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Sustainable Management of Carbon Sequestration Service in Areas with High Development Pressure: Considering Land Use Changes and Carbon Costs

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Abstract: In countries and regions where development projects are frequently implemented, there is a significant change in the value of carbon sequestration services according to land use and land cover (LULC) changes. In this study, we analyzed the changes in the carbon sequestration services which occurred due to the LULC changes over a 20 years period (1989–2009) in Korea where local development projects have been active, since 1990s. As a result, the total carbon stocks decreased by about 0.07 billion t C. Significant changes in the carbon stocks mostly occurred in areas where development projects were frequently implemented. The loss of economic value due to the changes in carbon stocks over 20 years was 4.7 trillion won (4159 million USD) when market price of carbon is applied. Therefore, in countries and regions where there is an active development, it is necessary to monitor the land-use changes with high carbon stocks, to reconsider the value of the carbon when making policy decisions which cause LULC changes, and to internalize social costs into the market prices. Especially at a local level, it is necessary to promote management policy based on carbon sequestration services in accordance with local conditions such as size and types of the changes in carbon stocks.

Keywords: carbon storage capacity; carbon sequestration service; development pressure; LULC change; carbon cost

1. Introduction

The climate change regulation service provided by the ecosystem through the carbon storage capacity is one of the most important ecosystem services [1]. In particular, the forest ecosystem plays a critical role as a carbon pool, accounting for approximately 40% of the carbon stored in land biomass [2,3]. However, all kinds of man-made global environmental change are giving serious negative impacts on the carbon storage capacity. Especially, the land use and land cover (LULC) changes, such as urbanization and deforestation, can be a spatial factor which gives direct impacts on the carbon storage capacity of the ecosystem [1]. Urbanization acts as a pressure to the ecosystem that plays a significant role in storing the carbon [1,4] and leads to a decrease of the carbon storage capacity [4,5]. Diminution of natural areas such as forest, agricultural land and wetland also leads to a decrease of the carbon storage capacity. In addition, the LULC changes in forest areas give impacts to the carbon storage and also carbon fluxes from local to global scale [6,7].

On the other hand, the market price of carbon can be an economic factor that indirectly affects the carbon storage of the ecosystem. The policy decisions whether to preserve the forests or to develop the lands for alternate use are influenced by the market value of the carbon. But, the current market prices of carbon cannot sufficiently reflect the environmental value as the natural capital [8]. Generally, carbon is stored in natural capital such as forests, farmland, wetland, etc., which have a role as public goods or environmental goods. Once public goods or environmental properties are destroyed, the effects are prolonged and recovery takes a long time. Therefore, the price of carbon, including the future cost of environmental destruction and recovery, must be taken into account in the decision-making process. But, usually, the market price is determined by reflecting the current value thought by the participants in the market using known information. For carbon, globally the carbon price mechanism has a short history and is still a growing market. This means that participants in the carbon market can underestimate carbon prices due to a lack of information. Therefore, the carbon sequestration service value can be underestimated if the current carbon market price is applied.

In an effort to get a reasonable price of carbon, the social costs which take the environmental and social values of the carbon into account can be utilized in the policy making process [9]. That is, the price of carbon should reflect, as Michaelowa et al. [9] argues, environmental and social costs so that the decision-making of development can be made based on the proper cost–benefit analysis. In addition, the appropriate price of carbon could be introduced by setting a clear policy objective and the scope of the carbon prices, and also by increasing the accuracy of the emission data collection and verification. For example, accurate measurement, reporting and verification should be in place for a specific operation or abatement technology of carbon emission so that the country operating the carbon pricing mechanism sets the accurate emission cap for the nation, sector, and company, which in turn affect carbon prices.

Thus, the scale and type of LULC change and carbon prices are the factors that either directly or indirectly affecting the carbon sequestration service of the ecosystem. The countries with high development pressure are experiencing many LULC changes, and they also tend to make economic growth-oriented policy decisions. Consequently, the carbon storage capacity provided by the ecosystem may have decreased greatly and the economic value of the carbon sequestration service may also have reduced. The Republic of Korea (hereinafter referred to as Korea) is a classic example. Korea is the country that has successfully achieved afforestation after the Second World War and the Korean War. However, there have been constant LULC changes, such as conversion of the forests, followed by the new town development and implementation of the local government development projects after the 1990's, and frequent economic growth-oriented policy decisions.

