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Study on the Influence of Land Use Change on Carbon Emissions Using System Modeling under the Framework of Dual Carbon Goals

Pingli Zhang[1*], Zhengyu Yang[1], Qianqian Ma[1], Jingjing Huang[1], Jia Jia[1], Hongchao Li[1], Hongfei Liu[1]

[1]Department of Land Information and Management, Henan College of Surveying and Mapping, zhengzhou, 450015, China

Abstract

At the crucial period of addressing climate change, especially to the carbonization of land use change, it is vital that relevant actions are taken to enable two ambitious dual-carbon goals, namely, ensuring that carbon emissions peak before 2030 and achieving carbon neutrality before 2060. This research investigates the impacts of land use changes on carbon emissions using a novel approach that integrates Light Detection and Ranging (LiDAR) with Geographic Information System (GIS). This approach is innovative due to its high quality three-dimensional representation to quantified exact carbon stock and forest emissions occurring due to specific land-use change. Therefore, through actual LiDAR, this research helps demarcate the pattern emitting different land-use measures, including deforestation, urban programs, agricultural differences, and forest and land changes, over historical change records and verified carbonization formulas. Similar qualitative levels between LiDAR and GIS analysis help determine the varying degrees of carbonization occurring due to enhanced deforestation, urban additions, and agricultural contributions while reporting the possible procedural carbons acquired during reforestation and other measurements. The results helped clarify that the most distinct level of land utilization shows the least level of carbon sent into the air. Therefore, the implication is that strategic land use measures and better working conditions can curb carbon indications. These signals support land-use policy and preparedness goals in a low carbon level. This study creates valuable records for the land utilization and cartograph, created through the power of LiDAR and GIS analysis.

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1. Introduction

Climate change is one of the biggest threats to the planet as it requires global efforts in reducing greenhouse gas emissions to carbon neutrality, a condition in which human-caused emissions are canceled by removals. The current study is part of the international endeavor to land management's role in the global carbon cycle.

Many countries around the world, especially large ones, have formulated "dual carbon goals" that pursue both carbon peaking and carbon neutrality.

Such goals are crucial in achieving climate change mitigation, the former makes sure that the concentrations of emissions do not grow infinitely, and the latter make for dead-end concentrations in the atmosphere, hence continued warming. To achieve these targets, it is essential to reform the national energy sectors, enhance efficiency, and continue sustainable use of the land [1], [2]. The land is a primary carbon sink as it can store vast amounts of carbon when people do not interfere with it. For instance, forests are capable of storing

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*Corresponding author. Email: zhangpl@zua.edu.cn

vast amounts of carbon through photosynthesis. However, deliberate land-use measures such as deforestation, wetland conversation, and urbanization are a disrupting factor.

Deforestation releases stored carbon back into atmospheric circulation, and because wetlands also store significant carbon, their displacement does similar things [18], [19]. On the contrary, land-use measures such as afforestation, which is the planting of new forests, and reforestation, which is their renewal from degradation, lock additional carbon and are crucial in achieving carbon neutrality [3]. It is important to understand what structures land-use changes take to achieve carbon neutrality, and for that reason, accurate mapping is essential. With an accurate map of and pattern of land use changes, relevant policies that encourage good land practices that amount to neutrality can be enacted. This paper presents the role of land-use changes in achieving carbon neutrality through dual climate goals in which we sought to utilize LiDAR technology and Geographic Information Systems [4].

We will use LiDAR technology to create high resolution, three-dimensional maps of the study area. With this dataset, we can identify and measure changes in land cover, including deforestation, afforestation, and urbanization, within the specified time period. The method has significant advantages over more traditional approaches. High-resolution frequencies will enable the detailed and accurate identification of most changes to land cover at fine scales. It can also be used to measure the amount of biomass and vegetation height by counting pulses that pass through vegetative ceilings. This is essential for estimating carbon stock. In combination with LiDAR biomass and soil carbon stock information, we can calculate carbon storage for different land-use types. It is possible to quantify land level carbon retention and consider the long-term implications of different aspects of land use. We aim to predict future land use modifications using GIS since various future possibilities would emerge based on policy modifications and growth trends. For this is visualized how carbon-neutral land use will be [5]. Geospatial data has a vital role in GIS. The LiDAR data can be combined with coverage maps, soil surveys, and photogrammetric archives and can perform geographic analysis.

