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Exploring an assessment framework for the supply–demand balance of carbon sequestration services under land use change: Towards carbon strategy

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A R T I C L E I N F O

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A B S T R A C T

The key challenge created by global climate change is to implement effective carbon–neutral programs. The carbon sequestration service (CSS) establishes spatial and temporal connections between carbon sequestration supply and demand, so accurate scientific quantification of the CSS supply–demand balance is essential. However, a standard assessment framework for quantifying CSS supply–demand is currently lacking. In this study, we developed a spatio-temporal assessment framework for quantifying CSS supply–demand balance under land use change, based on the SPANs model. We followed the flow of CSS from supply to demand areas through spatial visualization based on the main wind direction and defined the transport path and quantity of CSS flow, taking Lancang Mekong River Basin (LMRB) as a case. The results showed that: (1) The total supply of CSS decreased by 1.14 million tons from 2000 to 2020, and total demand for CSS increased by 8.1 million tons. (2) CSS surplus areas were mainly concentrated in forested regions, with a maximum surplus of 4.31 t/ha. Deficit areas were dominated by cultivated land and artificial surfaces, with a maximum deficit of −1101.21 t/ha. There was spatial heterogeneity in CSS distribution and a clear imbalance between supply and demand. (3) Three out of six countries in the basin showed significant changes in CSS flow, with a decrease in demand area observed in Thailand and an increase in demand area observed in Cambodia and Vietnam. (4) CSS flow was mainly from north to south, with higher CSS in Thailand and lower flow in China. Thus the analysis revealed supply–demand imbalances in CSS and provided an objective understanding of the spatial flow of CSS. This scientific and intuitive theoretical basis and data support can be used for regional carbon management in LMRB and global carbon balance control.

1. Introduction

Ecosystem carbon sequestration service (CSS) is critically important by fixing carbon from the atmosphere and offsetting some of the carbon dioxide (CO_2) emitted by humans into the atmosphere, thus playing a role in climate regulation (Assesment, 2005). CSS is the link between biological processes and human well-being, coupling service supply with human demand (Boerema et al., 2017; Meng et al., 2023). Since the industrial revolution, increasing atmospheric levels of CO_2 derived from greenhouse gas emissions have led to global climate change, with climate warming being one of the most obvious characteristics. Current research by the international community is focusing on CO_2 emissions (Boamah et al., 2017; Zhang et al., 2019), carbon cycling (Reichstein et al., 2013), peak CO_2 emissions (Zhu et al., 2015), carbon neutrality (Rollo et al., 2020; Yu et al., 2023), carbon emissions reductions (Bayer and Aklin, 2020), carbon capture (Kim et al., 2020), carbon footprint (Liao et al., 2020; Yang et al., 2020c), carbon trading (Liu et al., 2023a), carbon tax (Beiser-McGrath and Bernauer, 2019), beneficiaries of CSS (Zhai et al., 2021), and ecological compensation (Luo and He, 2023). Reducing carbon emissions has become an urgent environmental issue,

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prompting many countries to conduct research on carbon emissions and carbon sequestration in ecosystems according to their own interests and needs.

Although carbon capture and storage technology is well-established, all countries continue to encounter significant challenges in achieving carbon neutrality. One of the reasons is the lack of a science-based, effective evaluation framework and regulatory implementation policies. To promote international negotiation and cooperation, it is clearly important to identify the relationship between CSS supply–demand and flow. Wind can only transport CO_2 emissions into the atmosphere, so the flow of CO_2 will be from regions with high carbon sequestration to regions with high carbon sequestration, following the wind direction. Considering that there is no physical movement from CSS supply to CSS demand, the flow is defined as CSS from supply to demand. Therefore, it is necessary to study the whole process of CSS, i.e., generation, flow, and use. Only by clarifying the flow process of ecosystem services from supply to demand can we provide a reliable basis for decision-making (Fisher et al., 2009; Li et al., 2013; Xiao et al., 2016).

Identifying the spatial alignment between ecosystem service supply and demand is critical when studying the spatial dynamics process of ecosystem services flow. Land use is a major factor affecting the carbon cycle, and land use change is the main factor driving changes in terrestrial ecosystem carbon sequestration (Bai et al., 2021; Yang et al., 2020a), which affects CSS supply capacity (Stocker et al., 2017). Previous research on the impact of land use changes on carbon sequestration ecosystem services has primarily been conducted from the following perspectives: Firstly, the types of land use changes are categorised, encompassing deforestation (Portela and Rademacher, 2001), urbanisation (Ouyang et al., 2021), agricultural production (Jiang et al., 2023), and reforestation (Nave et al., 2019). Secondly, we address the methodologies used to identify the impact of land use changes on carbon sequestration. This includes the application of models such as DayCENT for simulating carbon cycling processes (Gurung et al., 2020), remote sensing techniques for carbon stock estimation (Xiao et al., 2019), soil carbon sample collection (Olson and Al-Kaisi, 2015), climate change modeling (Pechanec et al., 2018), hotspot analysis (Ramachandra and Bharath, 2020), and the PLUS model to determine the temporal and spatial trends and correlations between land use changes and carbon storage (Liu et al., 2022). Thirdly, the study delves into the mechanisms by which these changes affect carbon sequestration, noting that deforestation reduces carbon storage and increases emissions (Li et al., 2022), while cultivation and grazing alter soil structure and organic carbon content, potentially leading to carbon release (Piñeiro et al., 2010; Shepherd et al., 2001). Conservation agriculture and organic farming practices have been observed to increase soil carbon sequestration (García-Tejero et al., 2020). Urban expansion is identified as a factor that reduces carbon absorption capacity, but this can be mitigated through increased vegetation cover in urban green spaces (Demuzere et al., 2014; Niemelä et al., 2010). Therefore, land use changes, being a significant factor in ecological transition, have a critical impact on enhancing or reducing ecosystem carbon sequestration ability.

Because of this, the scientific community has begun to study CSS flow under land use change. CSS flow can effectively connect spatially heterogeneous supply and demand areas. Some researchers have begun to examine the balance between regional CSS supply and demand (Zhao and Sander, 2015), spatial flow (Zhang et al., 2021), service flow transmission (Fang et al., 2015), the calculation basis for service flow (Pulselli et al., 2011) and frameworks for analysis of service flow (Serna-Chavez et al., 2014a). These studies have improved understanding of carbon supply and demand, but have not mapped specific service flow routes or quantified service flow. Quantification of service flow is still in the stage of conceptualization and preliminary exploration (Gopal and Brij, 2016; Serna-Chavez et al., 2014b), and work is needed on the dynamics of CSS transfer from supply to demand along with geographical matching.

Accurate quantification of CSS flow is critical to resolve imprecise assessments of CSS supply and demand (Liu et al., 2017). In recent years, the “Service Path Attribute Networks (SPANs)” model, which is based on Artificial Intelligence for Ecosystem Services (ARIES) (Bagstad et al., 2011), has been proposed for this purpose. The SPANs model provides a comprehensive framework for analysing the dynamics of CSS supply and demand, spatial flows, and their relationship with land use changes (Rovai et al., 2021). This includes calculating the carbon sequestration potential of mangroves (Manoj et al., 2024), identifying high carbon absorption areas (Pereira et al., 2024), and determining sequestration rates (Rovai et al., 2021). By constructing a “source-sink-use” framework, the SPANs model quantifies and maps ecosystem supply and demand, and it can depict the spatial flow process of ecosystem services (Palomo et al., 2018; Turner et al., 2012). However, the SPANs model has not been widely used to simulate the spatial flow of a specific ecosystem service in practical cases (Xiao et al., 2016). In particular, there is a paucity of research on the methodology for delineating precise service flow paths (Ma et al., 2017), and there are still some limitations in the implementation of carbon management practices.

Lancang Mekong River Basin (LMRB) forms a link between six countries in Southeast Asia and is very important internationally due to its special geographical location. In the early 21st century, rapid economic development in the basin has led to a rapid increase in carbon emissions. However, a systematic understanding of the current situation of carbon supply and demand in the LMRB is still lacking. Quantitative research on the supply and demand of CSS and service flow can provide a scientific foundation for comprehension.

At the basic carbon emissions level, under the influence of vegetation cover and human energy consumption, appropriate land use allocation is an important tool to achieve effective regional carbon management and guide regional low-carbon development (Liu et al., 2023b). Specific objectives of the present study were thus to: 1) calculate the spatial–temporal balance of supply and demand of CSS under land use change in LMRB; 2) identify the service flow transmission path in the basin, using the SPANs model; and 3) quantify the service flow. The overall aim was to outline CSS supply–demand and spatial flow under land use change, to provide a methodological framework for carbon neutrality assessments, and to support decision-making on regional carbon management.

