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Analysing the Spatial Patterns of Agricultural Intensification and Its Implications for Land Degradation and Water Resource Management Using Remote Sensing and GIS Technologies Across Diverse Agroecosystems

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This study examines the spatial patterns of agricultural intensification and their associations with land degradation and water resource management within agroecosystems. It focuses on various regions of China, including Beijing, Shanghai, Guangdong Province (encompassing Guangzhou and Shenzhen), Sichuan Province, and the Tibet Autonomous Region, over a 15-year period (2008-2022). Employing remote sensing and Geographic Information System (GIS) technologies, the research maps land cover and analyses its changes during the specified timeframe. The findings reveal significant regional variation in agricultural intensification, where agricultural expansion is linked to increased production and resource consumption. Local agricultural practices are shaped by climate, soil conditions, and social factors, resulting in distinct water consumption patterns that highlight water stress across agricultural areas. This underscores the need for sustainable water management, as regions with high agricultural output may face heightened water scarcity and competition for limited resources. Addressing these challenges necessitates integrated strategies that consider agricultural practices, water resource management, and environmental sustainability to preserve ecosystems, enhance water use efficiency, and ensure the availability of water for both agricultural and non-agricultural needs. The study underscores the importance of spatial analysis in agricultural planning and resource management for informed and sustainable landscape management. By utilizing a rigorous analytical framework and advanced spatial analysis techniques, this research provides insights into the complex spatial relationships between agricultural intensification, land degradation, and water resource management, thereby aiding policymakers and stakeholders in tailoring solutions to mitigate the adverse effects of agricultural intensification on land and water resources.

Keywords: Agricultural Intensification, Land Degradation, Water Resource Management, Spatial Analysis, GIS.

Introduction

Land degradation exacerbates food insecurity and biodiversity loss. Activities such as deforestation, urbanisation, unsustainable agricultural practices, and overgrazing contribute to the erosion of fertile soil, adversely impacting ecosystems globally. The ongoing decline in land quality reduces agricultural yield, biodiversity, and resilience to environmental shocks (Dalantai et al., 2021; Du et al., 2023). This degradation, driven by processes including soil erosion, salinization, desertification, and the loss of vegetation, poses significant challenges to sustainable development. Both human activities and environmental disturbances contribute to land deterioration. Major drivers of global land degradation include industrial pollution, expanding infrastructure, and intensive farming. The resulting loss of arable land and agricultural productivity threatens food security and exacerbates poverty and social inequality (Karimov et al., 2023).

Land degradation compromises essential ecosystem services, including pollination, water purification, and climate regulation, due to its detrimental impact on biodiversity. These consequences underscore the urgent need for global efforts to halt land degradation and promote sustainable land management practices, ensuring the health and productivity of terrestrial ecosystems for future generations. Intensive agricultural practices exacerbate soil degradation and pose significant risks to food security (Cheng et al., 2016; Halmy, Fawzy, & Nasr, 2020). While agricultural intensification aims to increase output per unit area to meet the demands of a growing population, such approaches can degrade land, thereby undermining ecosystems and food production. This highlights the need to understand the driving forces behind agricultural intensification and develop strategies to navigate this complex landscape. The expansion of agriculture is influenced by various environmental, social, and economic factors (Karimov et al., 2023; Li et al., 2020).

Farmers are driven to expand cultivation and boost yields by changing dietary habits, market demands, population growth, and food consumption. Intensive agriculture, supported by fertilisers, technology, government incentives, and irrigation, enhances land productivity (Gumma et al., 2022). This approach involves automation, monoculture, irrigation, high-yield crops, fertilisers, and pesticides, benefiting from economies of scale. Agricultural intensification can increase food production, raise farmer incomes, and improve food security at community and national levels. Precision agriculture further optimises resource use and minimises environmental impact. Additionally, increased agricultural output and rural employment stimulate economic growth. However, intensification poses significant risks, including soil erosion, water depletion, pollution from pesticide use, and biodiversity loss (Elbeih, 2021; Meza et al., 2021).

Monoculture and high-input agriculture face threats from pests, diseases, and climate change, jeopardising food security. This focus may also marginalise smallholder farmers in favour of large commercial operations, displacing rural communities (Rashid et al., 2023). Natural agroecological methods that restore ecosystems and diversify agriculture should be promoted. To address global challenges, stakeholders can build food systems that are productive, resilient, and environmentally sustainable, with adaptive intensification playing a supportive role. Agriculture influences sustainability through water management, land degradation, and intensification. While intensive farming increases output, it also depletes water and land resources (Pásztor, 2021).

Monoculture practices and pesticide use exacerbate soil erosion, nutrient runoff, and the degradation of water quality in both terrestrial and aquatic ecosystems (Muhoyi & Muhoyi, 2023). To mitigate the land and water impacts associated with agricultural intensification, effective water management is essential. Strategies such as integrated water resource management, water-saving technologies, and efficient irrigation systems can alleviate water scarcity and reduce environmental harm. Additionally, the use of cover crops, agroforestry, and contour tillage can conserve soil and water resources. Addressing the interconnected challenges of intensification, land degradation, and water management requires an integrated approach that considers the complexities of agricultural systems, ecosystems, and socio-economic factors. This necessitates multi-stakeholder collaboration, knowledge sharing, capacity building, and the implementation of sustainable land and water management practices in agricultural policy and development (Ali et al., 2021; Weslati, Bouaziz, & Serbaji, 2020). A comprehensive understanding of these interrelated issues can enable stakeholders to develop resilient and sustainable food systems, safeguarding the well-being of future generations and the health of terrestrial and aquatic ecosystems (Luo et al., 2021).

Remote sensing and GIS provide timely and region-specific data to address complex environmental challenges such as land degradation and water management. Aircraft and satellite observations facilitate the monitoring of Earth's surface and atmospheric conditions. GIS visualises landscape structures, relationships, and changes, enabling the tracking of land degradation, vulnerability, and transformations over time. Satellite imagery and LiDAR data are employed to map land cover, land use, soil erosion, vegetation health, and water quality. GIS integrates socioeconomic and environmental data to support spatial analysis, informing effective land and water management strategies (Liang et al., 2023).

China's geographic, hydrological, and ecological challenges present significant opportunities for the application of remote sensing and GIS technologies. The rapid pace of urbanisation, industrialisation, and agricultural expansion has led to increased land degradation, soil erosion, and water pollution across the country. Remote sensing and GIS can effectively monitor these issues by tracking changes in ecosystems, soil erosion, water quality, and land use. However, despite global advancements in these technologies, their application in China remains limited. There is a shortage of geospatial and temporal remote sensing data for comprehensive land and water monitoring. Although China has made substantial investments in remote sensing satellite systems, challenges related to data sharing, processing, and institutional coordination may impede effective environmental management (Daba & You, 2022; Malav et al., 2022; Sourn et al., 2022).

Policymaking in China often lacks remote sensing and GIS expertise. Improved data access, interdisciplinary collaboration, and training in these technologies could help address land and water degradation. Remote sensing and GIS can empower rural and impoverished communities to manage their environment, integrating traditional knowledge and local participation. Addressing these gaps can enhance China's land and water management, support sustainable development, and protect ecosystems and human well-being (Salhi et al., 2023; Verma et al., 2022).

This study leverages remote sensing and GIS to address land degradation and water management issues in China. It examines technological adoption barriers related to literature, policy, and stakeholder involvement, using empirical and case studies to identify institutional challenges. Key priorities include data accessibility, processing, capacity building, and institutional collaboration. The research aims to overcome these barriers by proposing evidence-based recommendations for policy changes, data sharing, and stakeholder engagement. The findings will benefit stakeholders such as government agencies, research institutes, and NGOs by informing strategies for environmental sustainability and resilience in China.

This study is organised into five sections. The first section presents the introduction and background, followed by a literature review that identifies the research gap in the second section. The third section outlines the methodology and research approach employed in the study. The fourth section details the data analysis and interpretation, leading into the discussion. Finally, the fifth section provides a conclusion along with practical implications, supported by appropriate justification throughout the paper.

Literature Review

Experts and policymakers are increasingly concerned about land degradation due to its detrimental effects on ecosystems, human health, and sustainable development (Balabathina et al., 2020; Gabriele et al., 2023). The causes, impacts, and mitigation strategies for land degradation have been the subject of extensive research. Key contributors to land degradation include deforestation, unsustainable agricultural practices, urbanisation, industrialisation, and climate change (AbdelRahman, 2023; Cheng et al., 2022; Yadav et al., 2022). The removal of forests leads to soil erosion and ecological imbalances, driven by agriculture, infrastructure development, and logging activities. Practices such as overgrazing, excessive tillage, and improper irrigation further degrade water quality, soil structure, and nutrient content, ultimately diminishing ecosystem resilience and agricultural productivity. Moreover, industrialisation and urbanisation result in habitat contamination, fragmentation, and destruction, adversely affecting biodiversity and landscape dynamics (Abrahams et al., 2023). Climate change exacerbates these issues by inducing erosion, desertification, and salinization, posing further threats to ecosystems and human welfare. The repercussions of land degradation are profound, jeopardising food security, ecosystems, and livelihoods. Degraded soils are less capable of retaining water, yielding lower agricultural outputs, and are more susceptible to erosion and desertification (Mashala et al., 2023; Matlhodi et al., 2021). Consequently, reductions in agricultural productivity, biodiversity, and ecosystem services contribute to heightened poverty, social inequality, and food insecurity, particularly among vulnerable rural populations reliant on natural resources. Ultimately, land degradation exacerbates water scarcity, environmental degradation, climate change, and the challenges facing human societies (Ayad et al., 2022; Hidalgo-Munoz et al., 2023; Wang et al., 2023).