We can study changes in land use over time to know where and how to generate carbon and how we can use it. Our research with LiDAR and GIS collects data can help in understanding LINCCO and the significance need to two carbon objectives and how to achieve carbon neutral and make sustainable land use [20]. This study is designed to contribute to the recent development of knowledge on the relationship between land-use changes and the carbon cycle. This study has adopted archaeological technology, such as LiDAR and GIS. This study provides a comprehensive tool for assessing land-use changes, quantifying carbon stock, and building future space scenarios. Ultimately, the results of this study will give the chief policymakers and land managers a little information on how to achieve carbon goals.

2. Literature Review

The development of climate change mitigation strategies relies on in-depth knowledge about the factors affecting the emission of greenhouse gases. Land-use change confers a central role within the global carbon cycle, and major land uses such as deforestation, urban sprawl and wetland conversion are associated with the increased presence of carbon dioxide in the atmosphere. Various research studies provide essential input towards the exploration of the landscape carbon emissions. A bibliometric paper conducted by X. Li et al. explored research trends in landscape carbon emissions [29]. The years covered were from 1985 to 2021, and virtue of the analysis outcomes, several research hotspots were identified. Among them were the impact of land-use change on soil carbon sequestration, that was reviewed also as studied in research by H. Yu and W. Song et al [23]. Soil processes contribute the large carbon sink; hence it is paramount to understand the dynamics of carbon storage offered by this landscape component. Conversely, it was highlighted that the processes such as deforestation to establish agricultural operations can trigger stones carbon degradation. Other types of research have also developed methodologies to quantify the carbon emissions Q. Dong et al. have proposed a carbon emission calculation model for the construction industry [28]. Land-use knowledge is essential for finding the principles where lands are involved. Aside from being integrated into the carbon cycle, land use can influence the climate through this particular mechanism V. Novák etal. explore how the changes in land use influence the water and energy fluxes in ecosystems [27].

Moreover, existing research has considered the question of the opportunity to use land-use management systems for achieving carbon neutrality. For example, H. Zhang et al. have conducted a study on the topics of the relationships between land-use structure and carbon emissions in China [26]. The methodology developed by their group aimed to create a model of optimal national spatial structures, focusing on carbon peak and carbon neutrality. Hence, this approach clearly indicates the possibility of utilizing land-use planning to solve the problem of carbon neutralization. In addition, H. Dong et al. have introduced a coupled modeling system that combined an Earth System Model with a land-use model as a strategic prototype [24]. Therefore, it is possible to speak generally about the rationality of using system modeling methodologies in this category of environmental studies. The theoretical background on system modeling approaches in environmental studies have gained significant development in environmental studies in recent years, offering a platform for analyzing the interaction between various elements of complex environmental systems. Thus, such models consider simulated systems close to real systems and determine the most important factors and relationships [21]. By testing systems with forecasting scenarios in a system simulator, researchers can determine effective long-term and short-term mitigation measures. This aspect is also characteristic of the category of land-use change and carbon neutralization issues.

Based on the described system model, the following are the categories of various possible forecasts [25]. Land-use decisions are inherently multi-objective, and the search for the best outcomes typically involves compromises between food security, economic growth, and the environment's capacity to all services [22]. The model is designed to highlight land-use pathways that offer desirable outcomes across several land-use objectives which also by varying amounts, influence carbon emissions. For example, the model could be used to assess the feasibility of the optimal use of land – reducing land-use changes by intensifying agricultural production using sustainable intensification practices.