2. Materials and methods

2.1. Study area

Lancang Mekong River is a world-famous international river and the largest in Southeast Asia. LMRB is located between 93.63–108.47°E and 8.55–33.56°N, with a basin area of $81.40 \times 10^4 km^2$. The mainstream has a total length of 4880 km and a total fall of 6475 m (Fig. 1a).

Lancang Mekong River originates in the Qinghai-Tibet Plateau of China, flows through six countries (China, Myanmar, Laos, Thailand, Cambodia, Vietnam) from north to south, and enters the South China Sea southwest of Ho Chi Minh City in Vietnam. LMRB is an important pillar of the agricultural system, energy industry, manufacturing industry, and food security of the surrounding countries. It plays an indispensable role in cultural exchanges, economics, and trade among countries. The basin has 47 hydrological stations (Fig. 1b).

2.2. Operational framework of CSS supply–demand and service flows

We developed an operational framework for quantitative assessment of CSS supply–demand and spatial flow (Fig. 2). First, we analyzed land use change in LMRB using a remote sensing artificial interpretation dataset for 2000–2020. Based on annual net primary production (NPP) values, calculated using the Carnegie-Ames-Stanford approach (CASA) model for each land use type, we then calculated carbon sequestration supply in the three study years (2000, 2010, 2020) using GIS spatial analysis technology and mathematical statistics methods and estimated

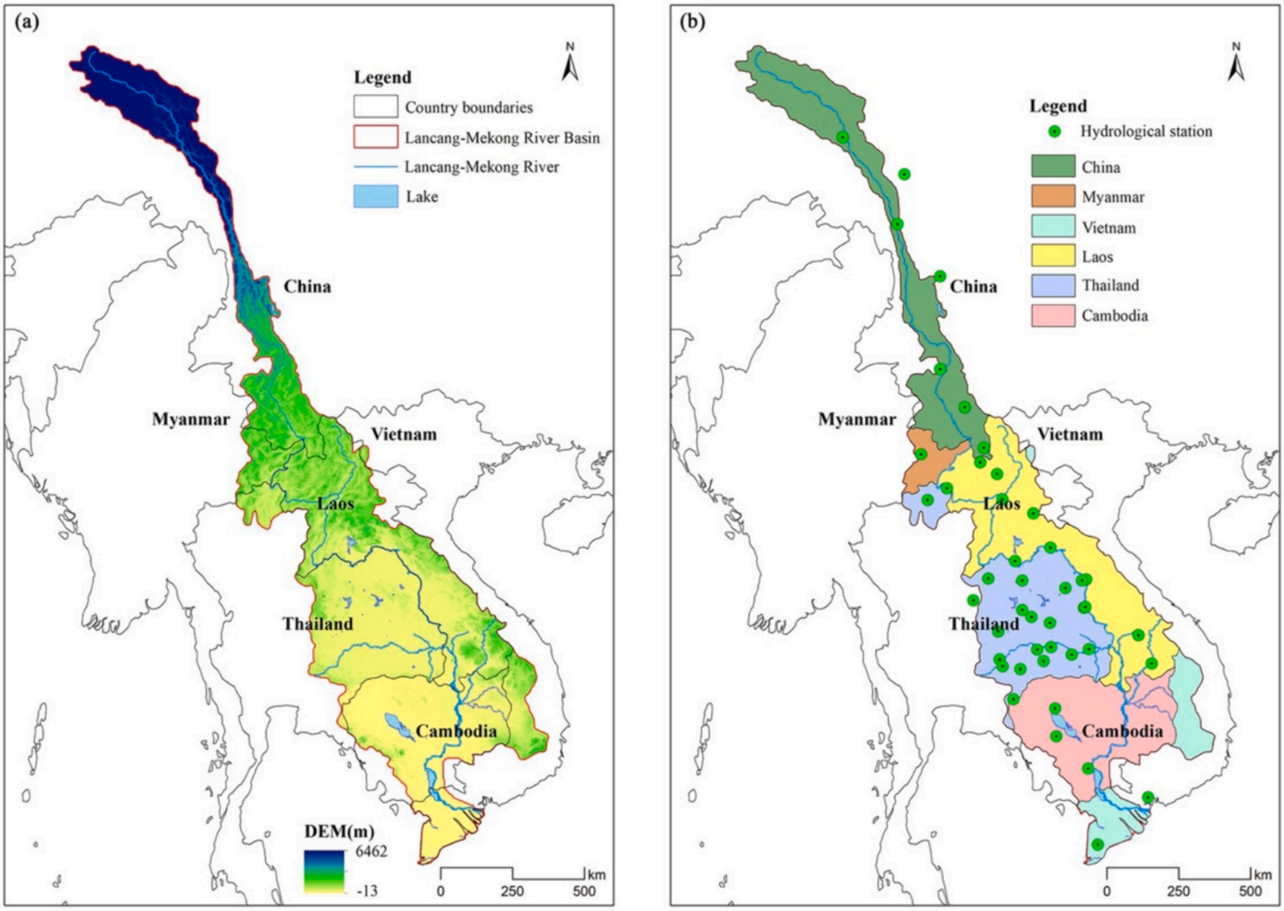

Fig. 1. (a) Location of Lancang Mekong River Basin (LMRB) and (b) the six countries within LMRB and its 47 hydrological stations.

CSS demand from the spatial population density. Next, we assessed the supply–demand balance pattern of CSS, including the supply–demand balance index, supply–demand balance area identification, and CSS flow and path. Finally, we assessed the implications of the results for low-carbon management policies.

2.3. Land use change

Land use/land cover (LULC) has significant effects on the function and spatial distribution of ecosystem CSS (Wu et al., 2006). We used a land use transfer matrix as the main tool for quantitatively analysing the quantity and direction of transformation between land uses. It specifically reflects the structural characteristics of land use change and the direction of land transfer between different types. Using the intersect module of ArcGIS and PivotTable in Excel, we superimposed and analyzed a land use classification map in ArcGIS, and obtained a land use transfer matrix for LMRB in 2000–2010-2020.

2.4. CSS supply and demand model

2.4.1. Carbon supply model

Net primary productivity (NPP) reflects the carbon fixation capacity of vegetation along with the initial material and energy entering the terrestrial ecosystem. In this study, we used NPP to characterize the supply of CSS, where the NPP data source (Gao et al., 2017) was based on MOD17A3 data calculated by the CASA model (see Part 2 in Supplementary Information (SI) for model theory).

The spatial change in NPP is closely related to the distribution of vegetation types and land use types (Zhao and Running, 2010; Zhou et al., 1998). Using ArcGIS, mask processing, and cell statistics, we obtained NPP values for different land use types and then used spatial grid classification to calculate the spatial–temporal change of NPP from 2000 to 2020, which represented the dynamic change in the supply of CSS in different years.

2.4.2. Carbon demand model

Ecosystem service demand refers to the sum of ecosystem products and services consumed or used by human beings in a certain area for a certain period, which can be characterized by demand distribution, demand quantity, and beneficiary distribution (Fu and Yu, 2016). Based on the quantitative relationship between DMSP/OLS global night light data and energy consumption and carbon emissions coefficient of energy consumption, the basic per capita carbon emissions of humans have been calculated (Ben-wu and Ya-li, 2017). The emissions coefficient method is suitable for multi-scale carbon emission estimation, but it is difficult to reflect spatial differences in carbon emissions by simple carbon emissions measurement. To more clearly demonstrate the spatial distribution of regional demand for CSS, we used the per capita carbon emissions data in energy statistics as a conservative estimate of the demand for CSS (LW et al., 2019; Sahle et al., 2018). We combined population density distribution data with gridding (Center For International Earth Science Information Network (CIESIN), 2018) to calculate the spatial distribution of regional carbon demand (Li et al., 2017), using the equation:

$$CE = \sum_{x=1}^{X} \rho(x) \times \varphi(x)$$

where *CE* is carbon emissions from human social and economic activities, i.e., demand for CSS; $\rho(x)$ is spatial population density in pixel x;