There is a need to analyze how carbon storage capacity changes according to the LULC change at the municipal/county level which is the basic units of the policy decision-making bodies, in countries such as Korea where development projects take place frequently. Moreover, it is also important to evaluate how the economic value of the carbon sequestration service alters when the market price of the carbon is applied. In the precedent research, many studies analyzed the changes of the carbon stocks according to the LULC change. Pan et al. [10] estimated that the carbon stocks of 1.3 ± 0.7 P g C year^{-1} were lost due to the LULC change in the tropical areas from 1990 to 2007 globally. Tomasso and Leighton [11], Han et al. [12], and Zhang et al. [13] used the LULC maps to analyze changes in the carbon stocks according to the land use changes. For the economic value of the carbon, Patton et al. [14] estimated the monetary value of the wetland ecosystems registered as the US National Wildlife Refuge. Hansen [15] estimated the economic value of the agricultural land and forest wetland restoration through social costs of the carbon. On the other hand, few studies have been carried to simultaneously consider both changes in the carbon stocks and its economic value according to the LULC changes.

Roh et al. [16] estimated the changes of the carbon stocks and its monetary value but only to cover the local area on the Jeju Special Self-Governing Province in Korea.

In this paper, we have investigated the changes of the carbon stocks according to the LULC change between 1989 and 2009 when the regional development projects were actively implemented in Korea. Next, we have analyzed how the economic value of the carbon sequestration services varied regionally when the market price of the carbon was applied. Through this, this study aims to clarify the management direction of the carbon storage capacity and carbon sequestration services of the national and local governments considering the changes of the carbon storage capacity in countries with high development pressure like Korea. We would also like to propose a policy direction, to take the social cost of the carbon into consideration in the process of establishing environmental policy decisions.

2. Materials and Methods

2.1. Study Area

Korea is located in the monsoon climate zone in the mid-latitude region of East Asia. It has four distinct seasons and due to its abundant rainfall, it has well-developed vegetation, including forests and agricultural land, which is a major carbon storage (Figure 1a) in the country. The most important carbon storage is in forests. The forest area occupies over 60% of the national land area and the mean stand volume density is 145.99 m^3 ha^{-1} in 2015 [17,18]. The agricultural land accounts for 24% of the national land area, and it plays a major role as a carbon pool near the main rivers where rice cultivation has developed.

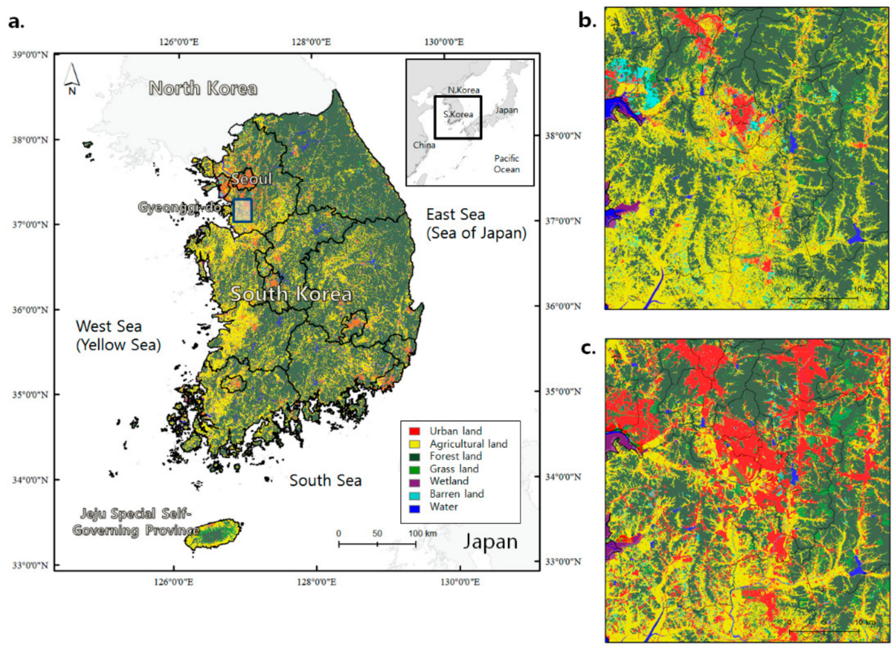


Figure 1. (**a**) Land use and land cover (LULC) map (2009) of the Study area (data source: [19]). The blue line box refers to the area near Hwaseong City in Gyeonggi Province, where development projects have been active since the 1990s, (**b**) LULC map of the year 1989 in blue line box (data source: [20]), (**c**) LULC map of the year 2009 in blue line box.

