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China's Socioeconomic and CO₂ Status Concerning Future Land-Use Change under the Shared Socioeconomic Pathways

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Abstract: China has experienced a huge socioeconomic advancement over the past few decades, resulting in great change in land use and land cover. To date, negligible attention has been given to examining the socioeconomic changes in the context of land-use change, especially from a futuristic standpoint. However, motivated by China's latest carbon neutrality target, this study analyzes the prospective changes in socioeconomic status, and carbon dioxide emission in the context of future land-use change, focusing on three future periods: 2026–2030 (carbon dioxide peak phase), 2056–2060 (carbon-neutral phase), and 2080–2099 (long-term period). In this regard, recently published land-use products under seven Shared Socioeconomic Pathways-based scenarios (SSP1-1.9, SSP1-2.6, SSP4-3.4, SSP2-4.5, SSP4-6.0, SSP3-7.0, and SSP5-8.5) as part of the CMIP6, as well as the projected GDP and population under five socioeconomic scenarios are used. To estimate socioeconomic change over prominent land-use types (urban), we combined five socioeconomic scenarios with seven corresponding SSPs-based land-use change scenarios (SSP1 with SSP1-1.9 and SSP1-2.6; SSP2 with SSP2-4.5; SSP3 with SSP3-7.0; SSP4 with SSP4-3.4 and SSP4-6.0; and SSP5 with SSP5-8.5 scenarios). Our results reveal that rapid urban land expansion in the future is the most dominant aspect in China. In the carbon neutrality phase (2056–2060), urban land is expected to expand ~80% more than that of the reference period (1995–2014). In the spatial aspect, the expansion of urban land is mainly prominent in the eastern and central parts of China. For socioeconomic changes, the most prominent increase in the urban population is estimated at 630.8% under SSP5-8.5 for the 2056–2060 period compared to the reference period. Regarding GDP for the urban area, industrial GDP will be higher than service GDP in the carbon emission peak phase (2026–2030), but it is projected to be overtaken by service GDP for the carbon-neutral target (2056–2060) and long-term periods (2080–2099). Further, the CO₂ emission in China was found to increase with intensified urban land for the historical period (1995–2019). In the future, the largest increase in CO₂ emission from the urban area is anticipated under SSP5-8.5 in the carbon-neutral target (2056–2060) phase, while CO₂ emission will largely decline after (2056–2060) under SSP1-1.9, SSP1-2.6, and SSP4-3.4. Importantly, population change is expected to be the most predominant factor in future urban land expansion in China. These findings highlight the importance of well-governed urban-land development as a key measure to achieve China's carbon neutrality goal.

Keywords: land-use change; population; GDP; carbon emission; SSP scenario; China

1. Introduction

The land-use effect plays a central role in future environmental change. Land-use change has a great influence on the local, regional, and global climate [1–3]. Besides, it indicates the direct reflection of anthropogenic activities as well as close interconnection with the ecosystem, water resources, and atmosphere [4,5]. The global climate system is likely to be affected by land-surface characteristics through energy, momentum, and moisture exchanges between the atmosphere and land-surface features [6,7]. Besides, land-use change largely influences different extreme events such as landslides [7–12]. Moreover, it is documented that land-use change and agricultural activities largely contribute to global greenhouse gas (GHG) emissions. From 1990 to 2010, a quarter of the global total GHG came mainly from animal feeding, deforestation, fertilizer use, and land-use management practices [13]. Hence, it is expected that land-use dynamics for future perspectives would play an inevitable role in the process of attaining the global CO_2 mitigation target. A better understanding of how future land-use change may occur and affect other land covers is vital to extrude the social and environmental problems that pose challenges to sustainable socio-economic advancement.

Socioeconomic development has been the key to land-use change. Changes in land-use morphology over time usually correspond to a certain socio-economic development period [14]. The changes in population and gross domestic production (GDP) vary over different land types. In general, cropland and urban land are the two major land types that are closely related to socioeconomic activities as well as climate, ecosystem, and biodiversity. Population and GDP development are the two most predominant drivers of urban expansion [15,16]. Urban land enwraps a small fraction of the global land surface, but more than half of the world's population lives there [17]. Even more, fast-growing urban areas contribute to 70% of global human-induced GHG [18]. Urban land-use change greatly contributes to destroying the natural ecosystem [19]. More than 80% of natural habitation in local areas is damaged due to urban land expansion [20]. Further, the increase in agricultural production has been the major driver of environmental degradation, such as biodiversity and habitat loss, nutrient flow disruption, and GHG emission [21,22]. However, it is obvious that the world is going to face interconnected challenges in the future. Both the GDP and population are expected to increase in the future, resulting in greater demand for food consumption, and environmental pressure from agriculture will even hasten. Thus, the intricate global interplay between demand–production, agricultural intensification, habitats for a growing population, and rapid economic development are considered as core drivers of future land-use change. Further, measuring the socio-economic impacts of sustainable domains (e.g., a bio-economy or circular economy) has been attracting growing concern [23–26]. Therefore, upon presenting the significance of land-use projections for decision-makers in the field of climate change, food security, and biodiversity conservation, it is important to elucidate the plausible evolution of land-use and socioeconomic changes in the future.

China is one of the densely populated countries with rapid economic development. The complex topography and climate structure have led to stimulating varied land-use types in China. In the past decades, rapid urbanization in China has accelerated unprecedented changes in land-use patterns. As socioeconomic restructuring has taken place in China, major changes in land-use patterns have also occurred. An intense urban area expansion has invaded a large portion of croplands in recent decades [27]. In the early 21st century, the country experienced speedy socio-economic development, reformation of the industrial structure, and rapid urbanization. As a diverse range of alternative futures is likely to evolve, it is expected that China will undergo significant land-use uncertainties, which are predominantly driven by population dynamics, GDP growth, and the demand for agricultural production under the climate mitigation target. Further, GHG emission from land-use change and rapid socioeconomic growth has been the key concern for China. More than 15% of the total carbon emission in China came from land-use change-related factors (urbanization, cultivation, and land-use conservation) in the 1990–2010 period [28]. There-

fore, understanding future land-use and socioeconomic changes in China is of paramount importance for policymakers to develop strategies on climate change mitigation, food security, sustainable development, and ecosystem and biodiversity protection.

