon sequestration, accelerating climate change. This is demonstrated in Table 6, which indicates LULC change detection between 1991 and 2020 in the lower Son River Basin, India, illustrating trends in agricultural land increase and vegetation decline. Furthermore, urban encroachment into agricultural lands alters food security, increases water resource competition, and shifts crop patterns due to climate variability, requiring adaptive land-use policies.

Table 4. Transition probability matrix for future land use (unitless probabilities due to land transitions).

Land use transition (km^2)	Agriculture	Bareland	Built up	Forest	Water
Agriculture	0.5638	0.005	0.4124	0.0189	0
Bare land	0.4994	0.4109	0.0853	0.0045	0
Built up	0.0069	0.0105	0.9825	0	0
Forest	0.3312	0.0103	0.0511	0.6074	0
Water	0.0081	0.0068	0.0009	0	0.9842

Source: Adjei and Antwi (2023).

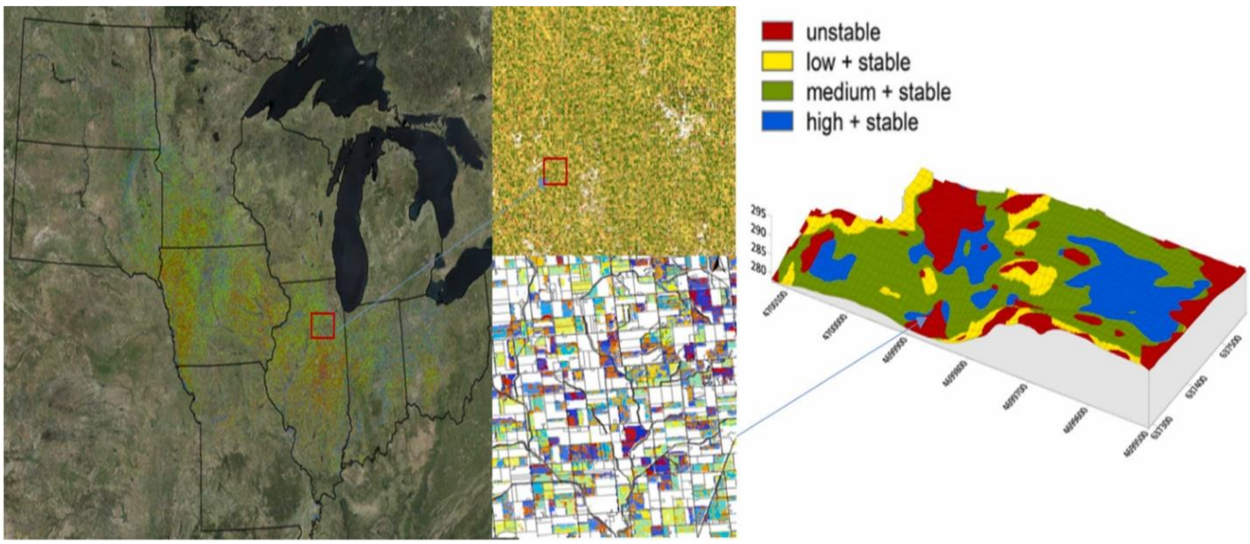

Figure 5. Crop yield stability a sub-field scale of 0.09 ha (photos in the lower corner) for 30 million hectares across the US Midwest (US Midwest map). Yield stability map is partitioned in Low Stable Zones (LS yellow), High Stable Zones (HS blue), Medium Stable Zones (MS green), and Unstable (U red).
Source: Cesco et al. (2023)

Figure 6 complements this by presenting the spatial distribution of land cover changes across zones from 1991 to 2020.

Therefore, enhancing policy frameworks that support agroforestry, agricultural management, and land restoration programs is crucial for mitigating the negative impacts of LULC changes while ensuring sustainable land management.