Since the 1990s, however, large-scale development projects have started to spread out of the existing metropolitan cities to local areas. In the early 1990s, new town development projects began to be implemented in response to the growing population in the Seoul metropolitan area (Figure 1b,c). In 1995, the local autonomy system was implemented and the regional development project was activated. Since 2000, regional development projects have been launched in the name of a "Balanced National Development Policy", which involves the relocation of public institutions and the development of residential and industrial complexes. This change in the LULC as a development site for forests and agricultural land leads to a reduction of the nation's carbon storage capacity. It also weakens the ability of ecosystems to adapt to the climate change and poses a great challenge in maintaining national and regional ecosystem services.

2.2. Price of Carbon

The carbon price is composed of all the costs that are charged to the carbon pollutants to reduce the carbon released into the atmosphere as a greenhouse gas. The global carbon pricing mechanism in force includes the emissions trading scheme (ETS) and carbon tax. ETS is a system in which countries or companies (businesses) are allocated carbon credits and emit carbon within their limits, and trade it which insufficient or remain in the market [21]. ETS can determine the upper limit of CO_2 emissions in advance, but there are limits to controlling the emissions of all economic actors (home, commerce, etc.). Carbon tax is a fee charged for carbon-based fossil fuels (coal, oil and gas). Carbon taxes can be imposed directly on all energy consumers who emit carbon, and can lead to innovations that allow companies to turn their production systems into clean input [22].

In many countries, carbon prices are still low. In April 2018, the global carbon prices are broad-ranging from a minimum of $1 to $139, and 46% (based on the greenhouse gas emissions coverage) is priced at less than $10 which is still below the carbon price range of $40 to $80 per tonne, that is required to be able to meet the Paris Agreement [23]. Although 189 countries, which account for 96% of the world's GHG emissions have agreed to cut emissions by participating in the Paris Agreement, 85% of the world's emissions have not be charged and 75% of the carbon prices is less than $10 per t CO_2 [21]. In addition, there is no consensus on the carbon conversion prices. According to the International Energy Agency report, the carbon conversion prices are different depending on the region, climatic conditions, fossil fuel prices, power plant technology, capital costs, and tax regimes [24]. Riahi et al. [25] stated that the range of the carbon prices is estimated to be $15–360 in 2030 and $45–1000 in 2050 and that there is no meaningful carbon price convergence. On the other hand, many countries have been imposing economic costs on carbon since the ratification of the Paris Agreement and the carbon prices are rising consequently. The 88 States Parties (56% of the global GHG emissions) have been planning, or considering using, the carbon pricing mechanism as a means to implement and achieve the nationally determined contributions (NDCs) [23]. In addition, the carbon prices are expected to continuously rise as many countries are making efforts to align the carbon prices with social costs, by introducing a carbon price floor for the purpose of encouraging investments in energy efficiency and mitigation measures.

The social cost of carbon is the discounted present value of future losses incurred by increasing one ton of CO_2 emissions into the atmosphere for a given year, or the benefits of CO_2 reduction [26]. The social cost of carbon reflects its environmental value and is used to measure the economic benefits of greenhouse gas reduction. In many countries, there is a continuing effort to raise carbon prices and reflect carbon's environmental and social values in policy decisions. In the United States and the United Kingdom, the social costs of carbon have already been estimated at the government level. Tol [27] analyzed 75 studies on the social costs of carbon, and suggested the mean marginal cost of carbon as $196/t C and the mode as $49/t C. The Intergovernmental Working Group on Social Costs of Carbon of the United States has applied a 3% discount rate on the social costs of carbon in 2007 and estimated it to be $32/t CO_2 in 2010, $52/t CO_2 in 2030, and $71/t CO_2 in 2050 [28]. The European Commission estimated the social costs of carbon to be €19/t CO_2 (median value), €9/t CO_2 (minimum value) and €80/t CO_2 (maximum value) [29]. Commission Quinet of France, by applying a 4% discount rate, estimated the social costs of carbon to be €32/t CO_2 in 2010, €100/t CO_2 in 2030 and €200/t CO_2 in 2050 [30].