Scenarios of land use and land cover have significant contributions in elucidating future development and policy interventions for climate change, food security, ecosystems and biodiversity, carbon emission, and sustainable development. Land-use change projections are greatly complex as it results from diverse interactions between regional-specific demand–supply systems, multi-folded feedback process, and smaller-scale features (i.e., land-use regulation and ownership). Previous studies stated some drawbacks in land-use projections based on the framework of shared socioeconomic pathways, and the first phase of the Land Use Harmonization dataset (LUH). The shared socioeconomic pathways-based projections have lacked sufficient spatial details, which yield uncertainties in environmental impact assessment [29]. LUH-based projections demonstrate too coarse a resolution to explain the details of land-use distribution on the regional level, and lead to underestimating the urban land quantities and failure to capture the impact of urbanization on regional and local climate change [30]. However, the latest CMIP6 (Sixth phase of Coupled Model Inter-comparison Project) Land-Use Harmonization dataset (LUH2) provides a harmonized set of land-use products under the integrated scenarios linking the shared socioeconomic pathways and the representative concentration pathways to contribute to the Sixth Assessment Report (AR6) [31]. However, this research has given importance to using up-to-date datasets produced under newly designed scenarios to yield more reasonable and reliable findings.

Nonetheless, in the available literature, contradictory assumptions regarding the relationship between socioeconomic changes and land use have existed. A decreasing population is not actually related to weakening economic development or even urban land shrinkage [32]. Contrarily, Wolf et al. [33] stated that urban land will expand in a region where the population is expected to decline. Furthermore, the contribution of land-use change to carbon emission has been broadly reported by several past studies [34–37]. Due to rapid land-use change, carbon emission in China has been also reported to increase [34]. The latest Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) [31] also sought the contribution of land-use change-based CO_2 emission to global climate change. However, as part of the Paris Agreement execution, recently, the Chinese Government has declared an ambitious carbon mitigation target; the CO_2 peak phase will be cut down by 2030, and CO_2 neutrality will be achieved by before 2060. Lai et al. [34] urged the performance of a comprehensive analysis of the effect of land-use change on carbon emission in China. Notably, most of the previous studies regarding the socioeconomic change, carbon emission, and land-use changes are conducted for the historical period, but negligible concern has been paid to the futuristic viewpoint using the upgraded data. In light of these issues, this paper aims to elucidate the projected changes in future land use and the interlinkage between land-use change and socioeconomic change under seven SSPs (Figure 1). We investigated how socioeconomic status and carbon dioxide emission will change in the context of prominent land-use change. Considering the recent declaration by the Chinese Government, we defined 2026–2030 as the carbon emission peak period, 2056–2060 as carbon neutrality, and the long-term period as 2080–2099. So, we expect that the estimation of future land-use changes under different climate and socio-economic scenarios, as well as its interconnection with socioeconomic variables and future CO_2 emission status, could help policymakers to understand the degree different land type changes, the population, and GDP can be considered to achieve this carbon emission target.
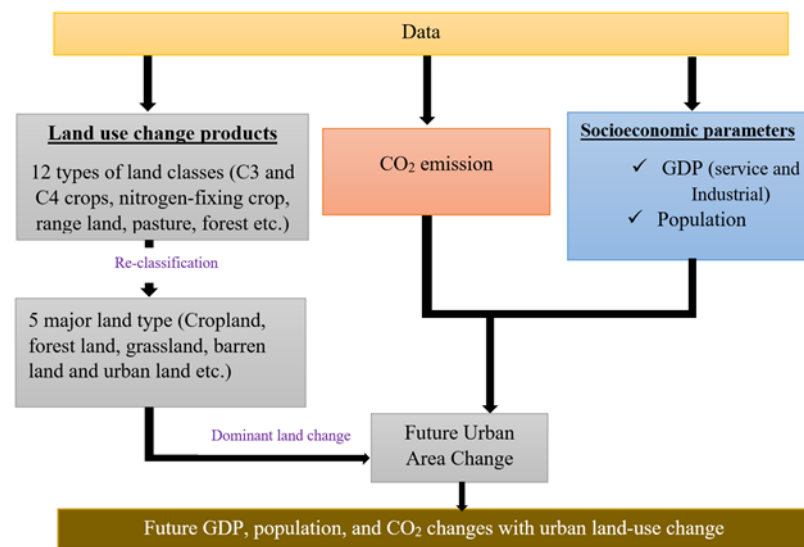
Figure 1. Methodological flowchart of the study.

2. Materials and Methods

2.1. Research Domain

This study focuses on the entirety of China, which has diverse land types and climate conditions (Figure 2). In terms of altitude, the west part is high, and the east part is a low land area. In total, 67% of the land comprises mountains, plateaus, and hills, while the remaining 33% includes plains and basins [38,39]. The land-use pattern in China can be classified into five major categories: Cropland, forest land, grassland, urban land, and barren land (Figure 2). Cropland is dominant in the eastern and northern parts of China, whereas forest land is mostly distributed across the northeast, southeast, and southwest hilly regions, grassland is in the northern and northwestern parts, and barren land is predominant in the western part of China. Notably, urban land is expanded mostly over the eastern regions. In terms of climatology, the regional climates in China usually vary from South and Southeast (humid) to North and Northwest (dry) with an uneven pattern of precipitation, which is mainly characterized by the distance from the sea [40].