Circular bioeconomy and waste valorization

The use of the circular bioeconomy model emerges as a transformative technology in agricultural sustainability, enabling effective resource utilization, waste reduction, and value recovery. Compared to the traditional linear economy, where resources are extracted, used, and disposed of, the circular bioeconomy integrates bio-waste valorization, production of renewable energy, and practices of regenerative agriculture (D’Amato and Korhonen, 2021). The main necessities required for waste valorization include biofertilizers from agricultural waste, biogas production from livestock waste, and the upcycling of crop by-products into animal feed, biochar, or biodegradable packaging materials. Therefore, governments and stakeholders are required to implement financial incentives, regulatory frameworks, and research investments to increase the rate of circular bioeconomy adoption among smallholder farmers.

Grazing system design and ecosystem health

The management of sustainable grazing is significant for conserving soil integrity, maintaining biodiversity, and mitigating the impacts of climate change. Overgrazing causes soil erosion, loss of vegetation cover, and desertification, while under grazing may decrease soil fertility and biodiversity (Rybchak et al., 2024). Recent advancements in GIS-based decision-making tools

Table 5. Estimate of annual symbiotic nitrogen fixation in Canadian agro ecosystems in 2016.

Crop	Harvested area	Total N uptake[a]		Biological N_2 fixation			%NDFA source
	million ha	Gg	kg N/ha/yea	%NDFA	Gg	kg N/ha/year	
Soybean	2.18	427.1	196	55	234.9	108	Yang et al. (2010)
Peas (dry)	1.69	394.6	234	54	213.1	126	Hossain et al. (2017)
Beans (dry field)	0.11	10.5	96	40	4.2	38	Hossain et al. (2017)
Lentils	2.32	173.8	75	53	92.1	40	Hossain et al. (2017)
Tame hay (other)	2.10	250.7	119	10	25.1	12	Janzen et al. (2003)
Tame hay (alfalfa & mix)	4.02	524.9	130	66	346.4	86	Yang et al. (2010)
Forage for seed	0.16	3.6	22	20	0.7	4	Janzen et al. (2003)
Vegetables	0.11	22.1	202	5	1.1	10	Janzen et al. (2003)
Other field crops	0.08	13.5	171	5	0.7	9	Janzen et al. (2003)
Faba bean	0.02	3.2	193	67	2.1	129	Hossain et al. (2017)
Chickpea	0.04	4.8	118	52	2.5	61	Hossain et al. (2017)
Pasture (natural land)	14.26	291.2	20	2	5.8	0	Janzen et al. (2003)
Pasture (tame/seeded)	5.08	187.7	37	5	9.4	2	Janzen et al. (2003)
Total					938.2		

Source: Karimi et al. (2020).

enable farmers and policymakers to optimize stocking rates and identify rotational grazing patterns that facilitate carbon sequestration and pasture growth. For example, the study "Improving Spatial and Temporal Variations of Ammonia Emissions for the Netherlands Using Livestock Housing Information and a Sentinel-2-Derived Crop Map" demonstrates how GIS-based tools, combined with remote sensing data, enhance agricultural land use planning by accurately mapping livestock distribution and emissions (Ge et al., 2023). Such applications indicate the potential of GIS in sustainable pasture management by integrating spatial data for better decision-making regarding stocking density and rotational grazing.

Riparian vegetation restoration and collaborative efforts

Riparian areas adjacent to rivers and streams are determinant in water filtration, controlling erosion, and conserving biodiversity. However, human activities such as deforestation, agricultural runoff, and urbanization significantly degrade ecosystems resulting in reduced water quality, flood risk increase, and loss of biodiversity (Yahaya et al., 2024). The highlighted approaches for restoring riparian vegetation include; reforestation and buffer strip establishment, community-led restoration programs, and policy-driven conservation initiatives. Therefore, the successful case studies highlight that integrating ecological restoration with community participation and regulatory enforcement results in long–term environmental and economic benefits. The governments, farmers, and environmental organizations' collaborations is important for scaling up these efforts.