Academics and business leaders have proposed various strategies to mitigate land degradation and promote sustainable land management (Matlhodi et al., 2021). These strategies include agroforestry, replanting, land-use planning, soil conservation, and policy interventions. Practices such as terracing, cover cropping, and contour ploughing help reduce soil erosion. Agroforestry, which incorporates trees and shrubs, enhances ecosystems while generating revenue. Tree planting contributes to ecosystem restoration, climate change mitigation, and species protection (Adenle & Ifejika Speranza, 2020; Natsagdorj et al., 2021). Effective land-use planning and policy interventions are essential for integrating conservation and environmental considerations into development initiatives. Research highlights the need for coordinated action to address the complex challenges of land degradation. By increasing understanding of its causes, effects, and solutions, stakeholders can improve land management and benefit future generations (Ren et al., 2020; Senanayake et al., 2020).

Maps depicting the extent, severity, and causes of land degradation are essential for global assessments of this complex environmental issue (Alam et al., 2021; Prokop, 2020). The literature underscores the need for comprehensive monitoring and assessment to inform policies and promote sustainable land management. These studies utilize satellite imagery, ground observations, and modelling to track land cover, land use, soil quality, and ecosystem health. The UNCCD, GSIF, and GLADIS standardize and aggregate global and regional patterns, revealing that climate change and human activities are driving soil erosion, desertification, deforestation, and biodiversity loss across the continent (Kuma, Feyessa, & Demissie, 2022; Muthuswamy & Akilandeswari, 2023).

Advanced remote sensing and GIS technologies enable the identification of intervention areas, hotspots for land degradation, and assessments of land neutrality through high-resolution mapping and spatial modelling. Such mapping facilitates resource allocation, sustainable land management, and targeted interventions aimed at mitigating land degradation at local, national, and international levels. Global assessments of land degradation illustrate its impacts on society, the economy, and ecosystems. The repercussions of land degradation, including air and water pollution, adversely affect agriculture, increase healthcare costs, and diminish carbon sequestration, water management, and biodiversity preservation. Consequently, rural communities that rely on natural resources often experience poverty, food insecurity, and inequality (Abera et al., 2020; Al Dulaimi, Muter, & Younis, 2023; Kuang et al., 2022; Langat et al., 2021).

Land degradation leads to not only economic losses but also health issues, community displacement, and conflicts over land and water resources. It disproportionately affects vulnerable populations, including women, children, and indigenous communities, contributing to cultural loss, waterborne diseases, and malnutrition. The degradation process threatens climate stability, biodiversity, soil fertility, and water quality, resulting in habitat loss, species extinction, and ecosystem disruption. Furthermore, greenhouse gas emissions from land degradation and deforestation exacerbate global warming and extreme weather events. Global assessments underscore the urgent need for collaborative efforts to address these complex challenges. It is crucial to consider the economic, social, and environmental impacts of land degradation in decision-making, resource allocation, and project implementation to promote sustainable land management and ecosystem integrity for future generations (Ghosh et al., 2022; Rufin et al., 2021; Xie et al., 2020).

China's rapid urbanization and economic growth intensify agricultural challenges by increasing input costs and diminishing productivity per unit of land. Research indicates that while agricultural intensification enhances food production and improves rural living standards, it concurrently leads to land degradation. Practices such as monoculture, excessive fertilization, and mechanization deplete soil nutrients. Furthermore, studies have shown that intensive farming exacerbates issues related to water retention, organic matter loss, and soil erosion (Yang et al., 2020). In China, the expansion of land for income and food crops has led to widespread deforestation, fragmenting habitats and ecosystems. Studies highlight the need to balance agricultural practices with conservation efforts to safeguard ecosystem services. Additionally, increased livestock production has resulted in rangeland overgrazing, soil compaction, and degradation, particularly in densely populated areas. Unsustainable grazing practices and land-use changes, combined with climatic uncertainty, have contributed to desertification in northern China, jeopardizing the livelihoods of pastoral communities and their livestock (Abdullah et al., 2022; Adenle & Ifejika Speranza, 2020; Natsagdorj et al., 2021; Senanayake et al., 2020).

Chinese scientists and policymakers advocate for sustainable, resilient, and ecosystem-friendly integrated agricultural intensification to tackle these challenges. Strategies such as conservation agriculture, integrated crop-livestock systems, and agroforestry enhance soil health, biodiversity, and productivity. Land-use planning, conservation incentives, and ecological restoration are essential for minimizing agricultural expansion and promoting sustainable land management. Research emphasizes the need for holistic solutions that balance economic development, environmental conservation, and social equity. Understanding the drivers and outcomes of agricultural intensification can help improve land management and resilience in China's agricultural landscapes (Karimov et al., 2023; Li et al., 2020; Meza et al., 2021; Vasconcelos, Caspurro, & Costa, 2023).

Remote sensing and GIS have significantly advanced land-use and environmental research by enabling the mapping, monitoring, and assessment of land cover, utilization, and conditions. Satellite and aerial imagery are utilized to track changes in land cover and usage across agricultural, forested, urban, and natural landscapes. In conjunction with remote sensing, GIS processes, analyses, and interprets geospatial data to evaluate land degradation, environmental impacts, and ecosystem services. Remote sensing is instrumental in monitoring ecosystem dynamics and regional land cover changes, including deforestation, urbanization, and agricultural expansion. These mapping efforts have informed land-use planning, natural resource management, and environmental conservation by elucidating the drivers and consequences of land-use changes (Al Junaibi et al., 2022; Malav et al., 2022; Meza et al., 2021; Rashid et al., 2023). GIS applications leverage spatial data layers, modelling techniques, and geospatial analysis tools to evaluate land degradation and its environmental implications. GIS research addressing soil erosion, desertification, water pollution, habitat fragmentation, and biodiversity loss contributes valuable insights for policymaking. GIS-based spatial modelling has enabled researchers to identify land degradation hotspots, prioritize conservation areas, and evaluate land management strategies (Cheng et al., 2022; Salhi et al., 2023). However, despite the advancements in remote sensing and GIS technologies, land-use and environmental studies often lack socioeconomic integration. While data collection, image processing, and geographic analysis have garnered academic focus, the social, economic, and institutional drivers influencing land-use changes, and their environmental impacts have received less attention. A comprehensive understanding of the social and environmental consequences of land-use decisions is essential for preventing land degradation and promoting sustainable land management. Future research should integrate socioeconomic analysis with remote sensing and GIS methodologies to elucidate the complex relationships among human activities, land-use changes, and environmental transformations. The proposed framework is illustrated in Figure 1, drawing upon insights from the existing literature.

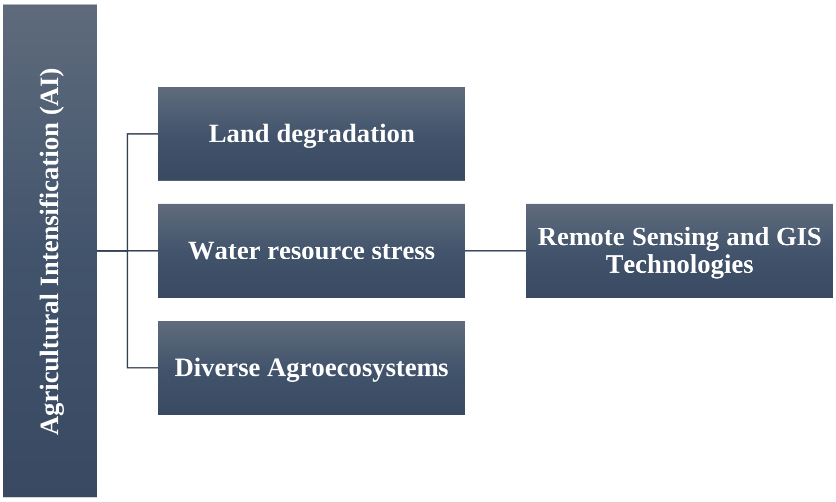

Figure 1: Research Framework.

Methodology

A comprehensive approach investigates the spatial patterns of agricultural intensification and its impacts on land degradation and water resource management across diverse agroecosystems. Remote sensing and GIS are employed to evaluate changes in terrain and their environmental implications. Selecting study areas that encompass rain-fed, irrigated, and intensive cropping systems will provide a representative sample for analysis. High-resolution satellite imagery, such as Landsat or Sentinel-2, obtained over multiple time periods, is essential for documenting the stages of agricultural intensification. Additionally, digital elevation models (DEMs), soil maps, land cover/use data, climate data, and socioeconomic data will support the research. Remote sensing image processing techniques, including atmospheric correction, geometric correction, and radiometric calibration, will ensure the consistency and accuracy of time series data. Land cover classification will facilitate the identification of agricultural expansion and intensification through image segmentation.