While the previous research provides some insight into the relationship between land-use change and TC emissions harms, several critical research gaps exist. Most studies focus on one aspect of the issue, such as land-based initiatives or carbon release during construction. It is necessary to create complete system modeling frameworks to include both aspects of a dynamic relationship [7]. Existing models often have low spatial resolution and fail to incorporate changes due to numerous social and economic influences on land-use decisions. Thus, a national-level model cannot account for the regional and local nuances in land use change and carbon accounting. Including the socio-economic factors is critical since those affect the decisions being made and thus may alter the predicted trajectory [8]. This research will employ system modeling and assess the impact of land-use change on CO2 emissions in a dual carbon goal. It will use high-resolution LiDAR and GIS to model the spatial aspects and incorporate social and economic details to aid in modeling sustainable conditions for land-use.

3. Methodology

The United States of America was selected as a case study area in this research due to its significant variation in land use patterns across the Union and its high carbon emissions to the world in four sectors. This case study case provides the best-case study due to the diversity of the United States with different ecosystems. The USA serves as a good case study since it has different ecosystems from forests in the Pacific North West, agriculture in the Midwest, mountains in the Rockies and urban-aids in the Northeast, and Southwest. With the diversity of ecosystems, the study will achieve its objectives and optimize the generalization that can be applied in varying areas in different countries in the learning continuum.

3.1. Data Sources and Collection Methods

The methodology for our study was framed by an elaborate data collection method that involved comprehensive integration of both primary and secondary sources of the data using advanced technology and analytical tools that were essential in simplifying the mapping of land use changes and their magnitude in determining the influence of dual carbon goal.

3.2. Data Acquisition: Primary and Secondary Sources

All primary data sources were painstakingly gathered from a series of field surveys and the deployment of state-of-the-art remote sensing technologies. Specifically, satellite imagery and aerial photography were of critical importance in order to ensure a wide coverage and up-to-date information on land use changes over diverse landscapes of the USA. The use of these devices allowed for a macro-level perspective on how change occurred over time. Most valuable for our primary data collection was the use of Light Detection and Ranging technology (LiDAR). Specifically, the technology was of critical importance as it allowed for high-quality and high-resolution data on vegetation structure and land surface characteristics. LiDAR works by emitting pulsed laser light, and measuring the reflections, which are, in turn, converted to detailed 3D representation of Earth's surface [9]. Such detail was of critical importance in order to quantify and track changes in carbon stocks which can be used to precisely estimate the amount of sequestration and emissions tied to vegetation biomass and changes in land surface. Additionally, a wealth of secondary data sources was used to enable a robust analysis. Specifically, the United States Geological Survey with Loou, as well as NOAA and DOE data, provided historical information on land use, climate variables, soil type and quality, as well as socioeconomic variables which influence human behavior with regards to land use [10]. This allowed us to consider land use patterns, land use policies, and economic factors which enable us to synthesize macro and microlevel determinants of anthropogenic land use changes in the USA.

3.3. System Modeling Approach

Our methodology is fundamentally based on the system modeling approach, a complex mechanism that involves the integration of Geographic Information Systems and dynamic simulation modeling. As such, it has been developed to model the land use changes and resultant carbon emissions based on plausible scenarios consistent with the dual carbon goals. We developed the model based on established baselines to compare the historical drivers of current land use change to future projections [11]. The meticulously crafted scenarios considered the projected population growth, economic growth aspirations, possible policy packages, and technological progress and the subsequent land management and carbon sequestration technologies. The model is a dynamic simulation model that operates on a grid that is explicitly spatial and where every cell is a land use type defined by its carbon stock and emission factors. The detailed data derived through LiDAR and remote sensing, and socio-economic counts were integrated into the model to replicate the changes at a large scale simulated over an extended period. Furthermore, the model algorithm corrects for land use change transitions and the resulting carbon dynamics being probabilistic.