Metrics used in analysis

The studies reviewed used different metrics to assess the conservation of biodiversity, land use, and agricultural sustainability which consists of emissions of greenhouse gas (GHG), to evaluate the contributions of agriculture to climate change. For example, GHG emission metrics used to quantify the contribution of agriculture to climate change. The analysis focused on emissions from soil management, livestock production, and the use of synthetic fertilizers (Saha et al., 2023). The normalized difference vegetation index (NDVI) is used to assess vegetation cover changes and ecosystem health, by measuring the difference between near-infrared, NDVI helps to track vegetation changes over time, serving as a proxy for land degradation. For example a study conducted in the Amazon rainforest (Zhao et al., 2022) utilized NDVI combined with GIS to assess vegetation dynamics and deforestation patterns. The study found that NDVI provided a reliable index for detecting changes in vegetation health, highlighting significant degradation in deforested areas, and showing the impact of agricultural expansion on ecosystem health. Nitrogen Use Efficiency (NUE) used to quantify the environmental impact of nitrogen fertilization in agriculture. This measures how effectively plants utilize nitrogen, reducing excess nitrogen runoff that can contribute to environmental pollution particularly in aquatic ecosystems. Remote sensing and satellite data essential for monitoring large-scale land use changes, forest degradation, and ecosystem disturbances. For example, a study in Southeast Asia (Liu et al., 2022) used remote sensing and GIS to monitor land use changes in tropical forest areas, correlating NDVI with higher rate of

Table 6. LULC change detection from 1991 to 2020, A case of Lower Son River Basin, India.

Category	1991		2000		2010		2020	
	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%
Agricultural land	1.779.993	36.648	1.890.967	38.933	1.982.895	40.826	2120.471	43.658
Barren land	143.263.7	2.950	125.186.3	2.577	124.603.7	2.565	12.389.67	0.255
Settlement	20.642.13	0.425	41.756.04	0.860	94.024.64	1.936	147.475.8	3.036
Sediment/Sand	65.333.25	1.345	75.969.9	1.564	55.167.94	1.136	44.269.47	0.921
Vegetation	2.723.354	56.071	2.595.265	53.434	2.470.647	50.868	2.395.941	49.330
Waterbody	124.370.8	2.561	127.812.1	2.632	129.618.6	2.669	136.409.9	2.809

deforestation, highlighting how remote sensing can effectively track ecosystem disturbances and guide conservation efforts.

DISCUSSION

The evidence from selected studies suggests that the use of remote sensing-especially the integration of Sentinel-1 Systematic Aperture Radar (SAR) data with deep learning models offers promising advancements for detecting tropical forest disturbances by enable more clear and near-real-time monitoring of forest health (Blickensdörfer et al., 2022; Mullissa et al., 2023). SAR data is mainly valuable in tropical regions where persistent cloud cover impedes the effectiveness of optical-based systems, providing consistent and weather-independent imagery. Notable freely accessible SAR sources such as ESA`s Sentinel-1 via the Copernicus open Access Hub, ALOS PALSAR from JAXA, and the upcoming NASA NISAR mission, while commercial sources such as RADARSAT, TerraSAR-X, ICEYE, and Capella Space offer higher-resolution data at varying costs, mainly ranging from $100 to $500 per scene. Access to these datasets is generally through online portals or APIs, and processing mostly requires tools like SNAP, ENVI SARscape, or platforms like Google Erath Engine. However, despite the strengths of deep learning in classification accuracy, it is crucial to note that these findings are based on a relatively limited set of review articles and should be interpreted cautiously pending broader empirical validation. Additionally, relying only on deep learning can be limiting; other adaptive models such as random forests, support vector machines (SVM), and gradient boosting algorithms which also shows high performance and merit comparative exploration. Challenges persist in SAR data aggregation, speckle noise reduction, and temporal analysis, and the high demand of computing of advanced models which remains a barrier in limited resource settings. A more diverse methodological approach and equitable access to both data and tools of computing are essential to realizing the full potential of SAR- based forest monitoring systems in biodiversity conservation.

Cocoa-based Agroforestry and Biodiversity Conservation systems have shown to be more effective for biodiversity conservation compared to monoculture cocoa plantations. These agroforestry system support a greater diversity of species, providing essential ecosystem services like pollination and improving soil health (Tschumi et al., 2020).

However, the adoption of such systems is hindered by the higher immediate economic returns offered by monoculture cocoa farming, which remains the dominant practice in many regions. Policymakers must therefore create strategies that incentivize the adoption of cocoa-based agroforestry, balancing the ecological benefits with economic viability.