2.2. Datasets

Scenario-based land-use projections are crucial to assess the long-term impacts and efficiency of land-use management and policies for global mitigation targets under various plausible future statuses [30]. In the CMIP6, there are seven integrated emission scenarios (SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP4-3.4, SSP4-6.0, and SSP5-8.5), which are designed with the combination of five Shared Socioeconomic Pathways and seven up-to-date forcing (RCP) targets [41]. Among these scenarios, four (SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5) are indicated as Tier-1, and the remaining SSP1-1.9, SSP4-3.4, and SSP4-6.0, as Tier-2 scenarios in the ScenarioMIP, which is the fundamental activity in the CMIP6 [41]. However, to contribute to AR6, land-use products in these eight emission scenarios are produced under the LUH2 project. Five Integrated Assessment Models (IAMs) participated in the production of the latest global land-use products for the historical period (830–2015) and future period (2015–2100) with a spatial resolution of $0.25° \times 0.25°$. In this study, we downloaded land-use products http://luh.umd.edu/ (accessed on 1 February 2022). The summary of the five IAMs is shown in Table S1. In this study, we used the updated cropland dataset under seven SSPs (SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP4-3.4, SSP4-6.0, and SSP5-8.5) derived from the LUH2 project. The cropland datasets are then upscaled at a $0.5° \times 0.5°$ resolution using the 'nearest grid' interpolation method.
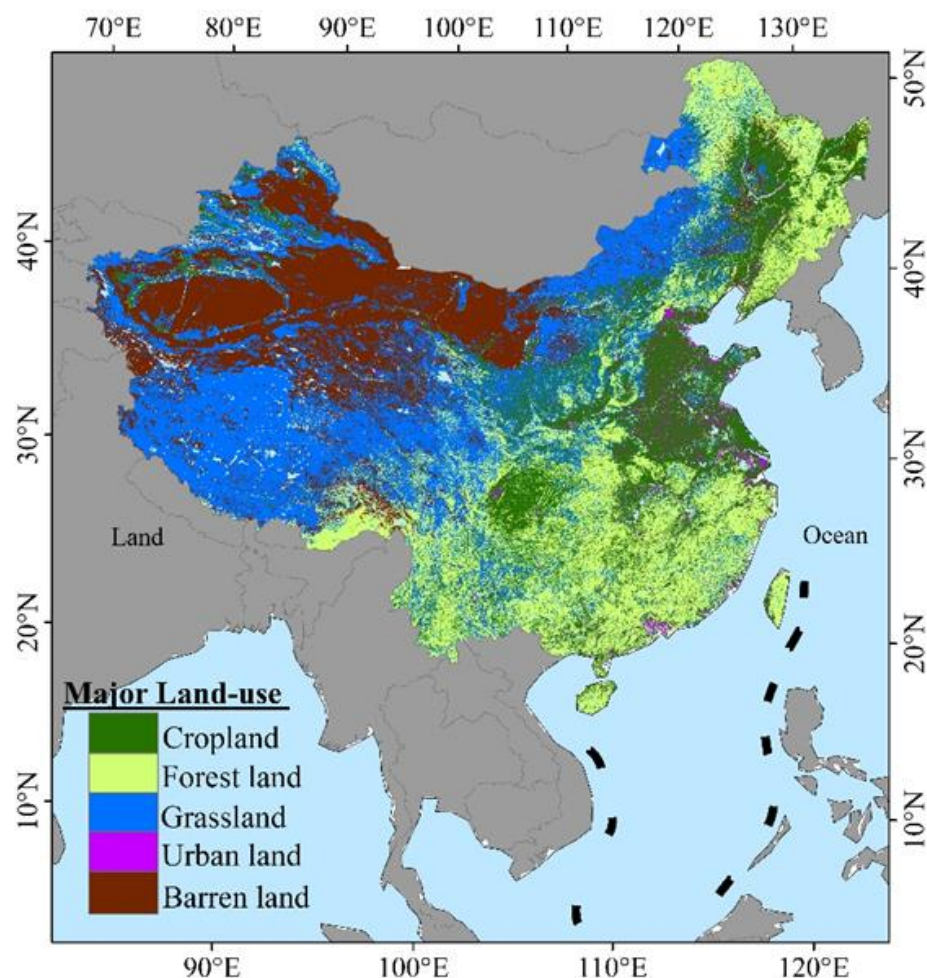
Figure 2. Map of study domain representing land-use overview in China, 2010.

The SSPs explore how global society, technology, consumer preferences, demographics, and the economy will evolve in the future relating to policy assumptions and the socioeconomic storyline [42,43]. In the Shared Socioeconomic Pathway framework, SSP1 represents a sustainable world using green roads that is people-oriented, SSP2 is a pathway of ''middle of the road'' that can be set between SSP1 and SSP3, SSP3 indicates a regional rivalry pathway that opposes global cooperation, SSP4 characterizes a divided world in which inequality and stratification are the dominant features both across and within countries, and SSP5 signifies a fossil-fuel-based development world where rapid global economic growth is dominant and people will face severe mitigation challenges. Within the framework of the Shared Socioeconomic Pathway, projections for the global population and GDP growth were harmonized in quantitative aspects [44,45]. The population and GDP data under five socioeconomic scenarios were reproduced for each grid by Nanjing University of Information Science and Technology (NUIST), China, and can be downloaded at the following link: https://geography.nuist.edu.cn/2019/1113/c1954a147560/page.htm (accessed on 1 February 2022). In addition, the country-wise socioeconomic data for the historical period were downloaded from the World Bank website. Moreover, the global mean atmospheric CO_2 concentration for the selected seven SSPs are obtained from the 'Greenhouse Gas Factsheets' webpage generated by the University of Melbourne, accessible at https://greenhousegases.science.unimelb.edu.au/#!/ghg?mode=downloads (accessed on 1 February 2022).

2.3. Methods

2.3.1. Land-Use Types Reclassification and Area Estimation

Land use in China can be classified into six major categories: Cropland, forest land, grassland, urban land, barren land, and water bodies [46]. In LUH2, 12 main types of land classes are projected under the different emission scenarios. In this study, the initial classes of LUH2 land-use products have merged into five major classes, that is cropland, forest land, grassland, urban land, and barren land (Table 1). Notably, land use for water bodies is not projected under the LUH2 project, as it implies that water areas in the future might not be changed significantly. In this study, trajectories for future land-use demand for cropland, forest land, grassland, urban land, and barren land from 2015–2100 under seven SSPs (SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP4-3.4, SSP4-6.0, and SSP5-8.5) are analyzed. The LUH2 projected land-use products are the fraction of each grid for all the initial land classes. To re-classify them as five major land categories, we summed the fraction of initial classes that fall under individual major land-use types. However, to quantify the total land-use area (km^2) for each major land type, we multiplied the grid-wise total area (km^2) with the fraction. In this study, the total land area for each grid is calculated for a $0.5° \times 0.5°$ resolution.

Table 1. Reclassification of land-use types.

LUH2 Projected Initial Land Classes	Re-Classified Land Classes
C_3 annual crop C_3 perennial crop C_4 annual crop C_4 perennial crop C_3 nitrogen-fixing crop	Cropland
Forested primary land Potentially forested secondary land	Forest land
Managed pasture rangeland	Grassland
Urban land	Urban land
Non-forested primary land Potentially non-forested secondary land	Barren land

2.3.2. Estimation of Socioeconomic Change over Major Land-Use Types

Over the last three decades, changes in urban land in China have attracted much scholarly attention, especially in light of the widespread economic growth and changes in demographic structure, as well as environmental aspects [47]. However, a quantitative investigation of the relationship between socioeconomic change and land-use change is imperative, especially at the regional or local scale. In this study, changes in socioeconomic variables (population and GDP) over each major land-use type are demarcated. We combined the projected major land-use types under seven SSPs with the five corresponding Shared socioeconomic scenarios. The combinations are as follows: SSP1 with SSP1-1.9 and SSP1-2.6; SSP2 with SSP2-4.5; SSP3 with SSP3-7.0; SSP4 with SSP4-3.4 and SSP4-6.0; and SSP5 with SSP5-8.5 scenarios. Similar combinations also can be found in the study by Mondal et al. [48].

2.3.3. Defining the Studied Periods

Addressing the 'Leaders' summit on Climate on Earth Day' (22 April 2021), President Xi Jinping announced an ambitious climate change mitigation target. Under this declaration, China aims to reach a carbon dioxide emissions peak before 2030 and the country will achieve carbon neutrality before 2060. Experts around the world have hailed such ambition as a more realistic and important fortitude that will lead to cooperative actions on global warming reduction and encourage global leaders to progress on the Paris Agreement goal.