In Korea, ETS was introduced and operated in 2015 as a carbon pricing mechanism [31]. For implementation of ETS, Korea enacted the 'Act on the Allocation and Trading of Greenhouse Gas Emission Rights' in 2012 and established the 'Basic Plan for Emissions Trading' in 2014. According to such a regime, the '1st Plan Period (2015–2017) Emissions Trading Scheme' was established, and ETS has been in force since 2015. Korea's ETS has grown 10 times in the past two years (63.1 billion won to 612.3 billion won) [31]. ETS transaction prices ranged from 11,007 KRW per t CO_2 in the first year (2015) to 28,879 KRW in the last year (2017). During the two years, the emission allowances allocated by companies accounted for 80.2% of the total national emissions (2122.5 million tons, in 2017) [31]. However, since the Korea's ETS has been started recent few years ago, the ETS carbon price is not stable. In addition, there is also discussion on the social cost of carbon in Korea, but there is still a lack of research that reflects the domestic situation. Therefore, it is not officially applied to national and local government policies.

2.3. Data

The data used in this study are shown in Table 1. To classify the ecosystem types and calculate the change areas of each ecosystem, the LULC map of the year 1989 and 2009, which were made by the Ministry of Environment [19,20], were used as the spatial dataset. Because it was made by the same methods used from 1980s to the recent years, it can be used to periodically analyze the changes of the ground surface in time series. The LULC map was verified through on-site inspection during the production process, so the accuracy is ensured. The 1989 LULC map has 7 categories but the 2009 LULC map has more detailed 22 categories. The 22 categories of 2009 LULC Map is a subdivision of the seven categories of the 1989 LULC Map. For the carbon stock calculation in 2009 and validation, we used the 2009 LULC map and reclassified it to 19 categories (Table A1 in the Appendix A). For the changes of 1989–2009 carbon stocks, we used 1989 and 2009 LULC map. To match the ecosystem types of them, we reclassified the 19 categories of 2009 LULC map to 7 categories of 1989 LULC map.

In order to calculate the carbon stocks for each ecosystem type, we used the data for each of the four carbon pools of the above-ground biomass, underground biomass, soil carbon, litter and dead wood (excluding wood products) (Table 1). The carbon stored in the above and underground biomass of the forest areas is the amount of the growing stock per unit area by forest type ([32]; Table A2 in the Appendix A) derived from the 2010 forest basic statistics presented in the Statistical Yearbook of Forestry and the carbon storage coefficient ([33]; Table A3 in the Appendix A) published by the Korea Forest Research Institute. For the carbon stored in soils and litter layers in forests and urban forests, the carbon stock data per unit area [33] was applied. The carbon stored in the dead wood of forests and urban forests and other ecosystem types (urban land, agricultural land, grassland, wetland, barren land, water) is cataloged using the results of the field research and modeling studies conducted in Korea and other countries. Carbon stocks per unit area stored in four carbon pools by ecosystem type show in Table A1.

Table 1. List of data used in this study.

Category	Ecosystem Type	Carbon Pool	Data	Year
Spatial data (Ecosystem type, area)	7 ecosystems	-	LULC map [20]	1989
	19(7) * ecosystems		LULC map [19]	2009
Carbon pools data (carbon stocks per unit area)	Forest	Above ground and underground biomass	Amount of growing stock per unit area by forest type [32]; Table A2	2010
		Soil carbon and litter	Carbon stocks data per unit area [33]	-
		Dead wood	Field research and modeling studies conducted in Korea and other countries [33–36] **	-
	Other ecosystem type	All		

* For the analysis of the changes of the carbon stocks between 1989 and 2009, we reclassified by changing the 19 categories of the 2009 LULC map to 7 categories of the 1989 LULC map. ** The carbon stored in dead wood of forest and urban forest, and other ecosystems are not updated annually with the statistical data required for calculations, so the values presented in previous studies are utilized.