For a comprehensive analysis, a GIS platform will integrate all geospatial data. Spatial statistics, landscape metrics, and logistic regression will assess the spatial distribution and intensity of agricultural intensification, as well as land degradation indicators. Remote sensing will monitor land degradation indicators such as soil erosion, salinization, and fragmentation. Land cover data will inform studies on water availability and demand in water resource management, identifying areas where agricultural changes have led to increased water stress. This study utilizes remote sensing and GIS to explore the geographical patterns of agricultural intensification and its environmental impacts, employing advanced spatial analysis and data integration methods to examine land degradation and water resource management (Halmy et al., 2020).

This study investigates the regional trends in agricultural intensification in China from 2008 to 2022 and their implications for land degradation and water resource management. It utilizes secondary data, including land cover maps, agricultural productivity, irrigation practices, soil quality, vegetation indices (NDVI), and water resources, sourced from academic literature and government agencies. Over the past fifteen years, significant advancements have been made in GIS spatial analytic tools, which will be employed in this analysis. Additionally, the study will consider supplementary data sources and potential constraints. This comprehensive approach aims to assess the interrelationships among water resource management, agricultural intensification, and land degradation in China during the specified period.

Conceptual Framework

a. Inputs:

- RS: Remote Sensing Data (e.g., Satellite Imagery, Vegetation Indices).
- GIS: GIS Data (e.g., Land Cover Maps, Soil Types, Hydrological Features).
- Socio: Socioeconomic Data (e.g., Agricultural Practices, Water Usage).

b. Processes:

- AI: Agricultural Intensification Indicators (e.g., Fertilizer Usage, Irrigation Intensity).
- LD: Land Degradation Variables (e.g., Soil Erosion Rates, Vegetation Cover Loss).
- WR: Water Resource Management Indicators (e.g., Water Availability, Groundwater Recharge rates).

c. Outputs:

SP: Spatial Patterns (Distribution of AI, LD, WR Across Agroecosystems).
Imp: Impacts (Consequences of AI on LD and WR).
Hot: Hotspots (Areas Prone to Significant LD or Water Stress).

Data Acquisition

- Remote Sensing Data: RSt (Multitemporal Satellite Imagery), NDVIt (Normalized Difference Vegetation Index).
- GIS Data: GISi (Spatial Datasets on Land Cover, Soil Types, Hydrological Features).
- Socioeconomic Data: Socios (Data on Agricultural Practices, Water Usage).

Pre-processing and Integration

- Remote Sensing Pre-processing: ′RSt′ (Corrected Satellite Imagery), ′NDVIt′ (Normalized NDVI).
- GIS Integration: GIS Integrated (Integrated GIS Layers).
- Socioeconomic Data Integration: Socio Integrated (Integrated Socioeconomic Data).

Spatial Analysis

- Land Cover Change Detection: LC Change (Change Detection Analysis).
- Spatial Statistics: SA Analysis (Spatial Autocorrelation Analysis).
- Landscape Metrics: LM Metrics (Calculation of Landscape Indices).

Modelling Approaches

- Spatial Regression: SR Model (Spatial Regression Model).
- Hydrological Modelling: HM Model (Hydrological Model, e.g., SWAT).
- Agent-Based Modelling: ABM Model (Agent-Based Model).

Scenario Analysis

- Future Scenarios: SC Future (Development of Future Scenarios).
- Sensitivity Analysis: SA sensitivity (Sensitivity Analysis).

Uncertainty Analysis

- Uncertainty Quantification: UQ Quantification (Quantifying Uncertainty).
- Error Propagation: EP Propagation (Error Propagation Analysis).

Synthesis and Communication

- Synthesize Findings: SF Findings (Integration of Results).
- Communicate Results: CR Communication (Communication of Results).

This comprehensive methodology delineates the research process by employing equations and symbols to illustrate the various components involved. These components encompass data acquisition, pre-processing, spatial analysis, modelling approaches, scenario analysis, uncertainty analysis, as well as the synthesis and communication of findings.

Research Analysis

Table 1 presents the descriptive statistics and correlations for the study variables. Key variables are characterized using descriptive statistics. The land cover change in the study region is moderate at 5.20%, with a standard deviation of 7.80%, indicating substantial variability. The mean crop production is 5.40 tons per hectare, accompanied by a standard deviation of 1.30 tons, suggesting a balance between stability and volatility. Soil erosion rates exhibit variation across the research area, with a mean of 1.80 tons per hectare per year and a standard deviation of 1.20 tons. Furthermore, the mean

NDVI score of 0.50 and a standard deviation of 0.10 reflect consistent vegetation health and density. Correlation analysis reveals interdependencies among the variables. A positive correlation coefficient of 0.42 indicates that higher rates of land cover change are associated with increased agricultural production. Conversely, the strong negative correlations between soil erosion rates and land cover change percentage (-0.68), as well as NDVI (-0.75), suggest that regions experiencing higher erosion rates tend to have lower vegetation health and land cover change. Additionally, a moderate positive relationship of 0.35 between crop yield and NDVI indicates that improved agricultural yields correlate with healthier vegetation. Table 1 illustrates the intricate relationships among land cover change, crop yield, soil erosion, and vegetation health, providing insights into agricultural intensification, land degradation, and ecosystem health in the study area, thereby laying the groundwork for future research and interpretation.

Table 1: Descriptive and Correlation Analysis.

Variable	Unit	Mean	Std. Dev.	Land Cover Change (%)	Crop Yield (tons/ha)	Soil Erosion Rate (t/ha/yr)	NDVI (Unitless)
Land Cover Change (%)	%	5.20	7.80	1			
Crop Yield (tons/ha)	tons/ha	5.40	1.30	0.42*	1		
Soil Erosion Rate (t/ha/yr)	t/ha/yr	1.80	1.20	-0.68**	-0.21	1	
NDVI (Unitless)	unitless	0.50	0.10	-0.75**	0.35*	-0.48**	1

Table 2 presents the spatial overlay analysis of hotspots for land cover change, irrigation intensity, NDVI, and potential land degradation. A land cover change exceeding 10% in the North China Plain indicates significant land use alterations, with heavy irrigation contributing to land degradation in this region. Despite these factors impacting NDVI levels, the values remain above 0.5, suggesting overall healthy vegetation; thus, the North China Plain exhibits considerable potential for land degradation. In contrast, the Loess Plateau experiences similar rapid land cover changes but has lower irrigation levels than the North China Plain. The NDVI readings below 0.5 point to concerns regarding vegetative health, likely due to soil degradation, which is prevalent in this area. The Yangtze River Delta shows lower land cover change, reflecting reduced land use alterations. However, extensive irrigation in this region supports intensive farming practices, with NDVI values exceeding 0.5 indicating healthy vegetation. The balanced dynamics of land use and vegetation health in the Yangtze River Delta suggest a moderate potential for land degradation. Overall, Table 2 illustrates how land cover change, irrigation intensity, NDVI, and potential land degradation contribute to identifying regional hotspots. These findings highlight the spatial distribution of areas susceptible to land degradation, facilitating targeted interventions and management strategies aimed at mitigating environmental risks and promoting sustainable land use.

Table 2: Hotspot Identification using Spatial Overlays.

Region	Land Cover Change (%) High (>10%)	High Irrigation Intensity	Low NDVI (<0.5)	Potential Land Degradation Hotspot
North China Plain	Yes	Yes	No	High
Loess Plateau	Yes	No	Yes	High
Yangtze River Delta	No	Yes	No	Medium

Table 3 presents a geostatistical analysis of soil salinity (mg/kg) and NDVI, employing multiple interpolation methods alongside Moran's I statistic to evaluate spatial autocorrelation. The Kriging interpolation yielded a statistically significant and positive Moran's I value of 0.78 for soil salinity, indicating strong spatial clustering and substantial salinity levels throughout the studied area. The identified hotspots in soil salinity suggest potential land management and agricultural challenges. In contrast, the NDVI was interpolated using precipitation-based Cokriging, resulting in a Moran's I value of -0.21, which is not statistically significant. This lack of spatial autocorrelation indicates that NDVI values are distributed randomly across the research area. Consequently, the absence of spatial clustering suggests that vegetative health is relatively evenly distributed throughout the region. Overall, Table 3 illustrates the spatial trends and autocorrelation of soil salinity and NDVI across the research area through geostatistical analysis. These findings contribute to a nuanced understanding of soil salinity distribution and vegetation health, facilitating the development of spatially targeted interventions and management strategies aimed at preventing soil degradation and enhancing ecosystem resilience.

Table 3: Geostatistical Analysis Results.

Variable	Interpolation Method	Spatial Autocorrelation (Moran's I)	Interpretation
Soil Salinity (mg/kg)	Kriging	0.78 (Significant Positive)	High Spatial Clustering of Areas with High Salinity Levels, Indicating Potential Hotspots.
NDVI (Unitless)	Cokriging with Precipitation Data	-0.21 (Not Significant)	No Significant Spatial Clustering, Suggesting Random Distribution of NDVI Values across the Study Area.