According to the Climate Action Tracker (CAT), if China's goal is attained, projected global warming will decrease by 0.2 to 0.3 °C. All this relevant information is collected from different online news portals (i.e., http://en.qstheory.cn/ (accessed on 1 February 2022)). However, we expect that the last 5 years of the target year is the highest-potential period to achieve China's carbon emission target. So, in this study, we selected the 2026–2030 period as the "Carbon Emission Peak" and 2056–2060 as the 'Carbon Neutrality period' based on China's climate mitigation target. In addition, to explore the changes in the far future, we selected 2080–2099 as the 'Long-term' period. Further, the 1995–2014 period is selected as the historical period to estimate the relative changes.

3. Results

3.1. Projected Changes in Population with Urbanization

As the projected changes in different major land types show that the most dominant area expansion will occur for urban land (see Supplementary Materials; Figures S1–S3), it is important to explore how socioeconomic parameters will change over this land type in the future.

Projected changes in the population over urban land in China for three defined future periods under seven SSPs are shown in Figure 3. The estimated average population in the historical period (1995–2014) was 40,055 persons per km^2 over urban land areas. From the future standpoint, relative to the historical period (1995), the greatest increase in population is expected over urban land under all selected scenarios and periods. In the carbon emission peak target (2026–2030), relative to the historical period, the average population over urban land is inclined to grow largely under all scenarios, ranging from 461.2% to 488.6%. The largest increase is estimated under the higher-emission scenario, SSP5-8.5 (488.6%), followed by ~470% under SSP2-4.5. In the carbon-neutral target period (2056–2060), the most dominant increase in population over the urban area is projected to be 630.8% under SSP5-8.5 and 589.3% for SSP2-4.5, while the lowest increase is found for low-emission scenarios (SSP1-1.9 and SSP1-2.6) with a value of ~558%. In the long-term period (2080–2099), the population increase across urban land ranged from 453.2% to 529.5% among scenarios. The largest increase is estimated under SSP5-8.5 and the lowest increase for SSP4-3.4. So, it can be noted that the population over China's urban land will grow larger during the carbon-neutral phase (2056–2060), especially under higher emission scenarios.
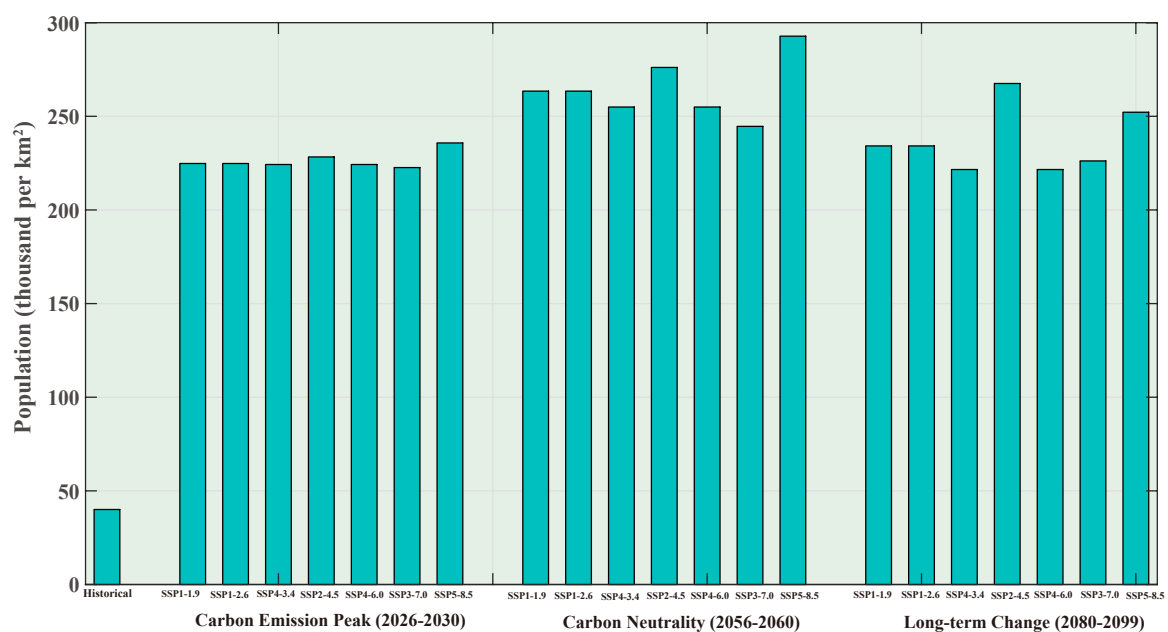

Figure 3. Changes in urban population across China for the historical period (1995–2014) and three future periods (2026–2030, 2056–2060, and 2080–2099) under seven SSPs.

3.2. Projected Changes in GDP with Urbanization

The prospective changes in GDP in terms of industrial and service perspectives over expected future urban area expansion are scrutinized under seven SSPs for three future periods (Figure 4). In the historical period, the estimated industrial GDP was higher than that of the service GDP over the urban land area, which was 5.8 billion and 5.1 billion, respectively. For the future change, the industrial GDP is projected to be higher than the service GDP in the carbon emission peak phase (2026–2030), but during the carbon-neutral target (2056–2060) and long-term (2080–2099) periods, the service GDP is higher than the industrial GDP for all the scenarios. In the carbon emission peak phase (2026–2030), the highest increase in industrial GDP over urban land is projected to be ~276% under SSP4-3.4 and SSP4-6.0 relative to the historical period, while the service GDP is likely to increase more under low -mission scenarios (SSP1-1.9 and SSP1-2.6), at ~270%. In the carbon-neutral phase (2056–2060), the service GDP will increase more than the industrial GDP under all the scenarios. Under SSP5-8.5, the leading increase accounts for 885.4% and 501.6% of the service and industrial GDPs, respectively. During the long-term period (2080–2099), the greatest GDP growth over the urban area will come from the service, rather than the industrial, sector. The strongest increase for both service and industry GDPs is projected under the higher-warming scenario, SSP5-8.5, with values of >1000% and 637.6%, respectively.
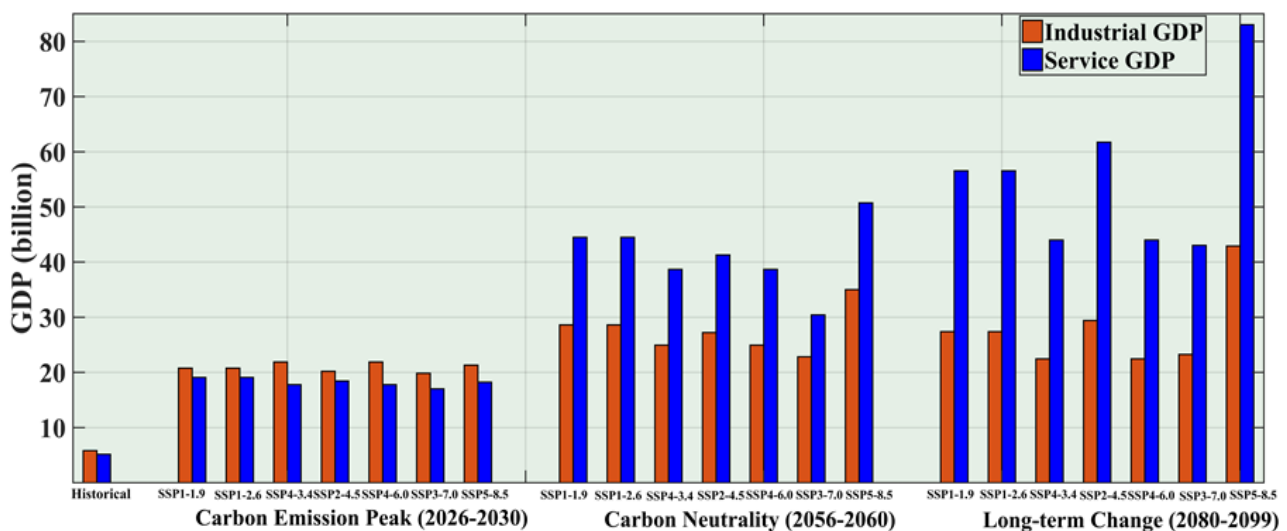