2.4. Methods

The study was carried out in three stages (Figure 2). First, the carbon stocks of the year 2009 were calculated for 19 ecosystem types. Using the 2009 LULC map [19], the ecosystem types were classified into 19 types (Table A1), and the areas of each ecosystem type were calculated. Using the carbon pool data, the carbon storages per unit area (t C/ha) were calculated for four types of the carbon pools (above-ground and underground biomass, soil, litter and dead wood) per each ecosystem type. Then, the carbon stocks for each ecosystem type were derived by multiplying the area by the ecosystem types and the carbon storages per unit area. After that, the 2009 carbon stocks by 19 ecosystems were spatialized in pixels (30 × 30 m). Validation was conducted on the 2009 carbon stocks of the standing timber biomass in forests (above-ground and underground biomass). The validation method was the comparison between the carbon stocks of the forest standing timber biomass derived from this study and the 2010 forest standing timber growing stocks based on field survey conducted by Korea Forest Service (KFS) [37].

Second, the changes of carbon stocks from 1989 to 2009 by seven ecosystem types as per LULC change were calculated using the carbon model of Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST). InVEST is a suite of models used to quantify and map ecosystem services provided by different LULC types. It can also be used to estimate the ecosystem service changes as per long-term LULC changes because the result value is generated on a yearly basis by using the spatial data on LULC. Since the results are derived on the basis of the 30 × 30 m grids, it can be efficiently utilized in establishing a space-based environmental plan. InVEST was successfully applied for the land use planning for the adaptation to climate change in Hawaii [38]. Furthermore, the changes in the ecosystem services according to the future policy alternatives can be analyzed by using a scenario analysis in conjunction with the land-use prediction model, and it can be utilized as a reference for policy decision-making [39]. In this study, the LULC maps of 1989 and 2009 by the seven ecosystem types and the carbon storage data of the seven ecosystem types in 2009 were used as input data for the InVEST carbon model. As a result of the model, we derived carbon stock maps by seven ecosystem types of 1989 and 2009. We also derived map of changes in carbon stocks from 1989 to 2009 by seven ecosystem types. The three result maps show carbon storage amount of each ecosystem type by pixel (30 × 30 m). The difference between the carbon stocks of the year 1989 and 2009 was analyzed in order to understand the carbon stock changes made during 20 years. After that, the changes in the carbon stocks of 162 local municipalities (cities/counties) according to the LULC changes during the 20 years from 1989 to 2009 were analyzed and the top 10 municipalities were identified. Also, the first and second LULC change types and its causes of 3 municipalities were analyzed to investigate the causes affecting the carbon stock changes per local government.

Lastly, the changes in the value of the carbon stocks (carbon sequestration service) according to the LULC change were analyzed. The carbon sequestration services of 16 regional provinces were also compared. As for the estimation of the monetary value of the carbon sequestration services in the ecosystem, the carbon market prices were used. In this study, the average price of 20,279 KRW (17.87 USD) (We converted our estimation in KRW into USD in a base year (2010) [40])/t CO_2 traded in Korea ETS during the '1st Plan Period (2015–2017) ETS in Korea' was applied [31]. However, in order to find the price that is closest to the research year (2009) and convertible through the GDP deflator, it was converted as of 2010. In addition, 44/12 was multiplied in order to meet the biophysical quantification (1 t C) even though the carbon credits are traded on the basis of one tonne of CO_2 in general. Through this process, the carbon price applied in this study is 68,303 KRW (60.19 USD)/t C. (Based on the Bank of Korea's economic statistics system (ECOS) [41], the GDP deflator figure for 2010 is set to 100), was applied as for the market price, as this is the first time that a unit of the carbon was being priced in Korea (We applied the average trading price of all tradable units in the first phase (2015–2017) in the Korean ETS market in order to visualize the value and the effect of the LULC changes).