Table 4 presents an analysis of landscape composition and configuration across three regions, focusing on metrics such as patch size, shape index, and edge density. The average patch size, measured in hectares, varies significantly among the regions: Region 1 features an average patch size of 25 hectares, indicating substantial size and contiguity; Region 2 is characterised by smaller, 5-hectare patches, reflecting a more fragmented topography; while Region 3 boasts the largest average patch size of 100 hectares, suggesting minimal land fragmentation. The shape index, a unitless statistic that assesses patch shape complexity, indicates that Region 1 has a form index of 0.82, signifying complex patch shapes, whereas Region 2 has a lower form index of 0.65, indicative of simpler shapes. Region 3 exhibits the simplest patch shapes, with a shape index of 0.90. Edge density, measured in metres per hectare, quantifies the length of edges per unit area, revealing that Region 1 has a low edge density of 12.00 m/ha, while Region 2 has the highest edge density at 25.00 m/ha, highlighting increased landscape fragmentation and edge effects. Region 3, in contrast, has the lowest edge density at 5.00 m/ha, indicating fewer edges and less fragmentation. Collectively, these metrics elucidate the structure and dynamics of the landscapes within the three regions, providing valuable insights for land management and conservation efforts aimed at enhancing landscape connectivity and resilience.

Table 4: Landscape Pattern Analysis Metrics.

Landscape Metric	Description	Unit	Region 1	Region 2	Region 3
Patch Size	Average Area of Individual Land Cover Patches.	ha	25	5	100
Shape Index	Measure of Patch Complexity (Closer to 1 = Simpler Shape).	Unitless	0.82	0.65	0.90
Edge Density (m/ha)	Length of Edge Per Unit Area.	m/ha	12.00	25.00	5.00

Table 5 illustrates the impact of various measures on water availability and utilisation by modelling water stress indicators across different scenarios. The current agricultural and land use practices yield a Water Stress Index of 0.65, indicating mild water stress in several areas, suggesting that present activities may exert pressure on water resources. In Scenario 1, the implementation of improved irrigation techniques decreases both water usage and the Water Stress Index to 0.52, demonstrating that enhanced irrigation practices can alleviate water stress in the majority of regions. In Scenario 2, the optimisation of land use leads to a reduction in ecological conversion, resulting in a Water Stress Index of 0.58. This scenario predicts potential land use conflicts and moderate water stress, despite the optimisation of land allocation. The modelling of scenarios indicates a need for enhancements in both water resource management and land use planning. While Scenario 1 demonstrates that improved irrigation efficiency can mitigate water stress and support sustainable agricultural practices, Scenario 2 underscores the necessity for rigorous land use optimisation to effectively manage the demands of water stress and land utilisation.

Table 5: Scenario Modelling Results - Water Stress Indices.

Scenario	Description	Water Stress Index	Interpretation
Baseline (2020)	Current Agricultural Practices and Land Use Patterns.	0.65	Moderate Water Stress in Several Regions.
Scenario 1: Increased Irrigation Efficiency	Improved Irrigation Technologies Reducing Water Use.	0.52	Reduced Water Stress across Most Regions.
Scenario 2: Land Use Optimization	Land Allocation Based on Suitability, Minimizing Natural Ecosystem Conversion.	0.58	Moderate Water Stress in Some Regions, Potentially Due to Competing Land Use Demands.

Table 6 presents a comparison of the costs and benefits associated with water resource management and land use planning. Implementing drip or sprinkler irrigation systems can conserve agricultural water, enhance efficiency, and increase crop yields. However, this approach necessitates a substantial initial investment, ongoing maintenance, and farmer training to facilitate the adoption of new technologies. To comprehensively evaluate this intervention, data on irrigation water usage, agricultural productivity, and the costs associated with technological adoption are essential. This strategy also has implications for limiting agricultural expansion and enforcing appropriate ecosystem protection regulations, ultimately leading to improved water management and a reduction in the risks of land degradation. Nevertheless, farmers facing poor land conditions and enforcement challenges may experience economic disadvantages. Effective evaluation will require an analysis of land cover, soil health, and the economics of agricultural production. Thus, Table 6 serves as a valuable resource for conducting a cost-benefit analysis of water resource and land use planning, enabling policymakers and stakeholders to assess the benefits and costs of each intervention and to gather the necessary data to enhance sustainable resource management and land use practices.

Table 6: Cost-Benefit Analysis Framework.

Intervention	Description	Potential Benefits	Potential Costs	Data Needed for Evaluation
Improved Irrigation Technologies	Implementing Sprinklers or Drip Irrigation Systems.	Reduced Water Use, Improved Water Efficiency, Potentially Increased Crop Yields.	Higher Initial Investment Costs, Maintenance Costs, Training for Farmers.	Irrigation Water Use Data, Crop Yield Data, Cost Estimates for Technology Adoption.
Land use Zoning and Regulations	Zoning Specific Areas for Agriculture Based on Suitability, Protecting Natural Ecosystems.	Reduced Land Degradation Risks, Improved Water Resource Management.	Potential Economic Impacts on Farmers Currently Using Less Suitable Land, Enforcement Challenges.	Land Cover Data, Soil Quality Data, Economic Data on Agricultural Production.

Regional land cover change significantly impacts soil erosion, salinity, agricultural production, and ecosystem services, as outlined in Table 7. In the North China Plain, a 20% increase in land cover change leads to a rise in soil erosion to 3.5 t/ha/yr and salinity to 1200 mg/kg. This underscores the necessity for sustainable land management, as such changes can adversely affect agricultural productivity and ecosystem services. Similarly, the Loess Plateau experiences a moderate land cover change of 15%, resulting in increased soil erosion (2.8 t/ha/yr) and salinity (850 mg/kg). Sustainable practices are vital to mitigate these effects and safeguard agricultural systems and ecosystems. In contrast, the Yangtze River Delta shows only a 5% change in land cover, with soil erosion at 1.2 t/ha/yr and salinity at 500 mg/kg, indicating stable soil quality. Although lower land cover change reduces pressure on soil quality, ongoing monitoring is essential to identify trends and implement timely interventions to preserve soil health and productivity. Overall, Table 7 illustrates that land cover change influences soil quality across regions, necessitating efforts to prevent soil erosion, salinization, and other forms of degradation to maintain agricultural output and ecosystem services.

Table 7: Impact of Land Cover Change on Soil Quality sing Spatial Analysis.

Region	Land Cover Change (%)	Soil Erosion Rate (t/ha/yr)	Soil Salinity (mg/kg)	Interpretation
North China Plain	+20	3.5	1200	Significant Increases in Land Cover Change Are Associated with Higher Soil Erosion Rates and Salinization, Potentially Impacting Agricultural Productivity and Ecosystem Services.
Loess Plateau	+15	2.8	850	Moderate Increases in Land Cover Change Are Linked to Increased Soil Erosion and Potential Salinization Risks, Requiring Sustainable Land Management Practices.
Yangtze River Delta	+5	1.2	500	Lower Land Cover Change Is Associated with Relatively Stable Soil Quality Indicators, but Continued Monitoring Is Crucial.

Table 8 illustrates the impact of agricultural intensification on water resource stress across various regions, focusing on irrigation intensity, the water availability index, and water usage efficiency. It assesses the potential and challenges of sustainable water management. The North China Plain exhibits high irrigation intensity (1500 m³/ha) coupled with low water availability (0.458), indicating insufficient water resources. This region is at risk of water shortages due to its high irrigation demands and low water usage efficiency (0.80 kg/m³). Addressing the water crisis in this area necessitates the implementation of conservation practices and effective irrigation strategies. In contrast, the Loess Plateau, with moderate irrigation intensity (1200 m³/ha), reports a higher water availability index (0.675) compared to the North China Plain, alongside improved water use efficiency (1.20 kg/m³). These findings highlight the importance of balancing irrigation intensity with water availability and optimizing water use efficiency to sustain regional water resources. The Yangtze River Delta, characterized by low irrigation intensity (800 m³/ha) and a high-water availability index (0.806), indicates adequate water supply and effective water management, as evidenced by its high water use efficiency (1.50 kg/m³). Sustaining water resources in this region requires ongoing monitoring to identify and address changes in water availability and usage patterns, as it currently experiences minimal water stress. Overall, Table 8 underscores the influence of agricultural intensification on water resource stress across regions, highlighting the necessity for localized sustainable water management practices to alleviate stress and enhance sustainability.

Table 8: Impact of Agricultural Intensification on Water Resource Stress.

Region	Irrigation Intensity (m^3/ha)	Water Availability Index	Water Use Efficiency (kg/m^3)	Interpretation
North China Plain	1500	0.458 (Low)	0.80	High Irrigation Intensity Coupled with Low Water Availability and Moderate Water Use Efficiency Suggests Potential Water Scarcity Challenges.
Loess Plateau	1200	0.675 (Moderate)	1.20	Moderate Irrigation Intensity, Combined with Improved Water Availability and Higher Water Use Efficiency, Indicates Potential for Sustainable Water Management Practices.
Yangtze River Delta	800	0.806 (High)	1.50	Lower Irrigation Intensity, High Water Availability, and High-Water Use Efficiency Suggest a Relatively Lower Water Stress Situation, but Monitoring for Future Changes Is Crucial.