Figure 4. Prospective changes in urban GDP (industrial GDP and service GDP) across China for the historical period (1995–2014) and three future periods (2026–2030, 2056–2060, and 2080–2099) under seven SSPs.

3.3. Changes in Historical Land Use and Carbon Emission

It is further important to explore how CO_2 emission varies with changes in different land types. The following figures denote the changes in CO_2 emission vary with five major land types across China for the historical period (1995–2019).

As indicated in Figure 5, in general, the total CO_2 emission ascended sharply over time, which was 3392 (Mt) in the year 1995 and 11,535 (Mt) in 2019. However, the rapid rise in CO_2 responds to five land-use types with varying performances. For cropland (Figure 5a), the carbon emission increased in the historical period, while the area of cropland showed a declining trend from 1.27 ($\times 10^6$ km^2) in 1995 to 1.20 ($\times 10^6$ km^2) in 2019. For the forest area (Figure 5b), both the CO_2 emission and forest area showed an upward trend. The increase in forest area was from 2.01 ($\times 10^6$ km^2) to 2.08 ($\times 10^6$ km^2) from 1995–2019, where the annual growth rate was 3.48%. However, the change in the area was not transformed clearly. For the forest area (Figure 5c), the CO_2 increased, with a downtrend in the grassland area. For the urban area (Figure 5d), there was a significant upward trend in the urban-land

area, from 33,812 km^2 in 1995 to 60,244 km^2 in 2019. With the increase in urban areas, the carbon emission in China also increased from 3376 (Mt) to 11,535 (Mt) for the period 1995 to 2019, where the correlation coefficient value was >0.85 for urban land change and CO_2 emission. So, it can be noted that CO_2 emissions over China are largely related to the changes in urban land.
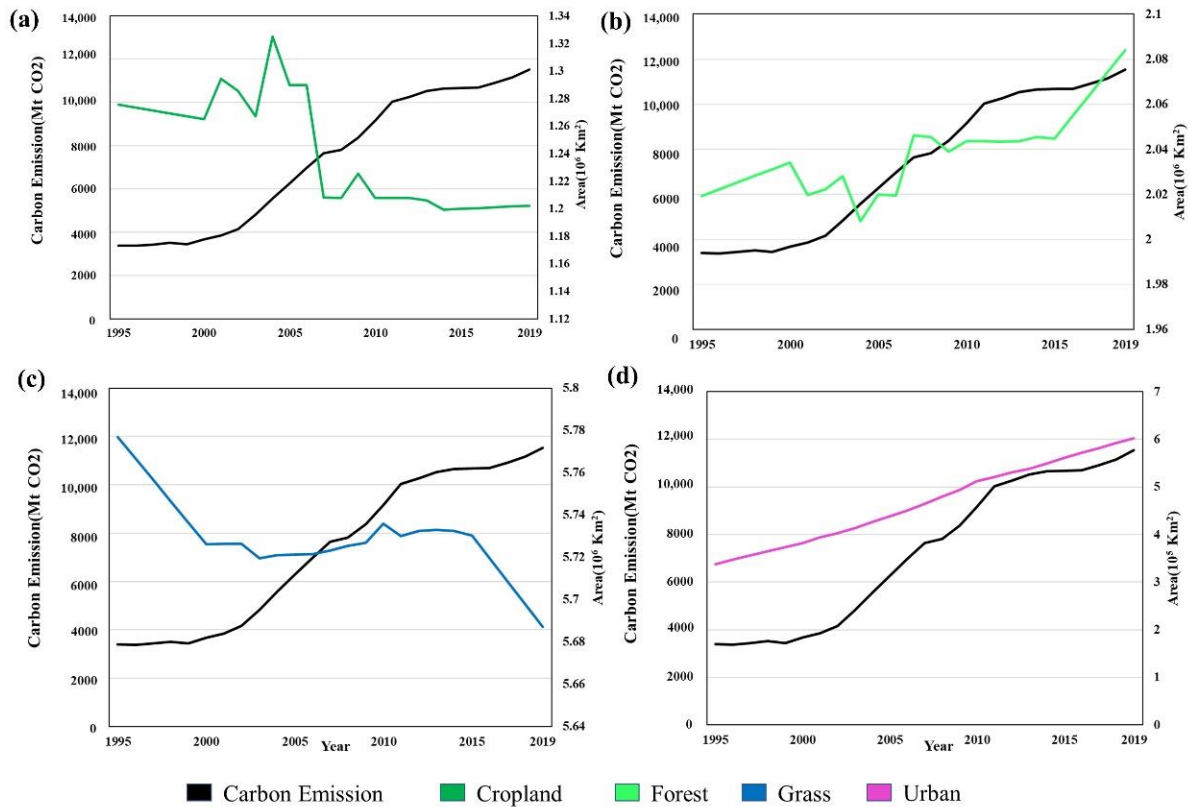

Figure 5. Changes in CO_2 emission with five major land types: (**a**) Cropland, (**b**) forest land, (**c**) grassland, and (**d**) urban land over China for the historical period (1995–2019).