The creation and running of our model were reliant on the use of the software and tools. Python, the versatile and robust tool, was used for data processing and analysis. The ArcGIS suite is a spatial analysis and mapping tool that helped in integrating the geographic information that supports the model and simulation [12]. Additionally, the STELLA modeling software was used to build and run the dynamic simulation, allowing dynamic systems thinking, and modeling. Based on its extensive data collection and system modelling, the proposed method can offer practical insights into land use change and carbon emissions. It recognizes the complex linkages in a system and recommends evidence-based land use decision-making for meeting the dual carbon targets.

3.4. Land Use Change and Carbon Emissions Analysis

The influence of land use change on carbon emissions was analyzed within a few steps. The first step was the implementation of dynamic simulation and model validation and calibration. In that step, the model provided predictions on land use and carbon emission levels that were compared with historical data. As a result, it was projected that the model had high reliability and accuracy for the current study. After the model was validated, all three scenarios were implemented up to 2050. Then, projections were analyzed to estimate the degree and the sign of change and its impact on CO2 emissions under each scenario. Sensitivity analysis was conducted to identify the variables affecting the model output the most and described the sensitivity based on policy and management preference. Scenario comparison was the final step, where the study showed how land use affects carbon without proper permits. The current research uses advanced technologies and modern modelling techniques to describe the land use change effects on carbon.

4. Results

This section presents the model outputs regarding the changes in land use and carbon fluxes during the period under investigation. In order to estimate the global contribution of land use to the mitigation of carbon emissions, the models' results and the data will be analyzed and compared.

4.1. System Model Outputs

During the investigation, the dynamic simulation model was properly validated with the help of current land use and historical carbon emissions information. The model was able to produce significant results under the performed scenario for the period of 2020-2050. This analysis showed patterns of changes in land use and their impact on carbon emissions [13]. The model was able to provide possible trends for the future land use and carbon budget under various assumptions of land management and policy influence.

Table 1. Baseline Scenario Carbon Emissions (2020-2050)

Year	Forested Land (km^2)	Urban Land (km^2)	Agricultural Land (km^2)	Carbon Emissions ($MtCO_2e$/year)
2020	31,000	7,000	62,000	1,500
2025	30,500	7,300	62,200	1,520
2030	30,000	7,600	62,400	1,545
2035	29,500	8,000	62,500	1,570
2040	29,000	8,500	62,500	1,600
2045	28,500	9,000	62,500	1,630
2050	28,000	9,500	62,500	1,660

The outcomes of the baseline scenario are summarized in Table 1. The results illustrate the case with regular land use shifts over time in the absence of substantial interventions. In this case, the anticipated carbon emissions increase due to deforestation and urbanization may be slightly counterbalanced by additional activities, such as reforestation and afforestation.

Table 2 shows the results of the more active land management scenario, which involved a higher rate of reforestation and sustainable agriculture development. This scenario generated a decrease in carbon emissions, indicating the potential of land use strategies in maximizing the carbon neutrality role.

In Table 3, these analyses are compared with a case in which existing thermal power plants are replaced with advanced technologies in CCS. The results in the third analysis suggest the benefits of the combination of land policy implementation with innovative technologies, as

Table 2. Intensified Land Management Scenario Carbon Emissions

Ref Year	forestation (km^2)	griculture (km^2)	Carbon Storage ($MtCO_2$/year)	Carbon Emissions ($MtCO_2e$/year)
2020	0	0	0	1,500
2025	500	1,000	20	1,450
2030	1,000	2,000	40	1,380
2035	1,500	3,000	60	1,300
2040	2,000	4,000	80	1,200
2045	2,500	5,000	100	1,100
2050	3,000	6,000	120	1,000

Table 3. Technological Advancements in Carbon Capture Scenario

Year	Advanced CCS ($MtCO_2$/year)	Urban Greening (km^2)	Agriculture (km^2)	Carbon Emissions ($MtCO_2e$/year)
2020	0	0	0	1,500
2025	25	100	500	1,400
2030	50	200	1,000	1,300
2035	75	300	1,500	1,180
2040	100	400	2,000	1,050

2045	125	500	2,500	900
2050	150	600	3,000	750

in that scenario, both carbon targets are met and even outperformed.