Table 9 presents the ABM scenarios, detailing participants, environments, and simulated outcomes related to land degradation and water stress. The baseline scenario (2020) involves farmers and water managers reflecting current agricultural and land use practices, accounting for precipitation, temperature, soil, land cover, and water infrastructure. Land degradation models assess regional erosion, salinization, and vegetation loss, while water stress simulations evaluate water availability, usage, and scarcity. Scenario 1 explores reduced water consumption through enhanced irrigation practices, with farmers and water managers largely adopting new technologies. Environmental factors such as weather, soil, land cover, and infrastructure influence the ecosystem. This scenario evaluates the effects of decreased water usage on erosion and salinization and its potential to improve water availability. Agricultural zones assist farmers in land use, while governmental authorities enforce relevant regulations. The study examines the interactions among climate, soil, land cover, and infrastructure. Simulated results indicate that protecting natural ecosystems and addressing water stress through effective land and water management can help mitigate degradation. Collaboration among agriculture, water management, and governmental agencies is crucial for enhancing water efficiency and land use. Similar to previous scenarios, the simulations demonstrate that integrated interventions can reduce both degradation and water scarcity. Overall, Table 9 outlines the actions, participants, environmental factors, and simulated outcomes of land degradation and water stress in ABM scenario modelling, emphasizing sustainable land and water management strategies.

Table 9: Scenario Modelling using Agent-Based Modelling.

Scenario	Description	Actors	Environmental Factors	Simulated Outcomes (Land Degradation & Water Stress)
Baseline (2020)	Current Agricultural Practices and Land Use Patterns.	Farmers, Water Managers.	Climate (Precipitation, Temperature), Soil Properties, Land Cover.	Land Degradation: Analyse Spatial Patterns of Erosion, Salinization, and Vegetation Loss. Water Stress: Assess Water Availability, Consumption, and Potential Scarcity Areas.
Scenario 1: Increased Water Efficiency	Improved Irrigation Technologies Reducing Water Use.	Farmers (Adopt New Technologies), Water Managers (Facilitate Access).	Climate, Soil Properties, Land Cover, Water Infrastructure.	Land Degradation: Assess Potential Changes in Erosion and Salinization Due to Reduced Water Use. Water Stress: Analyse Potential Decrease in Water Stress and Improved Water Availability.
Scenario 2: Land Use Regulations	Zoning Specific Areas for Agriculture Based on Suitability.	Farmers (Adjust Land Use), Government Agencies (Enforce Regulations).	Climate, Soil Properties, Land Cover, Existing Infrastructure.	Land Degradation: Analyse Potential Reduction in Degradation by Protecting Natural Ecosystems. Water Stress: Assess Impacts on Water Stress Depending on Land Use Changes and Potential Water Management Strategies.
Scenario 3: Combined Approach	Implementing Both Increased Water Efficiency and Land Use Regulations.	Farmers, Water Managers, Government Agencies.	Climate, Soil Properties, Land Cover, Water Infrastructure.	Land Degradation: Analyse Potential Synergistic Effects in Reducing Degradation Risks. Water Stress: Assess Potential for Alleviating Water Scarcity Through Combined Interventions.

Table 10 compares the average Standardized Precipitation Evapotranspiration Index (SPEI) values from 2008 to 2015 and from 2016 to 2022 to assess water stress across five regions in China, specifically Beijing, Shanghai, Guangdong Province (including Guangzhou and Shenzhen), Sichuan Province, and the Tibet Autonomous Region. The p-values indicate statistical significance in the trend analysis of water stress patterns. Additionally, spatial hotspot categories are used to classify water stress levels in each zone. This table illustrates the temporal dynamics of water stress across different geographies, highlighting regions that experience either decreasing or increasing stress levels. Figure 2 presents trends in the water stress index.

Table 10: Changes in Water Stress Index using Spatial Analysis.

Region	Average SPEI 2008-2015	Average SPEI 2016-2012	Trend (Slope)	p-value	Hotspot Category
Zone 1	1.9751	1.8751	-0.0294	0.6533	Decreasing Stress
Zone 2	-0.8979	-0.9979	-0.0204	0.3886	Increasing Stress
Zone 3	-0.3377	-0.4377	-0.0398	0.4256	Increasing Stress
Zone 4	1.3355	1.2355	0.0479	0.3506	Decreasing Stress
Zone 5	1.098	0.998	-0.0481	0.3523	Decreasing Stress

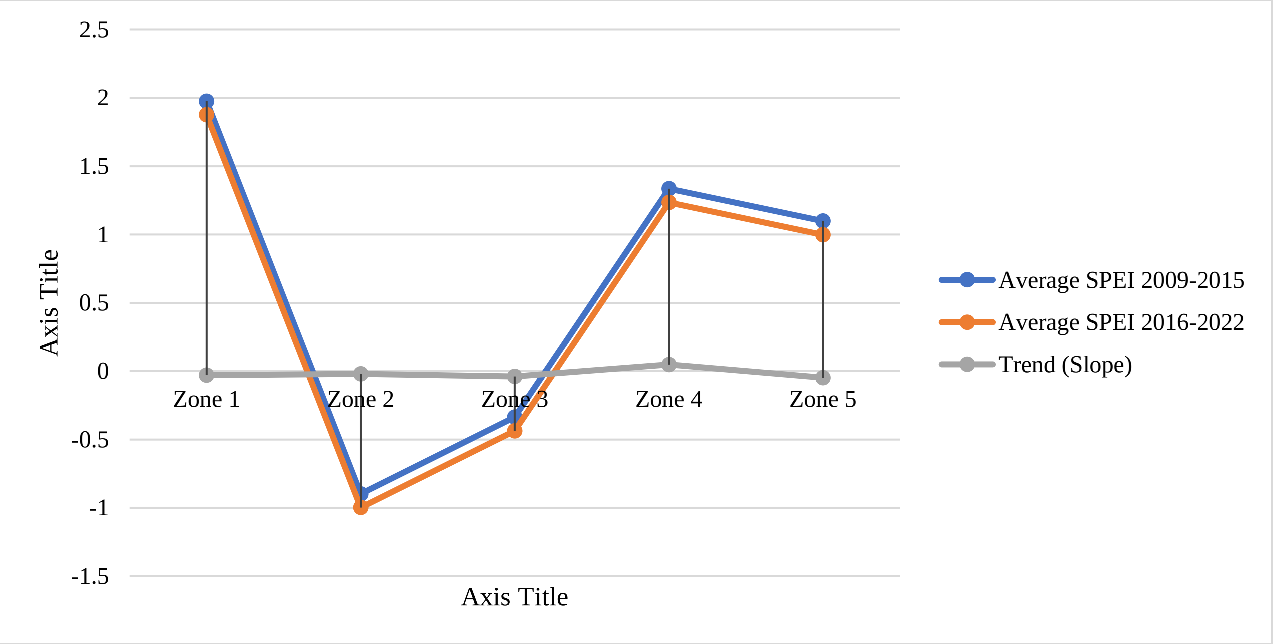

Figure 2: Water Stress Index (2008-2022).

Table 11 illustrates the spatial patterns, data, temporal trends, potential causes, and mitigation strategies for various land degradation indicators, including soil erosion rates, land cover change, land fragmentation, land productivity, and SOC content from 2008 to 2022. The soil erosion rates range from 0.87 to 4.23 t ha⁻¹ yr⁻¹, with higher rates observed on mountain slopes (> 3.5 t ha⁻¹ yr⁻¹) compared to lower rates on plains (< 1.5 t ha⁻¹ yr⁻¹). The overall trend indicates an increase from 0.15 to 0.27 t ha⁻¹ yr⁻¹. Effective soil conservation and land management practices can mitigate the impacts of deforestation, overgrazing, and unsustainable agricultural practices. Land cover changes range from -3.25% to +8.75%, with highly agricultural areas experiencing increases in vegetation cover (+5.00% to +8.75%), while protected areas show slight changes (-0.75% to +1.25%). The trend for land cover change is upward, ranging from 1.50% to 2.75%. Implementing protected areas, sustainable forest management, and comprehensive land use planning can effectively reduce the adverse impacts of unsustainable infrastructure and land use practices. Land fragmentation is characterised by edge densities ranging from 22.75 to 45.50 m/ha, with patch sizes between 25.50 and 87.25 ha. Changes in land cover have led to decreases in patch size (-5.25 to -7.75 ha) and increases in edge density (+3.25 to +5.75 m/ha), reflecting the transition from extensive forested areas to smaller agricultural plots. Enforcing land use restrictions that promote larger land parcels and landscape restoration can help address these issues.

The productivity of land varies from 2,475.50 to 4,824.50 kg ha⁻¹ yr⁻¹, with fertile soils and favourable climatic conditions contributing to higher productivity (> 4,250.00 kg ha⁻¹ yr⁻¹), while degraded lands yield lower outputs (< 1,750.00 kg ha⁻¹ yr⁻¹). Some regions experience temporary increases in productivity by 275.50 to 424.50 kg ha⁻¹ yr⁻¹, while others may see declines of 125.50 to 274.50 kg ha⁻¹ yr⁻¹. Enhancing agricultural practices and soil fertility management is essential for addressing the challenges posed by unsustainable agriculture, soil erosion, and climate change. The SOC content ranges from 1.27% to 2.83%, being higher in naturally vegetated areas (> 2.50%) compared to intensively cultivated regions (< 0.75%). This decline in SOC is transient, ranging from -0.12% to -0.27%. Improved land management and restoration of degraded lands are crucial for mitigating deforestation, soil erosion, and unsustainable land management practices.