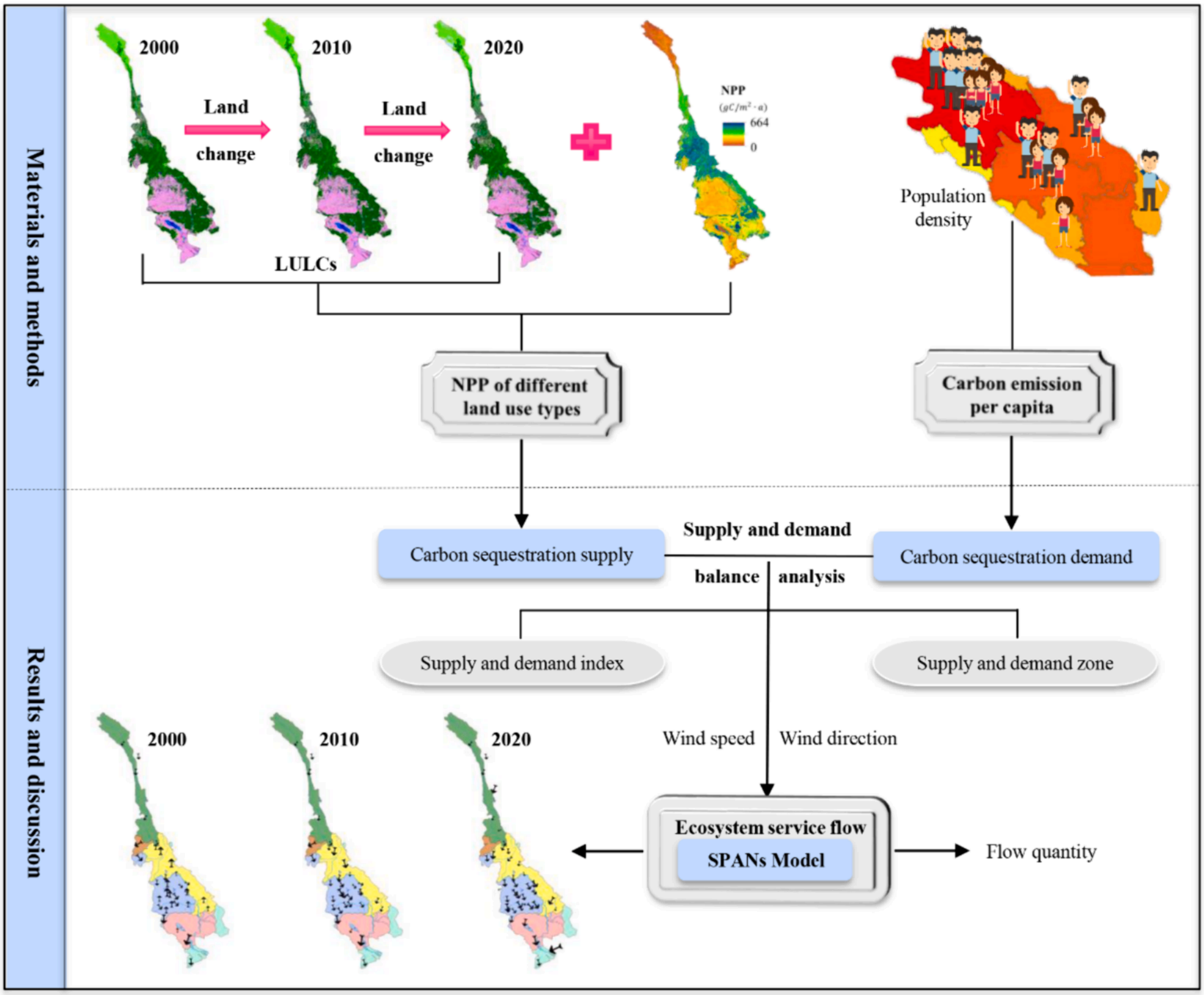

Fig. 2. Methodological framework applied to the present analysis. LULC = land use/land cover, NPP = net primary productivity.

$\varphi(x)$ is per capita carbon emissions in pixel x; and X is the total number of pixels in the study area. In 2008, major countries exhibited an average per capita carbon emissions that varied from 1.20 ~ 1.31 tons C (Cong-rong, 2012). About 1.6 tons per capita of carbon emissions could meet basic needs and 2.2 tons per capita could meet a normal standard of living (Pan and Zheng, 2009). Considering the advanced international standards for carbon emission reduction improvements, we have established a per capita carbon emissions target of 1.6 tons to meet the normal living standard for residents.

2.4.3. Supply-demand ratio and CSS supply–demand area identification

Regional carbon sources and sinks are affected by many factors, such as natural ecology, social economy, etc., and the balance between them is also complex. For this reason, we developed the novel concept of CSS supply–demand index. By calculating the ratio of carbon sources to carbon sinks, we quantified the carbon supply–demand balance in the study region and made the required coupling to supply–demand of ecosystem services (Zhai et al., 2019). The conceptual model was as follows:

$$SDI_i = \frac{S_{pi}}{D_{pi}} \times 100\%$$

where SDI_i is the source-sink flow supply–demand index of pixel i; S_{pi} is the carbon absorption of pixel i in a certain period, i.e., the amount of biological carbon sequestration; and D_{pi} is the carbon emissions of pixel i in a certain period, i.e., carbon emissions calculated by the carbon source model.

Based on the derived relationship between carbon supply and demand, we identified the carbon sink supply area and carbon source demand area in LMRB. A value of $SDI_i > 100$ % indicated that the regional carbon supply tendency was greater than the carbon demand tendency, i.e., a CSS supply area. A value of $SDI_i < 100$ % indicated that the regional carbon demand tendency was greater than the carbon supply tendency, i.e., a CSS demand area.

2.5. CSS spatial flow model

2.5.1. Calculation of service flow quantity

The ecosystem services that are actively used represent a service flow (Villamagna et al., 2013). We considered two situations: (1) If $S_{pi} \geq D_{pi}$, the service flow was calculated on the basis of demand, which was equal to the actual use or consumption of CSS per unit area and per unit time. (2) If $S_{pi} < D_{pi}$, the carbon sequestration capacity of the ecosystem could not meet the demand for human CSS. The service flow was quantified by calculating the supply of CSS per unit area and per unit time.

2.5.2. Service flow path

For the ecosystem CSS flow model, the carbon-releasing ecosystem was regarded as a carbon source, and all carbon sources were connected with the carbon sink and users through atmospheric circulation. The demand was calculated based on regional carbon emissions, and the fixed residual amount of vegetation in each region was allocated to each use site. Unfixed carbon was moved to other regions by atmospheric circulation and consumed by CSS in other regions. Therefore, the path of CSS flow was mainly determined by the annual average wind flow field, the flow was mainly influenced by the supply surplus, and the flow rate was mainly determined by the annual average wind speed.

Finally, considering the temporal and spatial balance in CSS supply–demand, and based on the main wind direction and wind field map, using the SPANs model and GIS tools we analyzed the service flow transmission path, quantified the service flow quantity, and mapped the direction and trend of regional CSS spatial flow.

2.6. Data requirement and preparation

The data needed for the evaluation framework developed in this study included a digital elevation model (DEM) of the study area, land use and land cover (LULC), NPP, population density, and meteorology. The data requirements and data sources are shown in Table 1. Meteorological data, including wind speed and wind direction, for the three periods considered (2000, 2010, 2020) were converted through Python programming into average values for the years. To facilitate analysis, all grid data were uniformly resampled to 1 km × 1 km, and the coordinate system was WGS_1984_Albers.

3. Results

3.1. Land use change

Forest and cultivated land were the main land use types in LMRB during the study period, followed by grassland. Together, these three accounted for nearly 95 % of all land use. From 2000 to 2020, the total area of cultivated land increased from 273600.72 km^2 to 294718.01 km^2, representing an increase of 2.59 %. The area of forest and grassland was 406376.53 km^2 and 102555.10 km^2, respectively, in 2000, and 383238 km^2 and 86051.64 km^2, respectively, in 2020, a decrease of 2.84 % and 2.02 % respectively (Fig. 3a). The area of artificial surfaces and permanent snow & ice increased from 2000 to 2020, while the area of shrubland first increased and then decreased. The area of water bodies decreased first and then increased from 2000 to 2020. Bare land area changed little from 2000 to 2010 but increased rapidly from 2010 to 2020. Other land use types showed little change (Table 2).

From the perspective of the land use transfer matrix (see Tables S1–S3 in SI for original data), the main land use change observed from 2000 to 2010-2020 was the conversion of forested areas into cultivated land and grassland (Fig. 3b). For the forest, it mainly came from the transfer of grassland (11351.999 km^2) and cultivated land (5538.821 km^2), while it had transferred to cultivated land (27697.577 km^2) and grassland (9844.289 km^2) from 2000 to 2020. Finally, the forest was reduced to 383238 km^2 in 2020.