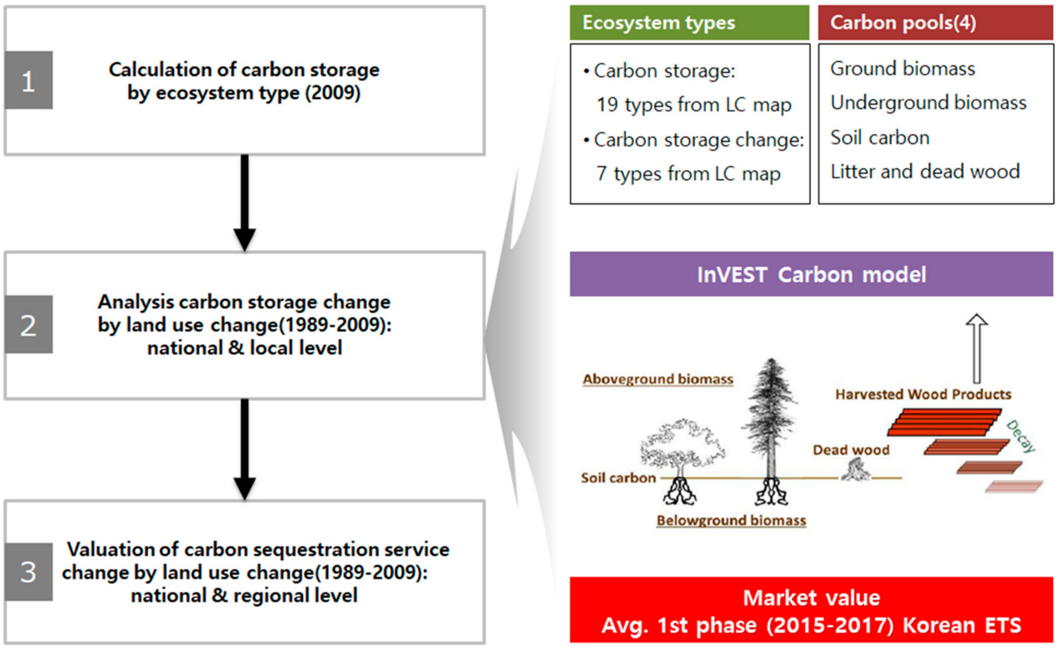


Figure 2. A study flow (**left**) and used methods (**right**), the picture of the InVEST Carbon model (right center) was modified based on Conte et al. [42].

3. Results

3.1. Carbon Stocks of the Year 2009 and Validation

The carbon stocks in the forest (above ground and underground biomass, soil and litter layer) of the year 2009 are shown in Table 2. The total carbon stocks of the forest were 769 million t C. The reliability of this result was confirmed by the validation. The standing forest carbon stocks based on the 2009 LULC map were well-corresponded with the KFS observation data derived from field survey (Table A4 in the Appendix A). As for the geographical distribution, there was a difference of more than 20% in the Jeju Special Self-Governing Province and Jeollanam-do Province but the coefficient of determination (R^2) appeared to be very high with 98.58% when fitting with the simple linear regression model using the two carbon stock values (Figure 3).

Table 2. Carbon stocks of the year 2009 in forests (excluding dead trees).

Carbon Pool	Ecosystem Types	Carbon Stocks Per Unit Area (t C/ha)	Area by Ecosystem Types (km^2)	Carbon Stocks by Ecosystem Types and Carbon Pool (Million t C)	Carbon Stocks by Carbon Pool (One Hundred Million t C)
Standing timber biomass	Broadleaf forest	87.46	17,440.71	152.54	4.27
	Coniferous forest	54.44	27,794.61	151.31	
	Mixed forest	73.37	16,792.64	123.21	
Litter layer	Broadleaf forest	6.63	17,440.71	11.56	0.58
	Coniferous forest	11.25	27,794.61	31.27	
	Mixed forest	8.94	16,792.64	15.01	
Soil	Broadleaf forest	55.68	17,440.71	97.11	2.84
	Coniferous forest	38.75	27,794.61	107.7	
	Mixed forest	47.22	16,792.64	79.29	
Total	·	·	·	·	7.69