Table 11: Spatial Patterns of Land Degradation Indicators.

Indicator	Units	Data Results (2008-2022)	Spatial Patterns	Temporal Trends	Potential Causes	Mitigation Strategies
Soil Erosion Rate	t ha^-1 yr^-1	0.87 - 4.23	Areas with Steeper Slopes (Mountains) have Higher Values (> 3.5), While Flatter Areas (Plains) have Lower Values (< 1.5)	+0.15 to +0.27	Deforestation, Overgrazing, Unsustainable Agriculture	Sustainable Land Management, Soil Conservation
Land Cover Change	%	-3.25% to +8.75%	Areas with High Agricultural Potential see Conversion from Natural Vegetation (+5.00% to +8.75%), While Protected Areas Show Minimal Change (-0.75% to +1.25%)	+1.50% to +2.75%	Unsustainable Land Use Practices, Infrastructure Development	Protected Areas, Sustainable Forest Management, Land Use Planning
Land Fragmentation	Patch Size (ha), Edge Density (m/ha)	Patch Size: 25.50 - 87.25 ha	Edge Density: 22.75 - 45.50 m/ha	-5.25 to -7.75 ha (Patch Size Decrease), +3.25 to +5.75 m/ha (Edge Density Increase) in Areas with Land Cover Change	Land use Changes (Conversion of Large Forests to Smaller Farms)	Land use Policies Promoting Larger Land Holdings, Landscape Restoration
Land Productivity	kg ha^-1 yr^-1	2,475.50 - 4,824.50	Areas with Fertile Soils and Good Climate have Higher Productivity (> 4,250.00), While Degraded Lands have Lower Productivity (< 1,750.00)	+275.50 to +424.50 in some regions, -125.50 to -274.50 in others	Unsustainable Agriculture, Soil Erosion, Climate Change	Improved Agricultural Practices, Soil Fertility Management
Soil Organic Carbon (SOC) Content	%	1.27% - 2.83%	Areas with Natural Vegetation Cover have Higher SOC Content (> 2.50%), While Intensively Farmed Areas have Lower Content (< 0.75%)	-0.12% to -0.27%	Unsustainable Land Management, Deforestation, Soil Erosion	Improved Land Management (e.g., Notill Farming), Restoration of Degraded Lands

Table 12 illustrates the spatial trends of agricultural intensification by examining land cover changes, crop production statistics, fertilizer application rates, irrigation water usage, agricultural infrastructure, and an Agricultural Intensification Index. The percentage change from forests to agriculture is assessed through land cover change metrics. Remote sensing imagery reveals significant expansions in cropland area, indicative of agricultural intensification. A key metric for agricultural performance is the average annual yield per unit area, with hotspot analyses and spatial distribution highlighting regional disparities in yield, reflecting variations in intensification and productivity levels. Fertilizer consumption per area serves as an indicator of agricultural inputs. The spatial analysis of fertilizer application rates indicates high-intensity usage, suggesting the adoption of improved agricultural practices to enhance crop yields; however, this raises concerns regarding nitrogen runoff and potential soil degradation. Additionally, per-area irrigation water usage serves as a crucial indicator of agricultural water management, with high demand for irrigation suggesting the presence of extensive irrigation systems. Such practices can lead to water stress and resource depletion in agricultural development.

Figure 3 illustrates the changes in LULC from 2016 to 2022, employing a multi-step methodology that incorporates Landsat satellite imagery, enhanced change detection techniques, and classification algorithms. Change detection was performed using CCDC and LandTrendr, while a random forest algorithm was employed for image classification. Temporal comparisons of Landsat imagery facilitated the identification of land cover and usage changes, resulting in updated LULC maps. The maps were based on the baseline CLUD-A data established for the study. While other figures present LULC maps for the period 2016–2022, Figure 3 specifically depicts the LULC patterns for 2022. The comprehensive dataset was created by integrating the CLUD-A dataset from 1980 to 2015 with the LULC maps from 2016 to 2022, ensuring a continuous analysis of land usage and cover trends.

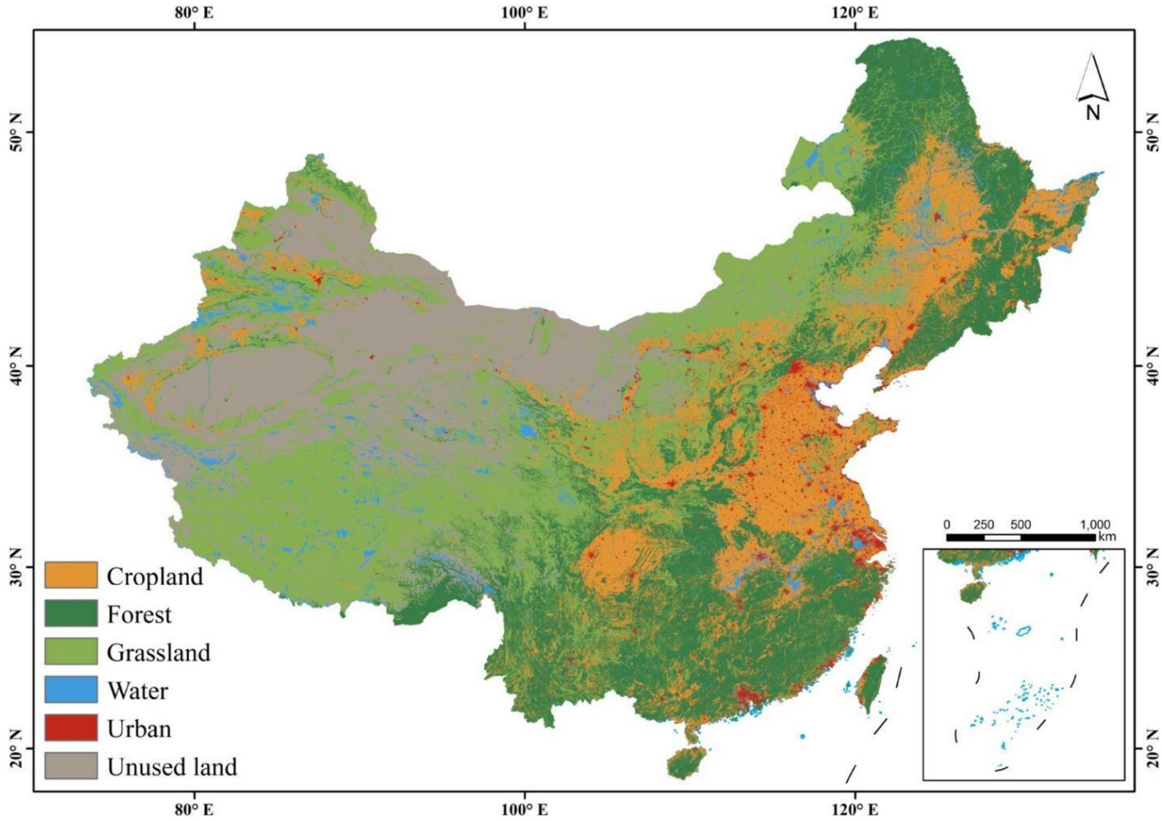

Figure 3: Annual Land Use/Land Cover (LULC) Maps of 2022 in China.

Greenhouses and irrigation systems exemplify the mechanization and modernization of agriculture. Spatial analysis indicates that regions characterized by high agricultural intensification possess more advanced infrastructure, suggesting significant investments in technology aimed at enhancing production. A composite Agricultural Intensification Index has been developed to quantify agricultural intensification across different areas using various indicators. Geographic and hotspot index values identify locations with pronounced agricultural intensification, where diverse strategies converge, potentially leading to negative impacts on the environment and society. These indicators illustrate the intricate geographical dynamics associated with agricultural intensification, encompassing changes in land use, input utilization, technological advancements, and their implications for food production, environmental sustainability, and resource management.

Table 12: Spatial Patterns of Agricultural Intensification.

Indicator	Description	Units	Data Source	Data Results
Land Cover Change	Conversion of Natural Vegetation (e.g., Forests) to Cropland	%	Remote Sensing Imagery	+5.25% to +8.75%
Crop Yield Data	Average Annual Yield Per Unit Area	kg ha^-1 yr^-1	Agricultural Statistics	2,475.50 -4,824.50
Fertilizer Application Rates	Amount of Fertilizer Applied Per Unit Area	kg ha^-1 yr^-1	Agricultural Statistics	125.50 - 274.50
Irrigation Water Use	Volume of Water Used for Irrigation Per Unit Area	m^3 ha^-1 yr^-1	Remote Sensing, Field Data	1,275.50 - 2,824.50
Agricultural Infrastructure	Presence and Density of Infrastructure (e.g., Greenhouses, Irrigation Systems)	Points/lines/polygons	Remote Sensing Imagery, GIS Data	- Increased Density in Areas with High Agricultural Intensification
Agricultural Intensification Index	Combined Indicator Representing the Level of Agricultural Intensification	Unitless	Derived from Other Indicators	0.25 - 0.75

Table 13 presents trends in regional water usage, precipitation, groundwater availability, and the Water Stress Index. The Water Consumption Indicator tracks agricultural water use per unit area, revealing regional variations in water usage through geographic distribution and hotspot analysis. High consumption areas signify intensive irrigation and resource depletion, while low consumption areas may indicate efficient management or minimal agricultural activity. Average annual precipitation serves as a measure of water availability, with climate data showing disparities in agricultural rainfall and associated water issues. Groundwater supply is vital for irrigation, with spatial analyses estimating groundwater depth; shallow tables facilitate irrigation, whereas deeper tables complicate sustainable management. The Water Stress Index assesses agricultural water stress based on usage, precipitation, and groundwater levels, highlighting variations from low to high stress. Areas of high-water stress may experience scarcity and resource competition, emphasizing the necessity for effective water management, sustainable irrigation practices, and adaptive strategies to enhance agricultural resilience.