For cultivated land, it mainly came from the transfer of forest (27697.577 km^2) and grassland (3973.672 km^2), while it had transferred to forest (5538.821 km^2) and artificial surfaces (4443.098 km^2) from 2000 to 2020. At last, the cultivated land was increased to 294718.01 km^2 in 2020.

For grassland, it mainly came from the transfer of forest (9844.289 km^2) and cultivated land (996.233 km^2), while it had transferred to forest (11351.999 km^2) and permanent snow & ice (7234.692 km^2) from 2000 to 2020. As a result, grassland had been reduced to 86051.64 km^2 in 2020. For other land use types, the land use change was small because of the small area involved.

3.2. Temporal-spatial changes of supply and demand of CSS

The supply of CSS in 2000, 2010, and 2020 was 255.61, 254.24, and 249.45 million tons, respectively, and the three-year average was 253.10 million tons (Table S5 in SI). The spatial distribution pattern of carbon sequestration supply showed little change from 2000 to 2020, but there was a significant change in the supply of carbon sequestration in the uppermost part of the basin (China region), with a trend for decreasing CSS supply year on year (Fig. 4a). Areas with a high supply of CSS were mainly concentrated in forested areas in the central part of the basin (Laos region) and in the southeast corner of the basin (Cambodia region).

Demand for CSS in 2000, 2010, and 2020 was 99.00, 104.76, and 117.53 million tons, respectively, while the three-year average was 107.10 million tons (Table S5 in SI). There was no apparent change in the spatial distribution pattern of CSS demand from 2000 to 2020. However, the demand for CSS in the center of the basin (Thailand region) showed a significant change and a decreasing trend year on year (Fig. 4b). Areas with high CSS demand requirements were concentrated in the southernmost part of the basin, specifically in the Vietnam region.

From a regional perspective (Fig. 5), the supply of CSS in the six countries ranged from 2.51 to 3.946 t/ha, and the CSS demand ranged from 0.388 to 4.915 t/ha. The country with the highest CSS supply as a three-year average was Myanmar (3.926 t/ha), and the country with the lowest supply was Thailand (2.525 t/ha). The country with the highest CSS demand as a three-year average was Vietnam (4.475 t/ha), and the country with the lowest demand was Laos (0.477 t/ha) (Table S6 in SI).

3.3. CSS flow quantity

From 2000 to 2020, the spatial distribution pattern of CSS flow quantity showed little change (Fig. 6). The surplus area of CSS flow quantity was mainly concentrated in the forest, with a maximum of 4.31 t/ha. The deficit areas were mainly cultivated land and artificial surfaces (urban areas), with a minimum of −1101.21 t/ha. The relationship between the flow of carbon from CSS and land use change is complex and significant. Changes in land use, including deforestation, afforestation, urbanization, and changes in agricultural practices, significantly

Table 1
Data requirements for the SPANs model.

Data	Type	Data source	Note
Digital Elevation Model (DEM)	Raster	Geospatial Data Cloud, https://www.gscloud.cn	Resolution 30 m × 30 *m*
Land use/land cover	Raster	National Geomatics Center of China (DOI:10.11769). https://www.globallandcover.com/	LULC for 2000, 2010, and 2020, including 10 different types of land use. Resolution 30 m × 30 *m*
NPP	Raster	Global Change Research Data Publishing & Repository https://www.geodoi.ac.cn/	Resolution 1 km × 1 km (https://doi.org/10.3974/geodp.2017.03.08)
Global population density	Raster	WorldPop Country Datasets (https://www.worldpop.org)	Resolution 1 km × 1 km
Meteorological data	.CSV file	National Oceanic and Atmospheric Administration (https://www.ncei.noaa.gov)	Data from all 47 meteorological stations in LMRB were obtained, including wind speed and direction data
Watersheds	Shapefile	Geospatial Data Cloud, https://www.gscloud.cn	A shapefile determined by DEM raster using ArcGIS tool and China Institute of Water Resources and Hydropower Research (DOI:10.3974)

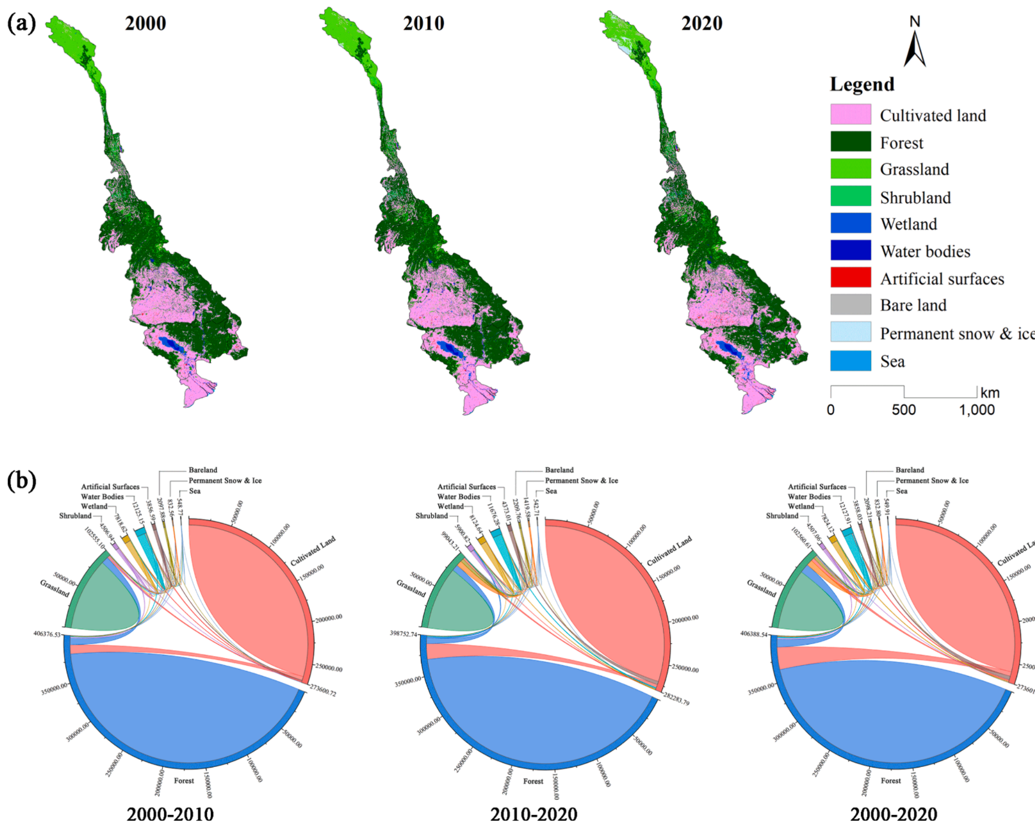

Fig. 3. (a) Land use/land cover in LMRB) in 2000, 2010 and 2020; (b) Land use change in LMRB in 2000–2010, 2010–2020 and 2000–2020.

Table 2
Land use composition of the whole Lancang Mekong River Basin (LMRB) in 2000–2020, as a percentage and as total area (km^2).

	2000		2010		2020	
	Area	Percentage	Area	Percentage	Area	Percentage
Cultivated Land	273600.72	33.60 %	282283.79	34.66 %	294718.01	36.19 %
Forest	406376.53	49.90 %	398752.74	48.97 %	383,238	47.06 %
Grassland	102555.10	12.59 %	99043.21	12.16 %	86051.64	10.57 %
Shrubland	4506.94	0.55 %	5900.82	0.72 %	5750.06	0.71 %
Wetland	7818.62	0.96 %	8124.64	1.00 %	8470.84	1.04 %
Water Bodies	12125.15	1.49 %	11676.28	1.43 %	13131.32	1.61 %
Artificial Surfaces	3856.59	0.47 %	4373.01	0.54 %	8652.3	1.06 %
Bare land	2097.88	0.26 %	2209.76	0.27 %	5732.17	0.70 %
Permanent Snow & Ice	832.56	0.10 %	1419.58	0.17 %	8023.81	0.99 %
Sea	548.77	0.07 %	542.71	0.07 %	594.66	0.07 %
Total	814318.81	100.00 %	814326.53	100.00 %	814362.81	100.00 %

affect ecosystem carbon sequestration capacity, thereby influencing CSS dynamics. As a result, there exists some spatial similarity between land use change trends and spatial variation in the flow of CSS.