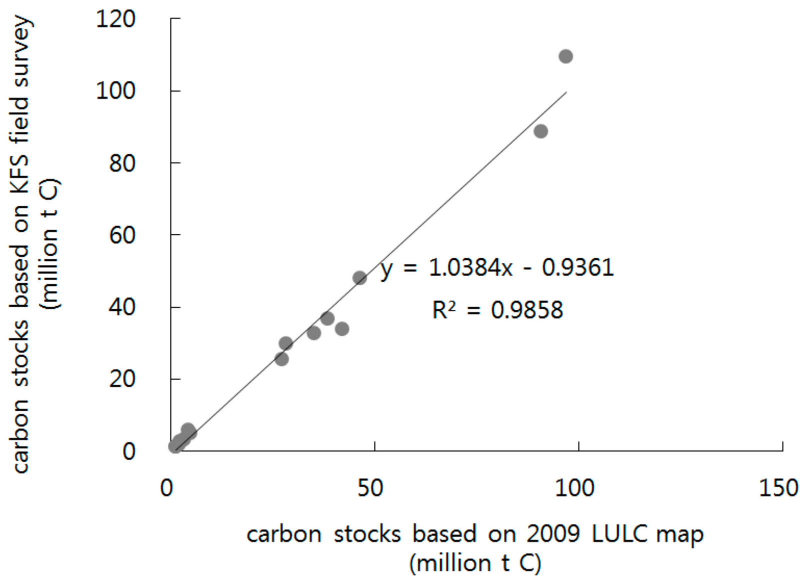


Figure 3. A comparison of between the standing timber biomass carbon stocks based on the 2010 Korea Forest Service (KFS) field survey [32] and 2009 LULC map.

The carbon stocks per unit area of the 19 ecosystem types in the year 2009 are shown in Table A1. The total carbon stocks of Korea were analyzed to be about 1 billion t C (Table A5 in the Appendix A) and the spatialized carbon stocks by pixels are shown in Figure 4. Each pixel of the ecosystem types has a value of 0–21.9 t C. In 2009, forests and agricultural areas account for 94.5% of the total carbon stock. But grassland, freshwaters and marine are only account for 5.5% of it. Urban area has been shown to have no carbon storage.