Additionally, further studies into the long-term environmental and economic outcomes of cocoa agroforestry, particularly in terms of enhancing resilience to climate change through the inclusion of indigenous species, is necessary to facilitate wider implementation (Maney et al., 2022).

Rewilding initiatives, which focus on the reintroduction of native species to restore ecosystems, present both ecological advantages and challenges for agricultural practices. The reintroduction of species, such as sea eagles, has proven beneficial for biodiversity but has led to conflicts with farmers, particularly when these species impact crop yields or livestock (Elphick et al., 2024). These conflicts highlight the need for adaptive management strategies that strike a balance between ecological restoration and agricultural productivity. Effective rewilding policies must incorporate compensation mechanisms for farmers and ensure comprehensive monitoring frameworks are in place to address the potential negative impacts of rewilding on agricultural activities. Without these measures, the long-term success and sustainability of rewilding projects may be compromised.

The impact of trade on ecosystem sustainability is profound, with the expansion of global agricultural trade contributing significantly to land-use changes that threaten biodiversity and ecosystem services. The focus on monoculture farming for export has intensified habitat loss and deforestation, creating trade-offs between economic benefits and environmental sustainability (Escobar et al., 2020; Kastner et al., 2021). Policymakers must prioritize sustainability when designing trade

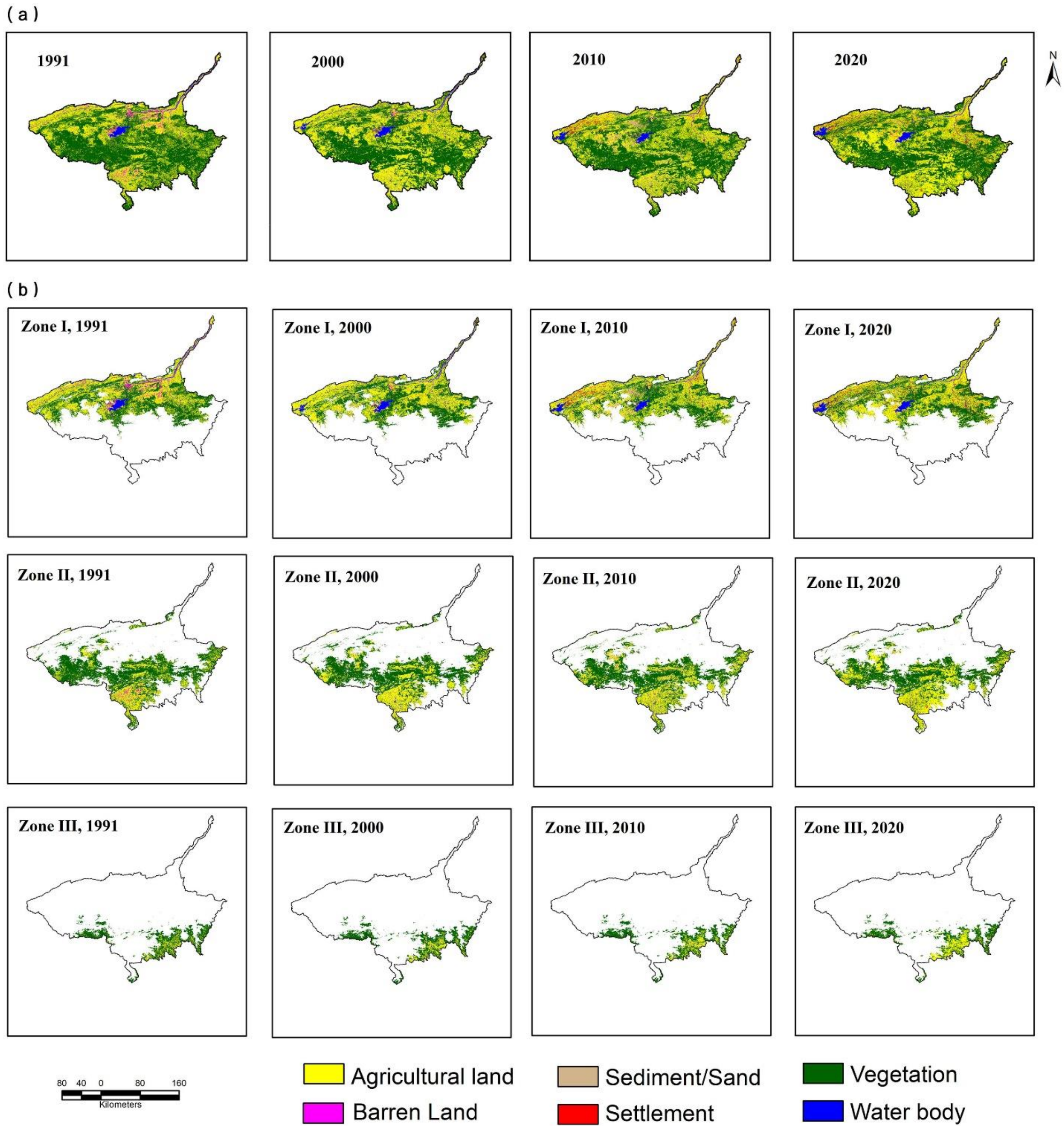

Figure 6. (a) LULC classification, 1991–2020, (b) Zone-wise LULC classification, 1991–2020.
Source: Singh et al. (2024).

agreements, integrating environmental safeguards to mitigate the impacts of export-driven land-use changes. The promotion of sustainable agricultural practices, such as agroforestry, and the establishment of certification systems for sustainable products are essential to align global trade demands with ecological preservation.

Climate change and food security are increasingly being addressed through digital technologies, such as digital twins, which optimize agricultural practices by integrating real-time data from sensors, satellite imagery, and machine learning models. These technologies facilitate precise nitrogen management, improving crop yields while minimizing environmental impact (García-Soria et al., 2024). However, the high costs and technological complexity of these systems limit their widespread adoption, particularly among smallholder farmers. To overcome these barriers, government policies that include subsidies, public-private partnerships, and incentives are necessary to make these technologies more accessible. Furthermore, nitrogen budgeting practices, such as Site-Specific Nitrogen Management (SSNM) and crop rotation, are essential for improving nitrogen use efficiency and reducing environmental pollution.