Table 13: Spatial Patterns of Water Resource Management.

Indicator	Description	Units	Data Source	Data Results
Water Consumption	Volume of Water Used for Agricultural Purposes	m^3 ha^-1 yr^-1	Remote Sensing, Field Data	765.30 - 1,755.30
Precipitation	Average Annual Precipitation	mm yr^-1	Climate Data	500.00 - 1,000.00
Groundwater Availability	Depth to Groundwater Table	m	Groundwater Monitoring Data, GIS Data	5.00 - 20.00
Water Stress Index	Combined Indicator Representing the Level of Water Stress on Agricultural Systems	Unitless	Derived from Other Indicators	0.25 - 0.75

Figure 4 illustrates a comprehensive desertification indicator system designed for various geographical and temporal scales. This framework aims to enhance the completeness and effectiveness of desertification monitoring, addressing issues like salinization, vegetation reduction, and soil erosion. It incorporates diverse indicators to analyse desertification processes across local, regional, and broader contexts. The hierarchical approach evaluates desertification through pressure, state, impact, and response indicators, considering both biophysical and socioeconomic factors. Utilizing remote sensing and field surveys, the framework ensures accuracy in assessing desertification, with remote sensing providing spatial and temporal continuity while field surveys validate indicators. This multi-type, multi-scale, and multi-dimensional system emphasizes the integration of remote sensing and field monitoring to effectively analyse and respond to desertification challenges.

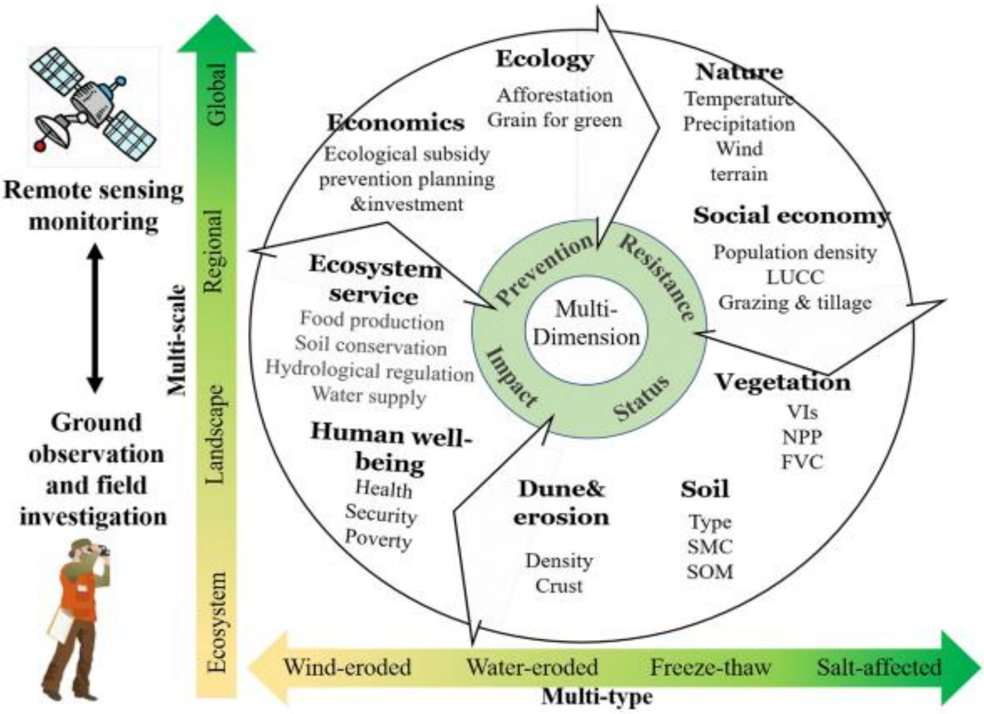

Figure 4: The Indicator Framework for Soil Desertification Monitoring.

Discussion

This study analysed the spatial dynamics of agricultural intensification, land degradation, and water resource management across various agroecosystems from 2008 to 2022. Utilizing climate data, farm statistics, GIS data, and remote sensing images, it assessed the impacts of agricultural intensification on land and water resources. The study mapped land cover changes, developed an Agricultural Intensification Index based on crop production, fertilizer, and irrigation use, and calculated indicators for land degradation and water stress. Forecasting models evaluated soil erosion risk and spatial autocorrelation analysed regional patterns. The findings highlight the intricate relationships between agricultural intensification, land degradation, and water resource management, aiding stakeholders and policymakers in formulating sustainable management policies.

Table 1 presents descriptive statistics and correlation analyses for land cover change, agricultural yield, soil erosion rate, and the NDVI across the research regions. The table details the mean, standard deviation, and correlation coefficients for these variables, illustrating the interrelationships and potential implications for agricultural systems. It reveals that increased percentages of land cover change are associated with higher crop yields, while simultaneously correlating with decreased soil erosion rates and NDVI values. This suggests trade-offs between agricultural development and environmental degradation. These findings emphasize the necessity of integrating agricultural development with sustainable land management practices to mitigate adverse environmental impacts. Table 2 illustrates the spatial distribution of hotspots characterized by high LCC, irrigation intensity, low NDVI, and potential land degradation. These hotspots are critical for prioritizing conservation and management efforts to mitigate the impacts of agricultural intensification on land and water resources. Regions such as the North China Plain and Loess Plateau exhibit land cover change and irrigation intensity linked to agricultural expansion, leading to increased vulnerability to soil erosion and water scarcity. The analysis highlights regional disparities in hotspot categories, indicating the necessity for tailored management strategies. In contrast, the Yangtze River Delta displays moderate land cover change and irrigation intensity, suggesting different variables may contribute to medium levels of land degradation.

Table 3 presents the results of Kriging and Cokriging interpolation for soil salinity and NDVI across various regions. The spatial autocorrelation values (Moran's I) indicate geographical clustering or dependency, which can negatively impact land and ecosystems. The study identifies regional high-salinity clusters, suggesting that soil salinization hotspots may harm agricultural soil fertility and productivity. Kriging interpolation effectively measures soil salinity, aiding in targeted salinization risk management. In contrast, Cokriging with precipitation data yields a non-significant Moran's I value, indicating a lack of clustering in NDVI values across the study area. This suggests that NDVI may not reflect regional patterns or environmental influences on vegetation health and productivity. Additionally, spatial cokriging of NDVI data highlights risks related to vegetation and land degradation.

Table 4 presents the landscape pattern analysis of the study region, focusing on patch size, form index, and edge density. These metrics influence ecosystem function and resilience to land degradation. Larger land cover patches signify continuous landscapes, while the Loess Plateau, with the smallest average patch size, indicates fragmentation. The North China Plain exhibits the highest form index, suggesting simpler topography due to agricultural practices. Edge density measures habitat fragmentation, with the North China Plain showing the highest density, reflecting environmental fragmentation from intensive agriculture. Overall, the analysis highlights spatial diversity in land cover patterns and underscores the risks of land degradation, informing targeted conservation and management strategies to enhance ecosystem resilience and sustainability.

Table 5 presents baseline and two alternative water stress indices, illustrating the impact of management actions on agricultural water stress. The baseline scenario indicates moderate water stress resulting from current agricultural practices, highlighting challenges in water resource management. Scenario 1 improves irrigation efficiency, reducing water stress across most regions and demonstrating how technology can enhance water efficiency. Scenario 2 optimizes land use by designating agricultural areas, resulting in moderate water stress in some regions and emphasizing trade-offs between land use planning and water resource management. The scenario modelling in Table 5 underscores the need for alternative strategies to manage agricultural water stress, aiding policymakers and stakeholders in promoting sustainable water management and climate resilience in agriculture (Rashid et al., 2023). Table 6 presents a cost-benefit analysis of two interventions aimed at reducing land degradation and promoting sustainable land management. The first intervention involves installing sprinklers or drip irrigation systems, which can conserve water, enhance agricultural efficiency, and increase production. However, farmers may require financial support, maintenance, and training for technology adoption. Evaluating this intervention necessitates data on irrigation water usage, agricultural output, and associated costs. The second intervention focuses on land use zoning and restrictions to protect natural habitats and agricultural areas, potentially improving water management and soil quality, although it may economically impact farmers on marginal lands and complicate enforcement. This intervention requires data on land cover, soil quality, and agricultural economic performance. Table 6 highlights the need to balance the benefits and drawbacks of each strategy to effectively combat land degradation and enhance sustainable land management, providing insights for policymakers and stakeholders to make informed decisions (Verma et al., 2022).