Although there were surplus and deficit areas of the flow quantity of CSS in a grid-scale analysis, from a regional perspective, the supply of CSS was less than the demand in Vietnam, while the supply in the other five countries (China, Myanmar, Thailand, Laos, and Cambodia) was greater than the demand (Fig. 7). From 2000 to 2020, the demand for CSS increased in all countries with the exception of Thailand. The supply of CSS first increased and then decreased in Myanmar and China, while it decreased in other countries. As a whole, total demand for CSS increased, while the total CSS supply decreased over the 2000–2020 period (see Table S6 in SI for original data).

3.4. CSS supply–demand index and identification of supply and demand areas

From 2000 to 2020, the spatial distribution of CSS supply–demand index changed little (Fig. 8a). However, the supply–demand index for the central part of the basin (Thailand region) changed significantly, with regions with a supply–demand index of less than 100 % showing a decrease. Overall, areas with a supply–demand index of less than 100 % were mainly concentrated in the center (Thailand region) and southernmost part (Vietnam region) of the basin, with a CSS supply–demand imbalance in these regions. Most other regions had a supply–demand index above 100 %, and in many cases, it was larger than 200 %.

On the whole, the CSS demand zone decreased in area from 132049.266 km^2 to 123896.624 km^2 from 2000 to 2010, while in 2020 it was 124945.583 km^2, a slight increase. The CSS supply zone increased in area from 669869.906 km^2 to 678048.289 km^2 from 2000 to 2010, while in 2020 it was 676985.541 km^2, a slight reduction. The average

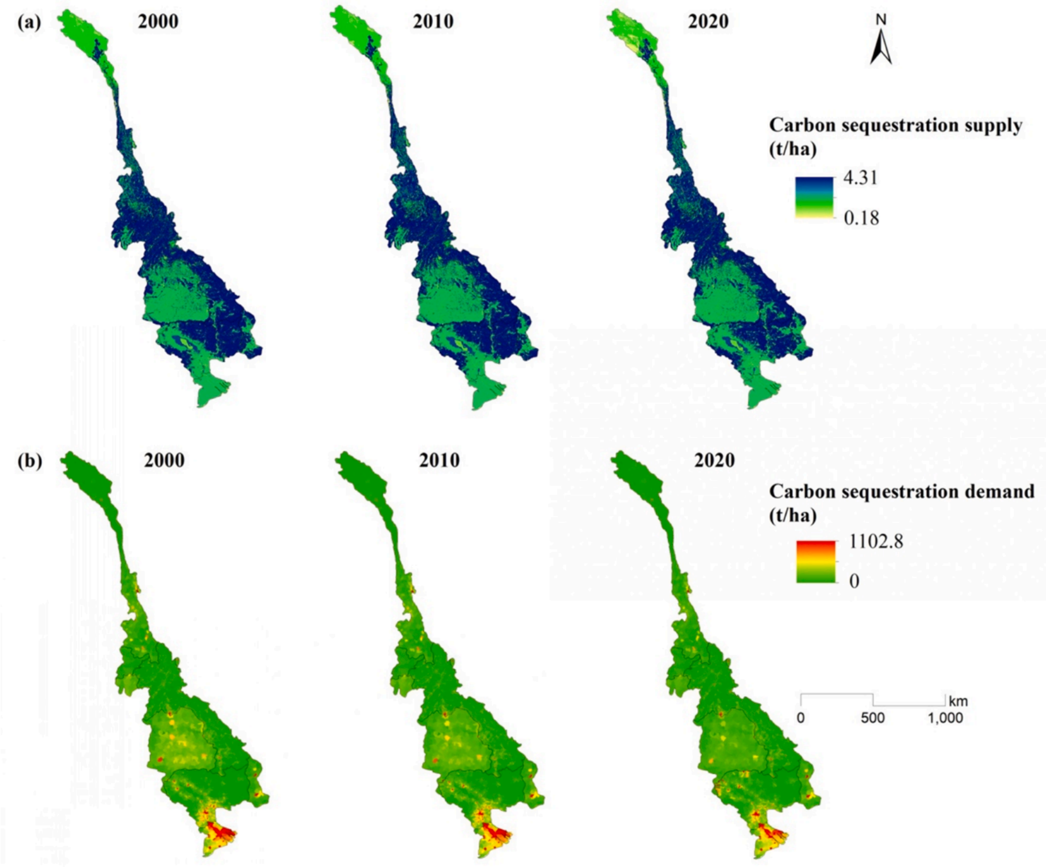

Fig. 4. (a) Supply and (b) demand for carbon sequestration services in Lancang Mekong River Basin (LMRB) in 2000, 2010, and 2020.

demand zone in LMRB in the three-year period comprised 126963.824 km^2, and the supply zone comprised 674967.912 km^2 (Table S7 in SI). In terms of individual countries, in 2000, 2010, and 2020 the net CSS demand zone was mainly concentrated in Thailand, Cambodia, and Vietnam, but the net demand zone in Thailand decreased in area from 63695.964 km^2 to 39465.113 km^2 from 2000 to 2020, while that in Cambodia and Vietnam increased from 23306.922 km^2 to 32792.596 km^2 and from 34020.825 km^2 to 37546.465 km^2, respectively (Fig. 8b).

3.5. CSS flow path

The highest CSS flow was mainly distributed in the southernmost part of the basin, moderate CSS flow was mainly distributed in the center, and low CSS flow was mainly distributed in the upper and scattered parts of the basin. The predominant direction of service flow in the LMRB was from north to south. There exists a reciprocal relationship between the flow of CSS and land use change (Fig. 9). We utilize wind direction as a proxy for simulating the flow of CSS under different land use scenarios. Changes in land use alter vegetation, soil types, and carbon cycling processes, while a reduction in carbon storage may exacerbate climate change, thereby impacting sustainability and ecosystem stability.

From the perspective of different countries, in China, the intensity of CSS flow from north to south was relatively small. In Myanmar, the service flow was in the southwest direction from 2000 to 2020 and the intensity was moderate in 2000 and 2010 but became very small in 2020. In Laos, the CSS flow was mainly from south to north in 2000, while the direction was mainly from north to south in 2010 and 2020, and the intensity of service flow was slightly higher in 2000 and 2010 than in 2020.

The CSS demand zone was mainly distributed between Thailand, Cambodia, and Vietnam from 2000 to 2020. The carbon demand zone in Thailand in 2000 was mainly fixed by inter-regional vegetation, due to the flow direction. However, in 2010 and 2020 the carbon that was not fixed by local vegetation was transferred by wind to the south of Thailand or other surrounding countries. In Cambodia, the carbon that was not fixed by local vegetation was transferred to the southernmost part of the basin with the wind and was mainly fixed by vegetation in the Vietnam region. In Vietnam, the carbon that was not fixed by local vegetation was transferred by wind to the sea, where it would be absorbed, or to other surrounding countries.

4. Discussion

4.1. Land use change and analysis of CSS supply–demand balance

High CSS supply areas were concentrated in the south of China, particularly in the mountain forest zone of Laos, indicating that forest carbon sequestration was the dominant carbon fixation area (Xu et al., 2016). From the perspective of land use change, much of the forest has been converted into cultivated land and grassland, which is not conducive to carbon sequestration. From the perspective of the carbon sequestration zone, although the supply of CSS was larger than the demand, on the whole, the basin was in a surplus state. The main reasons were the high proportion of forest and grassland (about 60 %) and strong carbon fixation capacity. From the perspective of the whole basin, total demand for CSS increased, while the total supply decreased, in the 20-year study period. The area of artificial surfaces increased sharply, mainly because of rapid economic development, while the forest area decreased. The rapid increase in carbon emissions far exceeded the corresponding carbon sequestration capacity, resulting in a “deficit” in carbon sequestration, which must not be ignored. Land use change plays