3.4. Changes in the Future Urban CO_2 Emission

The dynamic changes in CO_2 emission over the urban area for the historical period (1995–2014) and three future periods (2026–2030, 2056–2060, and 2080–2099) under seven SSPs are illustrated in Figure 6. In the historical period (1995–2014), the cumulative CO_2 was estimated at 3876 metric tons (Mt). In the future, the total CO_2 over the urban area in China is projected to increase for all the selected scenarios and periods, except SSP1-1.9, SSP1-2.6, and SSP4-3.4 in the long-term period. Notably, CO_2 is expected to increase in higher-emission scenarios for all periods. Relative to the historical period, the highest increase accounts for 248.6% under SSP3-7.0 in the carbon emission peak phase (2026–2030), followed by 222.1% under SSP5-8.5. During the carbon-neutral target phase (2056–2060), CO_2 emission is estimated to decrease under SSP1-1.9, SSP1-2.6, and SSP4-3.4, where the strongest increase in CO_2 is found under higher warming scenarios. The uppermost increase is 363.3% under SSP5-8.5. During the long-term period (2080–2099), compared to the historical period, CO_2 emission is projected to decline under SSP1-1.9, SSP1-2.6, SSP4-3.4, SSP2-4.5, and SSP4-6.0. The largest increase accounts for 300.2% under SSP5-8.5. So, it can be highlighted that the highest CO_2 emission is projected under SSP5-8.5 in the carbon-neutral target (2056–2060) phase, while CO_2 emission will decline after 2056–2060 under SSP1-1.9, SSP1-2.6, and SSP4-3.4.
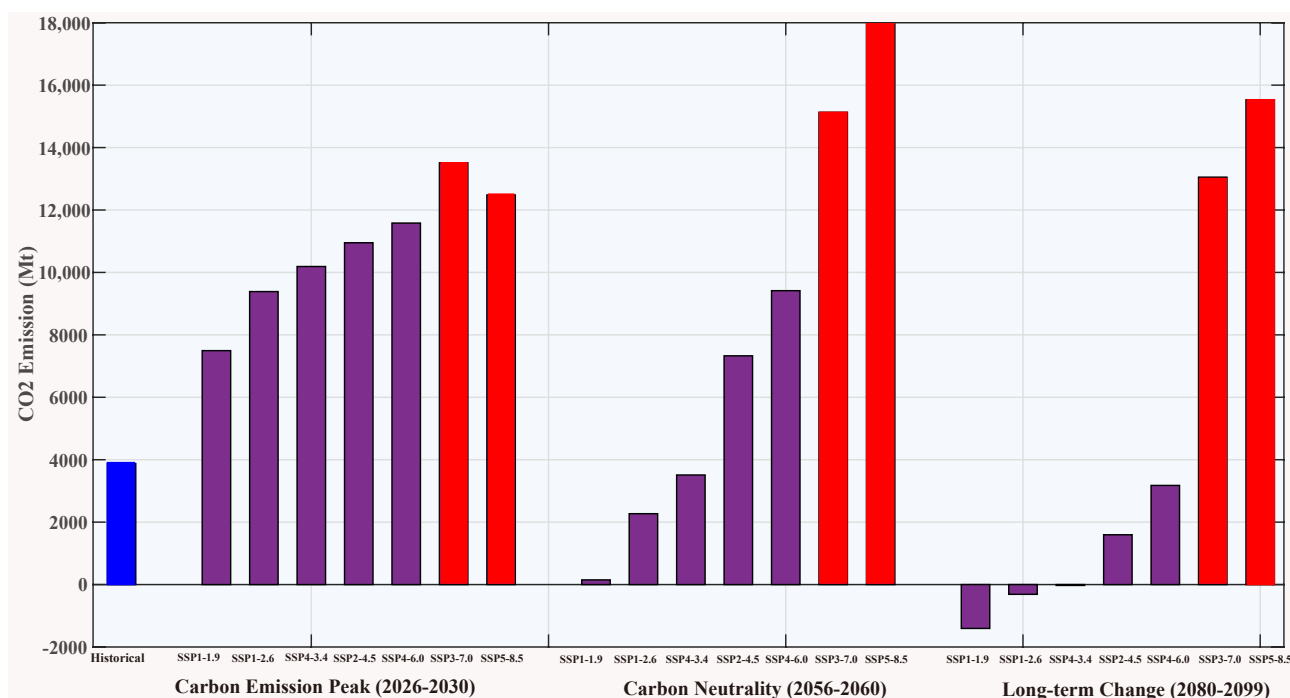
Figure 6. Potential changes in CO_2 emission in China's urban area for the historical period (1995–2014) and three future periods (2026–2030, 2056–2060, and 2080–2099) under seven SSPs. Red indicates higher emission scenarios, magenta signifies comparatively lower emission, while blue represents historical period.

3.5. Relationship between Future Urban Land-Use Change and Socioeconomic Parameters

In this section, we analyzed the relationship between projected land-use change and socioeconomic variables to explore how land-use change and socioeconomic variables are interlinked in future perspectives.

Relationships are examined by performing a correlation coefficient (R) test for projected urban land-use changes and socioeconomic variables (population, industrial GDP, and service GDP) over the urban area for three future periods (2026–2030, 2056–2060, and 2080–2099) under seven SSPs (Table 2). Notably, the correlation coefficient (R) value for all the variables is statistically significant at the 0.05 confidence level. The studied socioeconomic parameters (population, industrial GDP, and service GDP) represent a positive relation with projected land-use change under all SSPs and periods. The tested R-value between land-use change and population usually varies from 0.56 to 0.61 among scenarios and periods. The strongest relation is expected in the carbon dioxide emission peak phase (2026–2030), and afterward, it tends to be weaker on the way to the long-term period. Further, the relationship between land-use changes and the industrial GDP also shows a positive relationship with the R-value, ranging from 0.44 to 0.51. Similarly, the strongest relation is predicted in the carbon dioxide emission peak phase (2026–2030), compared to that of the carbon-neutral target (2056–2060) and long-term (2080–2099) periods. Likewise, land-use changes and the service GDP have a positive relationship under different scenarios and periods, which is dominant in the carbon dioxide emission peak phase (2026–2030). So, it can be highlighted that all the selected socioeconomic parameters (population, industrial GDP, and service GDP) will change with the projected land-use change under all SSPs and periods. The population has the strongest relation to land-use change compared to GDP. Besides, the strongest relationship is expected to occur in the carbon dioxide emission peak phase (2026–2030) for all the studied variables.

Table 2. Correlation coefficient (R) value in relation to land-use change and socioeconomic variables (population, industrial GDP, and service GDP).