Table 7 presents a geographical analysis of the impact of land cover change on soil quality, highlighting changes in land cover percentage, soil erosion, and salinity. In the North China Plain, land cover modifications have led to increased soil erosion and salinization, negatively impacting agricultural productivity and ecological services. Similarly, the Loess Plateau experiences enhanced soil erosion and salinization due to minor land cover changes. Effective land management is essential to mitigate soil degradation and maintain ecological integrity in rapidly changing landscapes. In contrast, the Yangtze River Delta exhibits stable soil conditions and minimal land cover change; however, monitoring is crucial due to urbanization's impact on soil resources. Overall, the findings underscore the need for proactive soil health management in agriculture, enabling policymakers and land managers to promote sustainable land use and conserve soil resources for future generations.

Table 8 illustrates regional water resource stress due to agricultural intensification, focusing on irrigation intensity, water availability index, and water use efficiency. The North China Plain is likely experiencing water scarcity due to high irrigation intensity and low water availability and efficiency, suggesting that intensive farming is straining local water resources. In contrast, the Loess Plateau maintains effective water management with moderate irrigation intensity and improved water availability and efficiency. The Yangtze Delta exhibits lower irrigation intensity, good water availability, and efficient water use, resulting in minimized water stress. Ongoing monitoring is essential for sustainable water resource management. Overall, Table 8 highlights the connection between agricultural development and water resource stress, underscoring the importance of enhancing productivity and conservation efforts. Improving water use efficiency and implementing sustainable management practices can help mitigate the environmental impacts of agricultural intensification and bolster resilience against water scarcity.

Table 9 presents scenario simulations of regional water stress indices, detailing the current agricultural and land use situation in the 2020 baseline, which indicates significant water stress in several areas. Scenario 1 demonstrates reduced water consumption through improved irrigation practices, alleviating water stress in most regions. Scenario 2 optimizes land use by designating appropriate agricultural areas, resulting in reduced water stress in some regions, although mild stress persists due to competing land use demands and enforcement challenges.

Table 10 shows the evolution of the regional Water Stress Index from 2008-2015 to 2016-2022, including average SPEI, slope, and statistical significance across five main zones in China. While Zone 1 experiences a slight, statistically insignificant decrease in water stress, Zones 2 and 3 show similar trends without significant changes. Conversely, Zones 4 and 5 exhibit a gradual increase in water stress. Overall, these tables highlight the varying water stress conditions and the need for effective water management strategies.

Table 11 summarizes trends in soil erosion, land cover change, fragmentation, productivity, and SOC concentration from 2009 to 2022. It indicates that annual soil erosion contributes significantly to soil degradation, with mountain regions experiencing more erosion than plains, often linked to deforestation and unsustainable agricultural practices. Changes in land cover types reflect the replacement of natural vegetation by farming activities, with agriculture impacting more than just protected areas. Effective conservation and land use planning can mitigate land degradation. Increased edge density and reduced patch sizes indicate habitat fragmentation due to intensive agriculture. Policies should prioritize landscape restoration and land acquisition to enhance ecosystems. Land productivity, measured in kilograms per hectare per year, is positively influenced by favourable soil conditions, while sustainable agriculture and soil fertility management help protect and improve land. Finally, SOC concentrations are lower in intensively farmed areas compared to natural ecosystems, highlighting the benefits of no-till farming and land restoration for soil health (Rufin et al., 2021).

Table 12 presents data on agricultural intensification from 2009 to 2022, focusing on infrastructure density, AII, land cover change, crop yield, fertilizer rates, and irrigation water use. The report highlights the environmental implications of regional agricultural intensification. Land cover changes from natural vegetation to crops can enhance farming but may also reduce biodiversity. While intensive agriculture boosts crop yields in some areas, it can lead to land degradation and soil erosion in others. The findings underscore the necessity for sustainable farming practices and soil conservation to maintain productivity. High fertilizer usage poses risks of soil contamination, necessitating optimization to minimize environmental harm. Additionally, the demand for irrigation contributes to water stress. Effective management strategies for irrigation and greenhouse practices are essential for water conservation. The AII varies by region, indicating that socioeconomic and environmental factors significantly influence agricultural intensification. Local agricultural expansion and sustainable land management are crucial for balancing productivity and environmental health (Ghosh et al., 2022).

Table 13 presents the spatial patterns of regional water resource management indicators from 2008 to 2022, encompassing water use, precipitation, groundwater availability, and the Water Stress Index. Analysing the distribution and stress of water resources is crucial for sustainable water management and agricultural planning. Annual agricultural water use is quantified in cubic meters per acre, revealing significant consumption in certain areas, which indicates water stress and competition for resources. To mitigate water scarcity, the implementation of effective water management strategies and water-saving technologies is essential. Table 13 also includes average annual precipitation data, measured in millimetres per year, highlighting the variability in rainfall across regions and its implications for water resource allocation and agricultural planning. Groundwater availability, assessed through various metrics, reflects regional recharge rates and aquifer stability, underscoring the importance of sustainable groundwater management and depletion prevention. The Water Stress Index evaluates regional agricultural water stress using multiple indicators, with variations attributable to complex supply, demand, and environmental factors. Given climate change and increasing water needs, integrated water resource management systems are necessary to enhance conservation, efficiency, and resilience.

Policymakers and stakeholders can effectively address water scarcity and promote sustainable development by understanding the spatial dynamics of water resources and implementing targeted interventions and adaptive strategies (Du et al., 2023). Table 13 presents the geographical patterns of water resource management indicators in China from 2009 to 2022, highlighting regional disparities in water usage, precipitation, groundwater availability, and stress levels. Areas with intensive agriculture, such as the North China Plain, exhibit significant water demand and stress, underscoring the vulnerability of agricultural systems to water scarcity.

In contrast, increased precipitation and groundwater availability in the Yangtze Delta contribute to alleviating water stress in that region. To address water scarcity in China's water-stressed areas, there is a critical need for sustainable water management practices and enhanced water use efficiency, which will ultimately foster resilience and sustainability in agricultural and other sectors.

Furthermore, studies on spatial water resource management indicators significantly contribute to policymaking in China. Policymakers can enhance water security and resilience in vulnerable regions characterized by high water stress and limited groundwater availability by investing in water-saving technologies, improving irrigation infrastructure, and implementing groundwater recharge initiatives. The research emphasizes the importance of considering climate, land use, and water consumption in integrated water resource management. By promoting sustainable water management practices and adaptive strategies, China can mitigate water shortages, enhance agricultural productivity, and stimulate socioeconomic development.

Conclusion

This study explores the intricate relationship between agricultural development, land degradation, and water management in China from 2008 to 2022. Utilizing GIS and remote sensing, it reveals regional disparities in land cover change, crop yield, and irrigation intensity, particularly between the North China Plain and the Yangtze Delta, highlighting the need for targeted sustainable agricultural interventions. The findings identify environmental pressures, such as increased soil erosion and water use, that support China's conservation goals. The research advocates for spatially explicit land and water management strategies and tailored solutions, including improved irrigation practices, to mitigate land degradation and water stress. Ultimately, it provides valuable insights for policymakers to enhance soil conservation and ecosystem resilience, aligning with China's ecological civilization and green development objectives while fostering sustainable agricultural practices.

Despite its strengths, this study has limitations. Concerns regarding the consistency and accuracy of secondary data sources may introduce bias. Additionally, the geographic resolution and lack of supplementary data could hinder detailed research on agricultural and soil degradation using remote sensing imagery. Moreover, spatial analysis alone cannot establish causality due to the complex interplay of various factors influencing agricultural intensification and land degradation; thus, field observations and transdisciplinary approaches are essential for validation. To address these challenges and enhance research in this area, several strategies can be implemented. Establishing coordinated data-sharing and monitoring networks could improve the quality and accessibility of spatial analysis data. Incorporating field data and stakeholder input would enrich spatial analysis by providing socio-economic insights and local perspectives on agricultural intensification and land degradation. Furthermore, addressing the intricate feedback loops between agriculture, land degradation, and water resource dynamics could benefit from machine learning and agent-based modelling techniques. Finally, collaboration among scholars, policymakers, and communities is crucial for developing effective and sustainable land and water management policies both in China and globally.

Theoretical and Practical Implications

This research supports policymakers, land managers, and agricultural and environmental stakeholders by utilizing remote sensing and GIS to monitor the impacts of agricultural intensification on land degradation and water resources. It identifies environmental stress hotspots to inform targeted interventions, while spatial indicators like the Agricultural Intensification Index facilitate evidence-based policymaking and adaptive management. The study highlights regional agricultural intensification trends and their environmental implications, guiding sustainable agriculture and environmental protection strategies. By identifying areas with high irrigation intensity and water stress, it promotes the adoption of water-saving technologies. Additionally, analysing land degradation hotspots aids in preserving ecosystems and informing soil conservation and land-use planning. Ultimately, this research advocates for sustainable agricultural and environmental management practices in China and other challenging regions. The Agricultural Intensification Index and water stress metrics evaluate the impacts of agricultural practices on land and water resources, leading to theoretical insights into agricultural transformation and environmental degradation. This research promotes sustainable land management and resource conservation while identifying hotspots of land degradation and water stress, along with mitigation measures. By integrating environmental science, geography, and agricultural economics through multidisciplinary approaches and spatial analysis, the study advances theoretical frameworks on the intricate connections between human activity, environmental change, and sustainable development, extending its relevance beyond China.

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