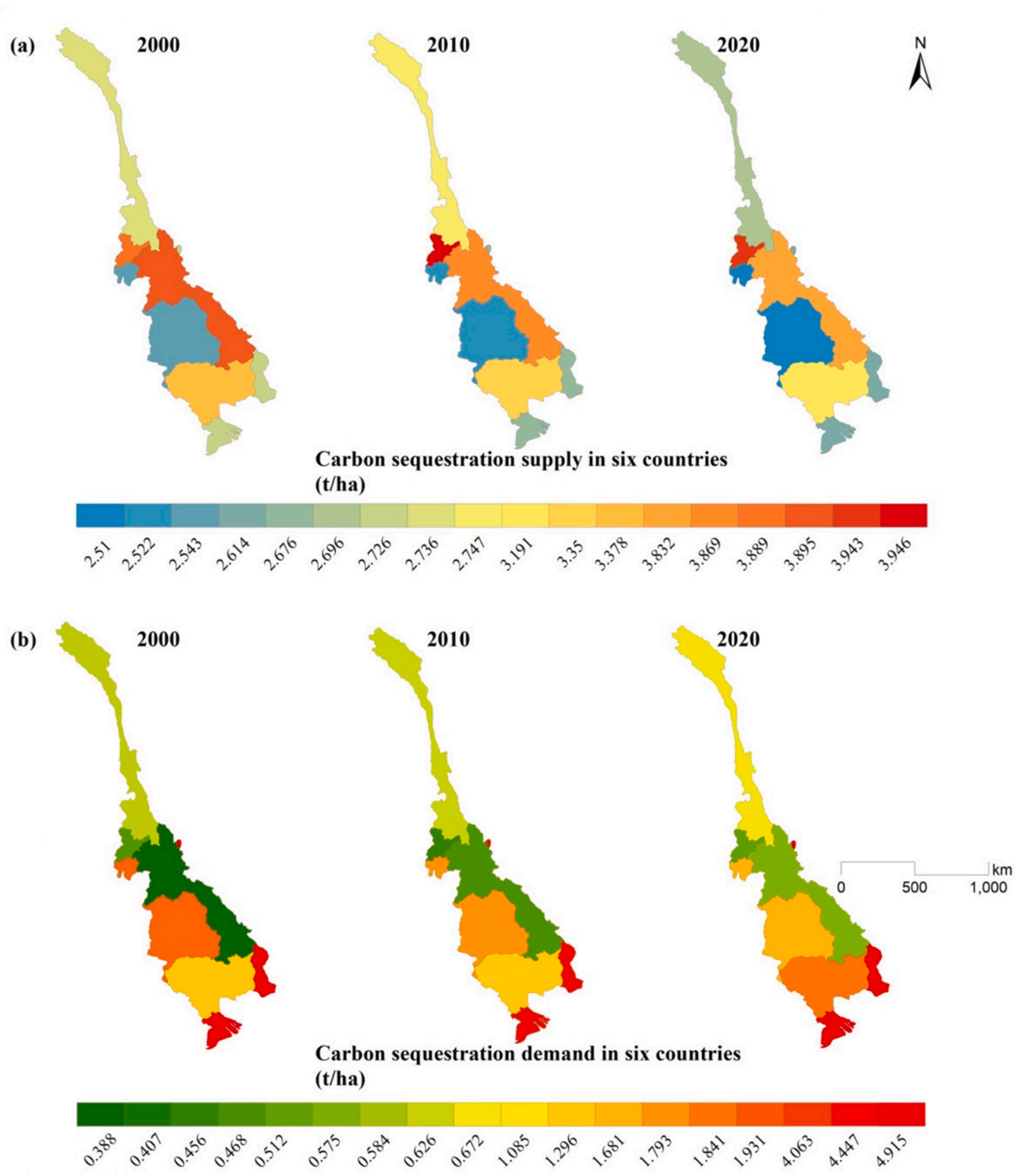

Fig. 5. (a) Supply and (b) demand for carbon sequestration services (CSS) in the six counties of Lancang Mekong River Basin (LMRB) in 2000, 2010, and 2020.

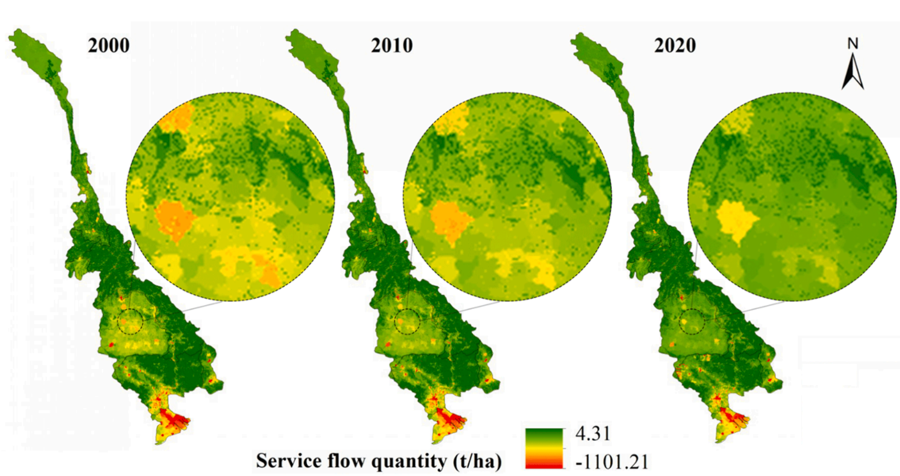

Fig. 6. Flow quantity of carbon sequestration services (CSS) in Lancang Mekong River Basin (LMRB) in 2000, 2010, and 2020.

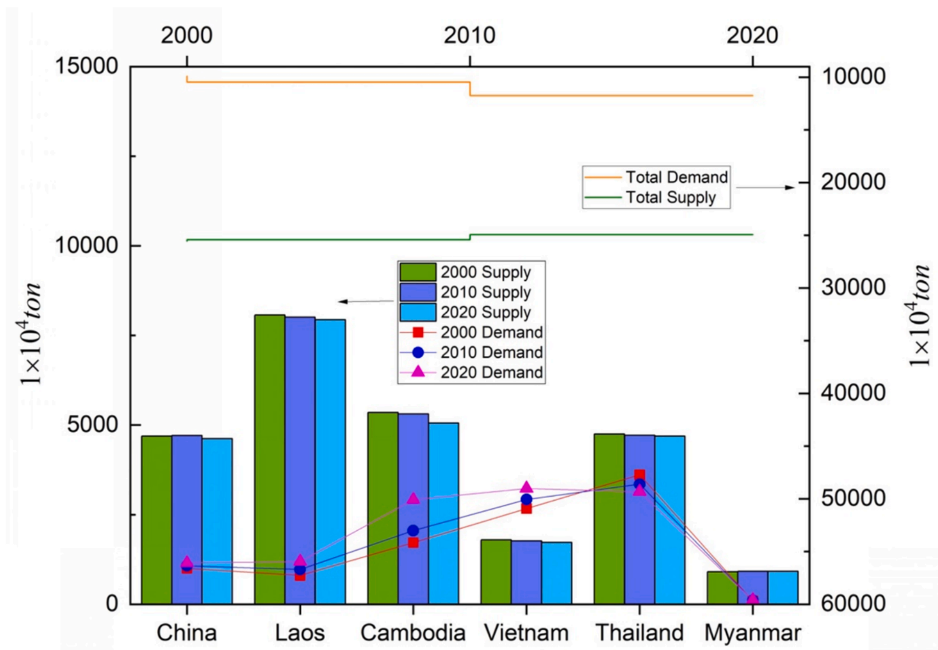

Fig. 7. Flow quantity (2000–2010) of carbon sequestration services (CSS) in the six countries of Lancang Mekong River Basin (LMRB) and in the whole basin.