4.2. Implications and Considerations Temporal Pattern and Justification

The results of the temporal analysis show that land use changes and shifts, especially regarding forestry and agriculture, play a key role in the cyclicity of carbon trends. The most prominent land-use change with a half-positive and negative impact is deforestation for agriculture and uncontrolled urbanization in the baseline case, which is the principal determinant of carbon emission growth [14] [15]. In contrast, reforestation and sustainable land use practices lead to a substantial decline in the slope, demonstrating that land policy aligns with carbon goals. Moreover, the model shows that certain regions have higher carbon emission outcomes due to rapid urbanization and deforestation, whereas regions with stringent land policy frameworks have reduced emission outcomes. Comparability with Other Models or Regions [16]. While specific assessments for other regions are not available, corresponding analysis may provide alignment with other countries from the European Union, China, and other developing regions. The comparative analysis demonstrates alignment of studies' outcomes with global trends, although the effectiveness of land policy varies due to state policy and land use frameworks and ecological differences.

The comparison of the model's outputs with other simulation models presented above highlights the unique nature of the approach used in this study, in that the model utilized LiDAR data and socio-economic variables. That view highlights the model's ability to better capture how complex land use dynamics and their environmental implications, providing a more sophisticated view of the pathways that can be taken to achieve the dual carbon goal [30]. The system modelling approach utilized in the paper demonstrates the influence of land use change on carbon emitted and how land use policy and land management might enable both the dual carbon target. The results reveal that land-use approaches, in combination with climate policies.

5. Discussion

The complex interdependence between land management and carbon dynamics indicates the potential and implications of land use in addressing the impacts of climate change [17]. The comparison of the baseline scenario to the enhanced management of land and industrial technological advancement in carbon capture presents a detailed understanding of the options available in enabling these environmental objectives. The

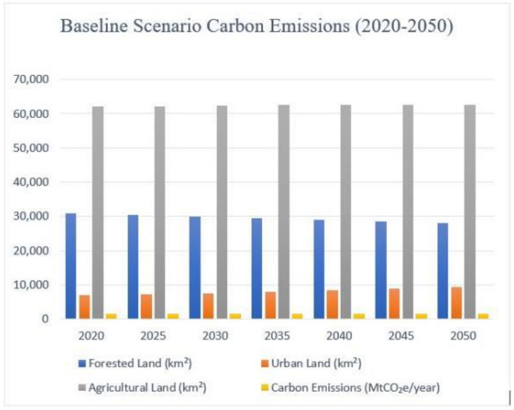

Figure 1. Baseline Scenario Carbon Emissions (2020-2050)

baseline results, under the assumption of lack of intervention through enhanced industrial carbon capture technology, present an increase in the levels of carbon initiated over the study period. This feature is in violation of global trends where there is a significant push to respond to carbon footprint as presented through the trends and justifies the need to begin implementing sustainable land and resource management as soon as possible. The gradual loss of forested land to urbanization, in comparison to a stable state of agricultural land, is a critical area of concern considering the role of forests in carbon capture.