Indicators	SSPs Scenarios	CO$_2$ Peak Phase (2026–2030)	CO$_2$ Neutrality (2056–2060)	Long-Term Change (2080–2099)
Population vs. Urban land	SSP1-1.9	0.61	0.60	0.57
	SSP1-2.6	0.61	0.60	0.58
	SSP4-3.4	0.61	0.60	0.56
	SSP2-4.5	0.60	0.58	0.56
	SSP4-6.0	0.61	0.59	0.56
	SSP3-7.0	0.60	0.60	0.57
	SSP5-8.5	0.61	0.58	0.53
Industrial GDP vs. Urban land	SSP1-1.9	0.51	0.48	0.47
	SSP1-2.6	0.50	0.48	0.47
	SSP4-3.4	0.49	0.46	0.44
	SSP2-4.5	0.49	0.48	0.46
	SSP4-6.0	0.49	0.46	0.44
	SSP3-7.0	0.49	0.47	0.45
	SSP5-8.5	0.50	0.49	0.48
Service GDP vs. Urban land	SSP1-1.9	0.49	0.47	0.49
	SSP1-2.6	0.50	0.47	0.49
	SSP4-3.4	0.50	0.49	0.50
	SSP2-4.5	0.50	0.49	0.48
	SSP4-6.0	0.50	0.49	0.49
	SSP3-7.0	0.49	0.49	0.49
	SSP5-8.5	0.49	0.47	0.47

4. Discussion

This study epitomizes the long-term scenario-based projection of future land-use change and its relationships with socioeconomic variables. Besides, we also explored the future CO$_2$ emission in the context of land-use change. We used a dataset projected based on the latest SSPs from CMIP6, which can heighten the effectiveness of our projected results to support scientific communities and policymakers. Moreover, this study focuses on two distinct future periods considering China's recent carbon dioxides emission target such as the carbon dioxide emission peak phase (2026–2030) and the carbon-neutral target (2056–2060).

Land-use change is the most dominant factor in changing climate and environmental degradation. The quantification of land-use projection indicates that urban land is expected to experience rapid growth over China in all periods and scenarios, where the most dominant expansion is apparent in the carbon neutrality target (2056–2060) under SSP5-8.5. A previous study also reported rapid global urban land growth before 2040 but losses of cropland and forestland [49]. A recent study by Mondal et al. [50] reported a massive increase in urban areas over South Asia. In some respects, substantial differences or even opposite trends are predicted in China compared to the world's perspective. Our analysis has revealed that major urban land expansion will transpire over cropland and grassland, especially in the 2026–2030 and 2056–2060 periods. It is expected that rapid economic advancement will promote the progression of urbanization and industrialization in the future, which will lead to a decrease in agricultural land and massive expansion of the urban built-up area in China. Some previous studies also reported a similar tendency in the historical period over the different cities of China. Shi et al. [38] found that urban built-up area has expanded largely in Shanghai city, with a decrease in arable land, and Li et al. [30] mentioned a similar status in Jilin province. The reduction in cropland could lead to a shortage of food production and supply. Reclaiming cropland is the most intermediate way to offset these agricultural-related losses. However, the decline in cropland and grassland could also exert weighty impacts on ecosystem services, habitats, biodiversity, and food provision for human societies. In spatial terms, urban land expansion in China is mostly inclined to occur across the eastern part, especially in the Haihe River Basin, Huaihe River Basin, the mid-lower Yangtze River Basin, and the Pearl River Basin where the changes largely occur among scenarios and periods. The findings of this paper are

largely corroborated with the study on land-use change projections in China by Liao et al. [46]. The conversion of agricultural land to urban land has been pronounced in the eastern and central parts of China [51]. Such dominant growth in urban land largely influences increased climatic risks [52–54]. Nonetheless, the uncertainty of socio-economic development and environmental safety plans are the key challenges in future land-use change. Seto et al. [55] also stated that large discrepancies exist among quantifying the land area in China. However, urban land expansion is expected to be the most dominant land-use change throughout China in the future.

Socioeconomic advancement is one of the key influential forces of land-use change throughout the process of rapid urbanization. Over the past decades, population change was the most predominant factor that directly affects land-use change, resulting in fluctuations in the structure and intensity of land use by altering the amount, value, structure, and production demand of land. The population flow and transfer process alter the structure of population distribution across different regions, which has a pivotal influence on the demand for land, as well as land-use patterns, causing enhanced land-use changes accordingly. From a futuristic standpoint, our study has demonstrated a positive relationship between urban land change and different socio-economic parameters. Previous studies also used the same process (the correlation coefficient test) to determine the relationship between land-use change and socioeconomic variables [38,51,56]. Our findings suggest that the urban population in China will grow larger during the carbon-neutral phase (2056–2060), especially under higher-emission scenarios. Population growth and perpetual urban land expansion resulted in decreasing the size of agricultural land, which yields conflict between the land system and human society. Some previous studies have projected future socioeconomic structures in China under different SSPs [57–62]. They reported that, except for SSP3, the total population of China would be topmost in 2025–2030 and then drop under the remaining Shared Socioeconomic Pathways (SSP1, SSP2, SSP4, and SSP5). However, as agricultural land is inclined to decline largely, people from the rural area will migrate to the urban area to maintain livelihoods, as well as for a better lifestyle. Further, future economic development is also strongly linked to land-use change. Our findings illustrate that the overall GDP in China is projected to increase in the future. While the industrial GDP is predicted to be more than that of service GDP in the carbon emission peak phase (2026–2030), during the carbon-neutral phase (2056–2060) and long-term period (2080–2099), the service GDP is more inclined to be higher than the industrial GDP for all scenarios. This is the indication that regions that offer more jobs in the service sector will increase largely in urban areas during the carbon-neutral phase (2056–2060) and long-term period (2080–2099), whereas areas with industries will increase even more in the carbon emission peak phase (2026–2030) to hasten economic development. In the future, it is likely that with rapid economic growth and changes in the industrial arrangement, the conversion of cropland to urban land will be further augmented, the urbanization of the population will upsurge, and vast urban expansion and investment in urban built-up will be enhanced in China. The migration of the Chinese population from rural areas to urban areas will cause the population growth in the urban area to upsurge, thus population growth and the desire for strong economic development will be the pivotal driving factors in land-use change. The correlation analysis in this study provides strong evidence that the population and GDP growth (both industrial and service) in China are closely interlinked with land-use changes in the future. For historical change (2005–2009), a past study stated that absolute land-use change is strongly correlated with absolute GDP growth, but a weaker relationship is detected between the growth rate of GDP and the rate of land-use change [50]. This signifies that the land amount is a critical input in economic development. On the other hand, for future change, our study suggests that population change is expected to be the most dominant factor in influencing land-use change than that of GDP growth. The extent of the correlation may vary due to changing conditions of the economy, population, location, and institutions. However, this form of land-centered urbanization will cause more adverse environmental degradation and social tensions.