However, challenges in the implantation of these practices remains, particularly due to a lack of farmer knowledge and inadequate monitoring tools.

Finally, sustainable agriculture and policy integration are key to addressing the interconnected challenges of climate change, biodiversity loss, and food insecurity. Effective policy frameworks that promote sustainable land management practices, such as agroforestry and waste valorization, are crucial for achieving long-term sustainability in agricultural systems (Zvobgo and Tsoka, 2021). The adoption of circular bio economy models, which focus on recycling agricultural waste and improving resource efficiency, offers a promising strategy for enhancing sustainability (D'Amato and Korhonen, 2021). However, transitioning to a circular bio economy requires strong financial incentives, robust regulatory frameworks, and increased research investment, particularly in smallholder farming systems. Without these supportive measures, the shift to more sustainable agricultural practices will likely be slow and uneven.

Conclusion

The integration of advanced technologies and sustainable agricultural practices presents significant opportunities for addressing environmental challenges. Remote sensing, including Sentinel-1 SAR data, significantly enhances monitoring of forest disturbances; however, broader integration of diverse satellite platforms, such as optical and radar, is necessary. This integration also requires addressing challenges related to data aggregation, resource limitations, and accessibility of open-source versus commercial datasets. Cocoa-based agroforestry offers ecological benefits but needs economic incentives for wider adoption. Rewilding efforts require adaptive management to balance ecological restoration with agricultural productivity. The impact of global trade on ecosystems necessitates sustainable practices and policies.

Climate-smart technologies, like digital twins, improve food security but require broader adoption through supportive policies. Sustainable agriculture and circular bio economy models are key to long-term sustainability, but financial and regulatory frameworks are needed to enable the transition. Therefore, future studies should focus on examining the long-term ecological and economic impacts of agricultural expansion on biodiversity loss and exploring adaptive management strategies to balance ecological restoration with agricultural productivity.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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