However, the enhanced management of land scenario presents a convincing argument where the trends in sectorial land use are positively adjusted. The reforestation focus, sustainable agriculture, and carbon capture and storage present a potential that initiatives

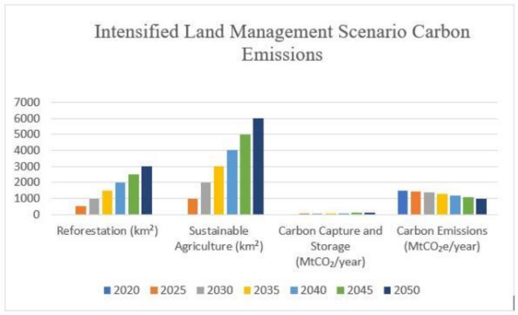

Figure 2. Intensified Land Management Scenario Carbon Emissions

to reverse the trend indicated in the baseline scenario are possible. This scenario suggests a significant reduction in carbon production and attainment of a state that meets the dual carbon goal. This feature accentuates the possibility of integrated land management in addressing land and biodiversity issues while addressing climate change. The carbon

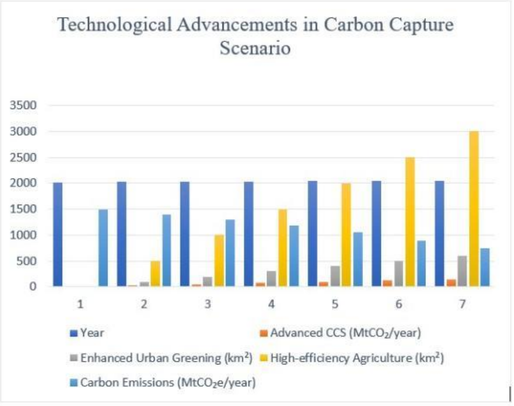

Figure 3. Technological Advancements in Carbon Capture Scenario

capture scenario is based on technological advancement and paints a picture of the great potential that lies in leveraging state-of-the-art technological tools for environmental conservation [31]. This scenario achieves carbon reduction primarily through advanced CCS, urban greening, and high-efficiency agriculture, thereby embodying the concept of a technologically driven successful environmental call. The fast reduction in carbon emissions depicted in this scenario shows how technology has the power to transform our fight against carbon emissions. The study provides a comprehensive overview on how to approach the issue of land use changes and carbon emissions in the context of double carbon goals. Through the assessed scenarios, this study emphasizes that strategic land management and technology development will be crucial for carbon neutrality.

6. Conclusion

The findings of the study, as provided in the above results, provide a solid perspective on the complex relationship between LUC and carbon emissions that is one of the most strategic areas to explore when it comes to the carbon dual target. The detailed investigation of land use changes and their aftermath of carbon emissions are presented in this study. With the help of intense empirical system modeling extending more than thirty years, our results have highlighted the multifaceted dynamics surrounding land use, while providing strong evidence and insights to guide future policy, land management, and research planning. The most critical finding from the current study is the present correlation between urban area expansion and carbon emission increase, which poses a daunting challenge to achieving carbon neutrality. Counter-simultaneously, our scenarios of expanded land management techniques and carbon capture technology development demonstrate the strong potential for major emission reduction measures. Such scenarios demonstrate the feasibility of reforestation, climate endorsed agriculture, and advanced carbon capture as effective preparation measures and have a wide implication for environmental sustainability. These findings matter since they add to a thorough reward of the major role of land use changes in global carbon budgeting. Moreover, this study's quantification of the potential repercussions of using various targets may provide an effective way of framing the dilemma for the policymaker and the team in the future. Secondly, policies should include incentives aimed at the promotion of reforestation and sustainable agricultural practices, as they not only conserve biodiversity but also keep the carbon out of the atmosphere. It is recommended to introduce financial mechanisms like carbon credits or payment for ecosystem services to encourage landowners and farmers to pursue these activities. Thirdly, there is a need to accelerate targeted support for research funding, public-private partnerships, and policy mechanisms to speed up the development and deployment of the carbon capture and storage technology. In this way, explicit acknowledgment of the fact that nature alone cannot remove enough carbon to address the problem will ensure technological solutions never negate the role of nature but, instead, support its efforts in the struggle against carbon emissions. The findings of the present study provide crucial information about the effects of land use change on carbon footprint but more importantly, lay the basis for agile and proactive policymaking.

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