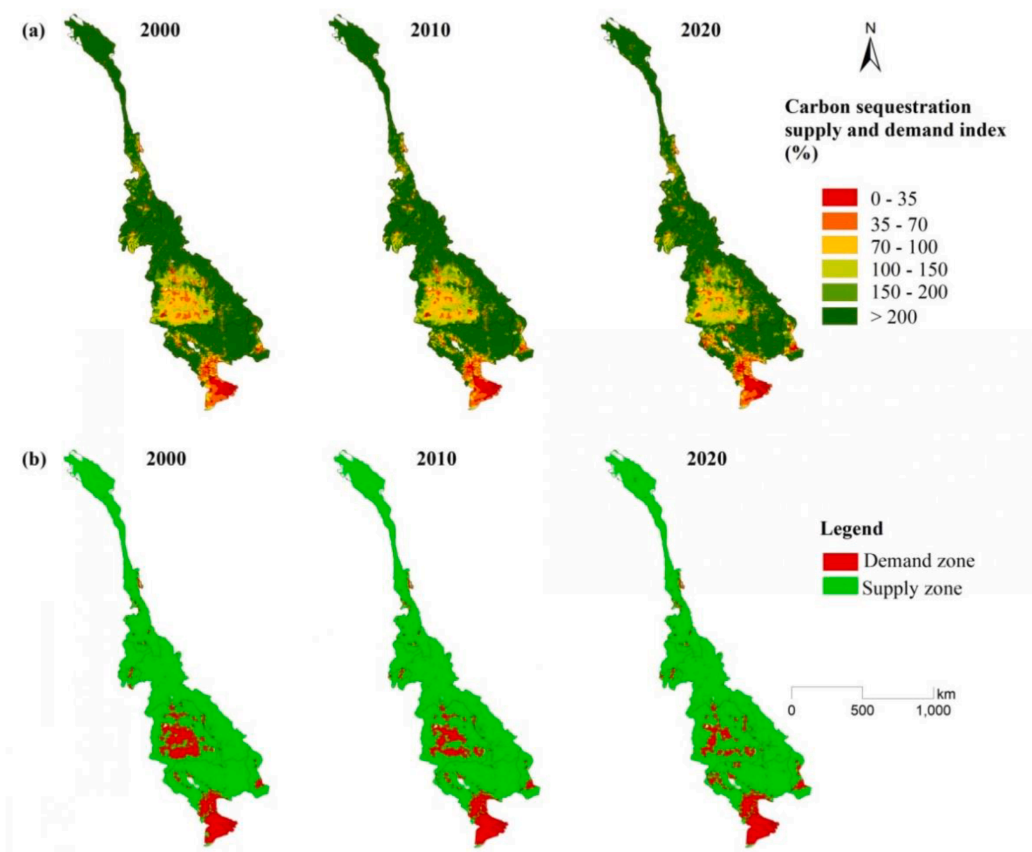

Fig. 8. (a) Carbon sequestration service (CSS) supply–demand index in Lancang Mekong River Basin (LMRB) and (b) supply and demand areas in the basin in 2000, 2010, and 2020.

an important role in CSS change, so CSS is vulnerable to land use change.

The spatial distribution pattern of CSS supply–demand balance changed greatly from 2000 to 2020, particularly in Thailand, Cambodia, and Vietnam. Thailand's demand zone decreased, while Cambodia and Vietnam increased. For Thailand, the main reason was a decreasing population density and lower demand for CSS. Cambodia, in contrast, had an increasing population density and the demand for CSS was higher. For Vietnam, the main reason was a decrease in forests, which

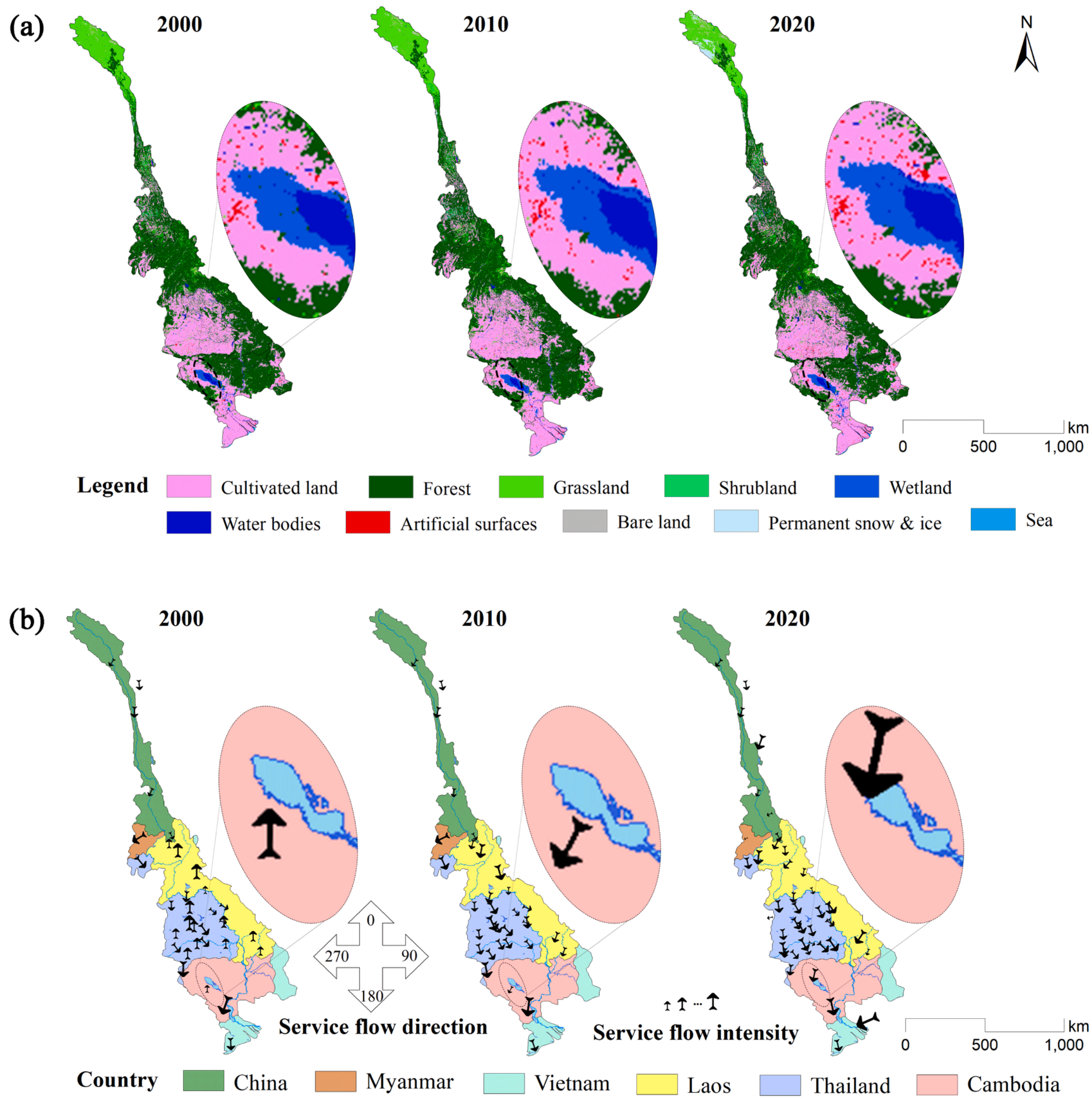

Fig. 9. Path of carbon sequestration service (CSS) flow in Lancang Mekong River Basin (LMRB) in 2000, 2010, and 2020.

led to a decrease in CSS supply. It should be noted that, of the six countries in LMRB, only Vietnam's supply is currently less than demand, making it necessary for Vietnam to adjust the supply and demand structure of CSS as soon as possible, starting by reducing carbon demand or improving carbon supply. In China, carbon consumption increased between 2000 and 2010, but modestly. This was due to a decrease in forest area and an increase in permanent snow & ice in China, resulting in a decrease in CSS supply. Thus the results obtained in this study were influenced to a major extent by the carbon source of densely populated areas and the carbon sink function of natural forests. Quantifying regional carbon emissions based on the difference between CSS supply and demand can provide technical support for cross-regional carbon offsets.

4.2. Characteristics and potential deficiencies of CSS flow under land use change

The flow supply area of CSS was larger than the demand area mainly in regions with forest and grassland, while the flow demand area was larger than the supply area mainly in regions with cultivated land and artificial surfaces, i.e., concentrated population distribution, high industrialization, and lack of large ecological sources. The direction of CSS flow was mainly from the northernmost to southernmost parts of the watershed, proving that supply and consumption of ecosystem services were the start and end points of the spatial flow of this ecosystem service. Through complex and dynamic supply chain approaches, CSS ultimately reaches human beneficiaries (Jian et al., 2017). In the long run, governments should consider the importance of vegetation for carbon sequestration to maintain a regional carbon balance while pursuing economic development.

The emission, storage, and flow of carbon constitute a complex network system that encompasses a diverse array of pathways and cycle mechanisms (Liang et al., 2023). In our initial analysis, the focus has been primarily on the impact of land use changes on the equilibrium of CSS, with wind direction introduced as a crucial factor to elucidate the characteristics of ecosystem service flows. This simplified methodology, especially when discussing variations in CSS flows between countries, land use changes, and the balance of CSS supply and demand, has provided us with enlightening insights. Nonetheless, it is essential to acknowledge that relying solely on wind direction as a conceptual framework for the spatial flow of CSS may overlook other significant factors and processes in the carbon cycle, such as soil carbon storage and carbon transport in the hydrological cycle (Casas-Ruiz et al., 2023). Therefore, future research should aim to expand the current model to more comprehensively cover various carbon flow pathways, including but not limited to, the entrance of timber into consumer markets, ecosystem restoration, the transformation of crops into firewood, ecological compensation, and carbon trading. This broader, systems-level approach is expected to more accurately reveal carbon flow dynamics within this intricate CSS network system.