Land-use dynamics is one of the most predominant sources of GHG emissions. Land-use change, especially the conversion of forest land to cropland, has been a substantial source of global CO_2 emission, which is approximately 12% of all anthropogenic emissions from 1990–2010 [63]. Agricultural activities and industries greatly contribute to emitting various GHG into the earth's atmosphere. In this study, we found that the CO_2 emission in the historical period (1995–2019) over China is strongly related to the changes in urban land. Gurney et al. [64] also reported a dominant increase in urban Co2 emissions. Further, as we find a vast expansion of urban land in China in the future, this paper focuses on future CO_2 emissions from the urban area of China. In the carbon emission peak phase (2026–2030), the highest emission is projected under SSP3-7.0. The highest CO_2 emission is expected under SSP5-8.5 in the carbon-neutral target (2056–2060) phase, while CO_2 emission will decrease after 2056–2060 under SSP1-1.9, SSP1-2.6, and SSP4-3.4. A recent study reported that the cumulative increase in urban emission over Asia will vary from 65% to 73.3% from 2022 to 2100 among scenarios (Gurney et al. (2022)). However, annual CO_2 emissions from the urban area will decrease gradually (especially under lower emissions) after the mid-century, whereas emissions are inclined to become even negative in the long-term period (2080–2099) in China. This signifies that massive CO_2 uptake will occur in China during the carbon-neutral phase towards the end of the 21st century. Carbon uptake may occur through an enlarged vegetation process by applying more advanced technology. The carbon uptake process of adopting the regrowth of vegetation will help with massive CO_2 reductions in Asian countries from mid-century onwards [62]. Further, our study determined that, from mid-century onwards, the service sector will contribute to China's GDP enhancement rather than industries. It is also an indication of CO_2 reduction in China. Therefore, our study suggests following a lower-emission pathway (SSP1-1.9 and SSP1-2.6) to achieve China's carbon neutrality goal by 2060.

The limitations of this study are mainly related to inherent uncertainties. This research yields some uncertainties related to land-use modeling and projection methodologies, which might influence the trustworthiness of our results. In this paper, unescapable uncertainties can yield from climate change scenarios, emission level considerations, and estimation methods of different land types. Moreover, this study used only relative change to estimate the degree of land-use change, which can lead to imperfection and one-sidedness of the findings. Moreover, even though the recently created land-use data are considered to have a high resolution, longer timeframe, detailed input datasets (multiple crops and pasture types, and related management practices), and well-run algorithms, they still exert uncertainties in some respects. These data are produced considering a hypothesis of the future demand aspect that global land-use dynamics are inclined to further enlarge to meet the rising needs of food, fiber, and energy [65,66]. However, they do not take into account individual countries' policy intervention changes associated with land-use planning and management. Furthermore, the ecological control line has also not been considered in this study. Therefore, this study urges researchers to conduct further studies based on future land-use products that consider individual countries' policy interventions and how future socioeconomic changes in the context of land-use change could affect ecosystems and biodiversity. Further, it is also important to explore the relationship between future land use policy in achieving the Sustainable Development Goals (SDGs), which is also stated by a previous study [67].

5. Conclusions

From a futuristic viewpoint, studies related to future land-use change and associated socioeconomic status and GHG emission considering different land types in China are rare. In this study, the latest SSPs-based land-use projections are taken to quantify the future land-use change in China. This study emphasizes three future periods, namely the carbon emission peak phase (2026–2030), the carbon-neutral phase (2056–2060), and the long-term period (2080–2099) to epitomize changes in studied variables as well as their interconnections under seven updated scenarios.

For changes in major land types, urban, barren, and forest land are likely to expand over China under all the periods and scenarios. Although cropland and grassland are likely to decline for almost all scenarios and periods, the greatest increase in cropland is found under SSP4-3.4 in the long-term period. Considering the changes under all scenarios and periods, the utmost increase in urban land is obvious over China in all periods, where prominent expansion is estimated in the carbon neutrality target (2056–2060) under SSP5-8.5. In the spatial aspect, the expansion of urban land is mainly prominent in the eastern and central parts of China where the variation in quantity occurs for all periods and scenarios. Furthermore, this study estimated changes in population and GDP (industrial and service) in the context of urban land expansion. For population change, it is suggested that the population over China's urban land will largely increase during the carbon-neutral phase (2056–2060), especially under higher-emission scenarios. Further, the industrial GDP will be higher than the service GDP in the carbon emission peak phase (2026–2030), but it is service GDP that will increase most for the carbon-neutral target (2056–2060) and long-term (2080–2099) periods under all scenarios. To estimate CO_2 in the context of the future, land use is important to achieve China's carbon neutrality goal. The largest increase in CO_2 emission is anticipated under SSP5-8.5 in the carbon-neutral target (2056–2060) phase, while CO_2 emission will decline after (2056–2060) under SSP1-1.9, SSP1-2.6, and SSP4-3.4. Finally, this study investigated the relationship between urban land expansion and socioeconomic variables. Different socioeconomic variables (population, industrial GDP, and service GDP) will change with the projected land-use change under all SSPs and periods. The population is the most dominant factor in relation to land-use change compared to GDP.

However, this study provides a concrete foundation for considering pathways in dealing with future land-use change and designing a more comprehensive CO_2 mitigation policy, in the context of urban land expansion and its relationship with population growth and economic development. Our findings suggest initiating a strict land-use management policy to balance cropland, forest land, and urban land considering socioeconomic challenges. Notably, taken together, these insights emphasize informing and formulating effective policy interventions regarding achieving carbon neutrality goals. As CO_2 is expected to decline under lower-emission pathways (SSP1-1.9 and SSP1-2.6), we strongly suggest following the future socio-economic development pathway SSP1 (sustainability pathway) regarding policymaking to achieve China's carbon neutrality goal by 2060. In this aspect of scenario-oriented policy interventions, different socioeconomic pathway-based challenges should be considered for mitigation and adaptation. Further, this study urges the execution of the Paris Agreement goals through reducing CO_2 emanations.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/su14053065/s1, Figure S1. Anticipated changes in land-area quantities of (a) five major land types and (b) individual land use of the urban area in China under seven SSPs for three future periods and historical period (1995–2014), Figure S2. Projected changes in the urban area in China under SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 for the three de-fined future periods compared to the historical period, Figure S3. Projected changes in urban area in China under SSP1-1.9, SSP4-3.4, and SSP4-6.0 for the three defined future periods compared to historical period.

Author Contributions: B.S., Z.W.K. and S.K.M. conceived the study. S.J., J.Z. and S.K.M. contributed equally to this paper by performing analyses and drafting the paper. J.H. and R.X. calculated the simulation and projection of land-use changes. Z.C., T.J. and J.Z. conducted the analysis of relationships with CO_2 emission and land-use types. B.S., S.J. and S.K.M. analyzed the relationships among urbanization, population, and GDP in the context of land-use change. All authors have read and agreed to the published version of the manuscript.

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