4.3. Strategies and policy

4.3.1. Protection and restoration of important ecosystems in important zone

Natural ecosystems play an important function in carbon sequestration; forests vegetation, soil fauna, and microorganisms all contribute significantly to the process (Baldrian et al., 2023). Of these, the forest ecosystem is the largest "carbon pool" on land, with its organic carbon storage accounting for 76–89 % of total carbon storage in terrestrial vegetation (Dang, 2013; Pan et al., 2011), and around 66 % of total carbon storage in terrestrial organisms (Kramer, 1981). Thus the forest ecosystem plays an important role in reducing the greenhouse effect, adjusting the carbon balance, and stabilizing climate (Bai et al., 2021; Korosuo et al., 2023). In Thailand and Cambodia, this study revealed an imbalance zone between supply and demand, while in Vietnam demand for CSS far exceeded supply in an unbalanced state. Afforestation and reforestation, which are recognized ways of reducing emissions under the Kyoto Protocol, are a low-cost and effective strategy to improve forest carbon sequestration. Therefore, all countries in the LMRB should protect and conserve natural forests in their CSS deficit zones, actively carry out afforestation activities, and build a forest carbon sequestration system.

On the other hand, unreasonable land use can lead to forest soil becoming a major carbon source. Converting forest into cultivated land reduces soil organic carbon (SOC) content, resulting in a reduction in soil carbon storage and carbon sink function. Soil is a huge carbon source and appropriate land use changes, such as returning cultivated land to forest and constructing shelter forests, could increase soil SOC storage (Chi et al., 2023). Reasonable land use planning to control the ecosystem carbon cycle and influencing factors, to reduce land use change, and to prevent release of the forest carbon pool can maintain the balance of ecosystem carbon supply and demand. Therefore, all countries should harness bare land, optimize land use structures, speed up construction of regional carbon sink capacity, and improve carbon capture, utilization, and storage (CCUS) technology.

4.3.2. Strengthen regional collaborative management

"Green earth" is the common home for human survival and development. All countries should firmly establish the concept of a "community of human natural destiny" and cooperate according to the principle of "common but differentiated responsibilities", to strengthen collaborative management in the fields of carbon neutrality, climate change, environmental governance, etc. Policy coordination promotes the development of the international carbon trading market, provides economic incentives for CSS, and strengthens monitoring and cross-border ecosystem management through unified carbon reporting standards (Xian et al., 2024). These are the keys to global carbon emission reductions and enhancing carbon sequestration capacity.

In the case of LMRB, all countries involved should first form an alliance and identify joint prevention and control mechanisms to share services and responsibilities. Ecosystem services should be the main focus of supervision and the principle of equal rights and responsibilities should be clarified so that relevant agreements are effective in practice.

Next, all six countries in LMRB should agree to the inclusion of the carbon neutrality goal in climate change negotiations and seek to reach a consensus on the carbon neutrality goal through the alliance platform. They should strengthen the exchange of technology and policy path design, provide a reference for domestic carbon–neutral targets, and promote climate action and governance for fair, reasonable, and win–win cooperation.

4.3.3. Implementation of low-carbon management and ecological compensation mechanism

Low-carbon management and ecological compensation mechanisms are key measures to harmony between natural ecological resources, humans, and intergenerational equity. As an effective tool to mitigate climate change, carbon trading can help each country in LMRB achieve the goal of low-carbon management more definitely, flexibly, and efficiently, through total amount control and quota trading. Differences in economy, industry, and resources among countries affect the feasibility of low-carbon management and ecological compensation strategies. When formulating these strategies, it is necessary to consider local culture, values, and lifestyles, while considering the political environment and the government's willingness, in order to seek cooperation and mutual benefit.

The alliance of LMRB countries should then establish carbon compensation between regions, optimize the layout of ecosystems, improve the supply of ecosystem services, coordinate CSS supply and demand, and balance supply and demand on an appropriate scale. The flow difference in basin carbon emissions can be considered for regional compensation and coordination, but an important precondition is to clearly identify the supplier (supply zone), the consumer (consumption zone), and their flow relationship. All countries should make full use of ecological compensation, encourage active participation in the market and the public, give reasonable compensation to areas that provide external economic effects, and clarify the principle of equal rights and responsibilities. This would allow the ecological compensation system to play a practical role in maintaining the function of CSS.

4.4. Implications and limitations

The supply and demand sides of ecosystem services are the main components of service formation, flow, and final consumption. Without human demand, ecosystem functions and processes cannot provide services. In this study, carbon sinks in LMRB were calculated by analyzing ecological carbon sequestration capacity, while carbon sources in LMRB were calculated based on terminal human energy consumption. The carbon sinks and carbon sources were then compared, to clarify the supply–demand balance relationship. This revealed the carbon transfer caused by the CSS flow of each country in the basin, which can provide a basis for the implementation of ecological compensation policy and for carbon emissions responsibility sharing in the future. Introducing the difference between supply and demand of CSS flow into the framework of basin ecological compensation is a key measure to improve regional equity in ecological resource utilization.

By considering the atmospheric circulation path of ecosystem service flow, this analysis was exploratory in nature. However, the current conceptual framework has been constructed solely around wind direction to explore a possibility for the spatial flow of CSS. This approach inevitably neglects numerous other significant factors and processes in the carbon cycle, such as the soil carbon cycle and physical phenomena associated with hydrological processes, as well as the attenuation or accumulation effects of service flows along transmission pathways. Both carbon emissions and wind flow fields are instantaneous, and we use the average value for approximate treatment. Although the study examined the supply and demand of CSS in quantity and space, it did not fully reflect the internal and driving mechanisms of the CSS supply and demand balance. Meanwhile, NPP represents annual net carbon fixation by vegetation through photosynthesis. However, not all of this fixed carbon is retained within plants or ecosystems. Consequently, NPP is not a net and final terrestrial carbon sink. Finally, the demand for CSS starts with meeting the basic needs of human beings, considering external environmental conditions and actual demand (e.g., demand for carbon sequestration declined sharply in early 2020 due to the influence of COVID-19 (Yang et al., 2020b). To achieve a more comprehensive understanding of the flow characteristics of carbon, it may be necessary to consider a broader array of factors, including transportation networks, economic activities, and policy decisions; these are the points where future work needs to begin.

5. Conclusions

To support the sustainable development of ecology, economy, and society in the LMRB, it is imperative for each country in the basin to implement low-carbon management services. These services should be informed by quantitative data on the supply–demand balance and service flow of CSS. We used the SPANs model to quantify CSS supply–demand balance in LMRB, identify the supply–demand ratio of CSS, simulate the spatial flow of CSS in the basin, and explore strategies for optimizing the CSS pattern in the basin. Clarify land use strategies (such as agricultural expansion, forest protection, urbanization, etc.) and their anticipated impacts on CSS flows. Establish a model within the SPANs framework and accurately parameterize it to reflect the influence of these strategies on the supply and demand of CSS.

We draw the following conclusions: (1) The CSS supply in LMRB exhibits spatial variation. The primary source of carbon sequestration is forest carbon, while the primary source of CSS consumption is human activity. (2) The CSS supply–demand deficit in LMRB is mainly concentrated in the south, in Thailand and Cambodia, while supply–demand in Vietnam is very imbalanced. Land use changes alter the balance between CSS supply and demand. (3) Total demand for CSS in LMRB is increasing, while total supply is decreasing. Afforestation and reforestation, as carbon sequestration measures, are needed in the future to alleviate the increasing human demand. (4) The quantity and direction of CSS flows provide the basis for ecological compensation, but stronger collaborative management by the countries in LMRB is needed to achieve carbon neutralization.

The relationship between CSS supply, human demand, and the spatial balance between these is key to identifying spatial flows of ecosystem services. Our novel evaluation framework can be used as a standard decision support model for quantifying CSS supply and demand, rational land use planning, promoting international cooperation on carbon neutrality targets, and ensuring that carbon offset policies achieve regional low-carbon management and equitable development among regions.

CRediT authorship contribution statement

Shiliang Yang: Writing – review & editing, Writing – original draft, Software, Methodology, Data curation. **Yang Bai:** Writing – review & editing, Software, Methodology, Conceptualization. **Juha M. Alatalo:** Writing – review & editing. **Yi Shi:** Data curation. **Zhangqian Yang:** Data curation.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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