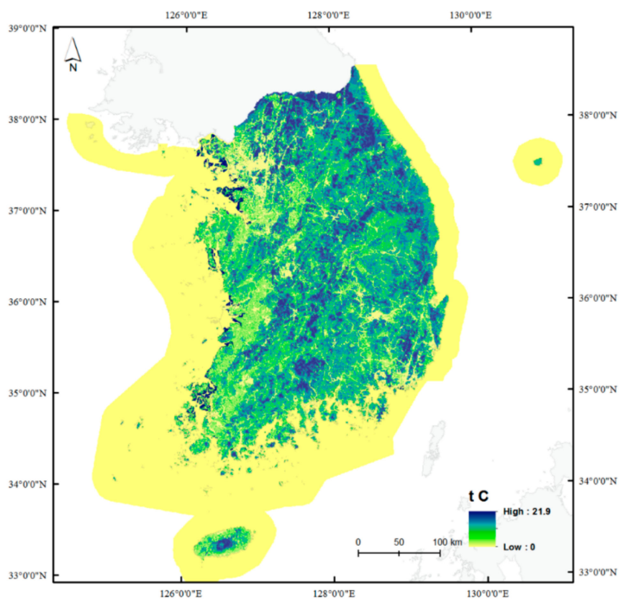
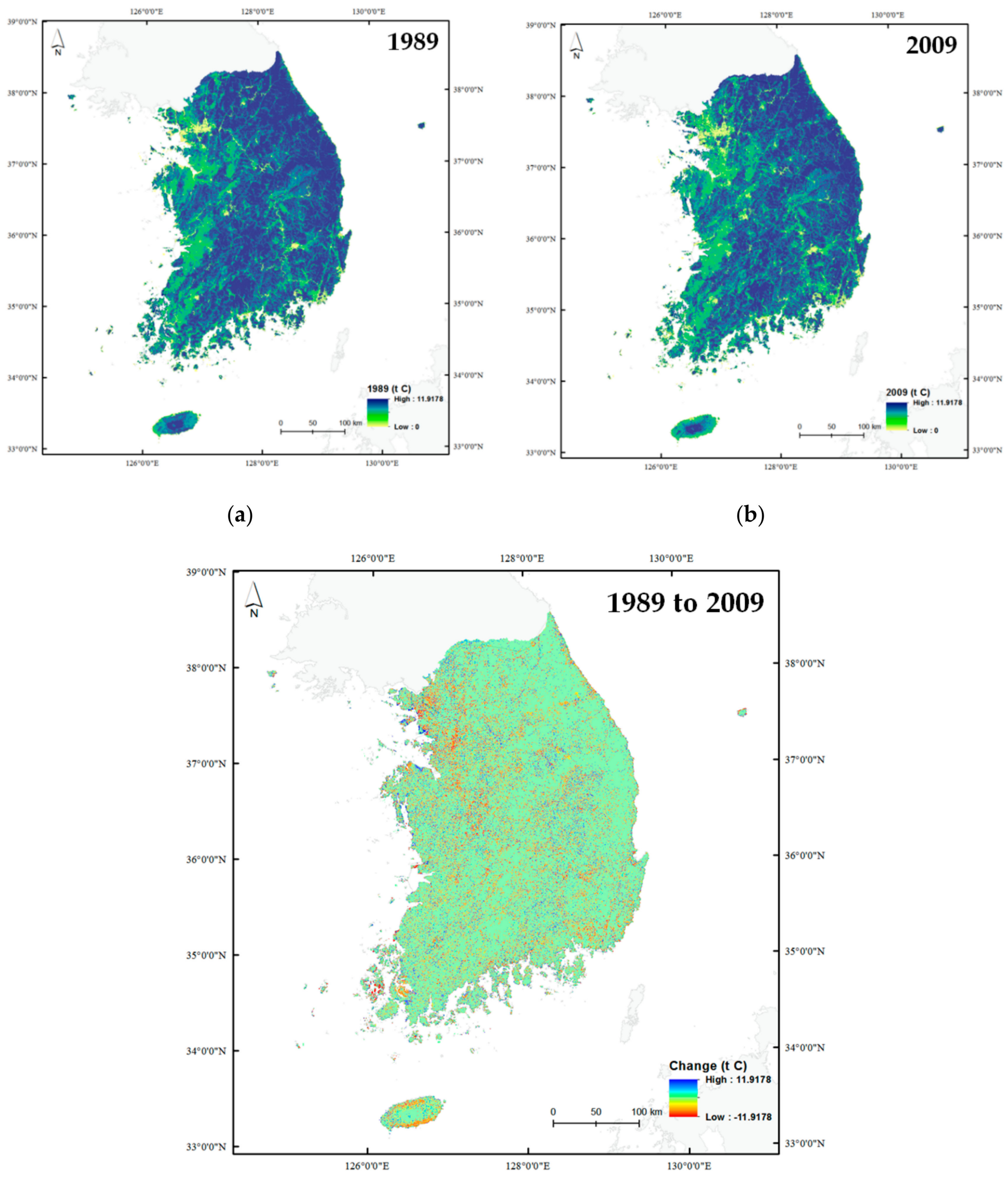


Figure 4. Carbon stocks of the year 2009.

3.2. Carbon Stock Change between 1989 and 2009 LULC Change

The carbon stocks of Korea in 1989 and 2009 and the carbon stock changes during these 20 years are shown in Figure 5. The carbon stocks of each pixel in 1989 and 2009 were between 0 and 11.9 t C in the seven ecosystem types. The total carbon stocks of the ecosystem in 1989 were estimated to be 1072.5 million t C. Compared to this, the total carbon stocks in 2009 were 1003.4 million t C, showing a decrease of 69.1 million t C of the carbon stocks due to the changes in the LULC over the past 20 years (Table 3). The positive value indicates the areas with an increase of the carbon storage capacity and the negative value indicates the areas with a decrease of the carbon storage capacity.



(**c**)

Figure 5. Changes in the carbon stocks according to the LULC changes: (**a**) carbon stocks of the year 1989, (**b**) carbon stocks of the year 2009, (**c**) changes in the carbon stocks between 1989 and 2009 according to the LULC change.

In order to see how the LULC change affected the changes in the carbon stocks, the changes of the LULC type on the 1989 and 2009 LULC maps and the carbon stock changes were analyzed conjunctively (Table 3). As a result of the analysis, it was found that the carbon storage capacity of 74.5 million t C was reduced as the forest land changed into other types of LULC and it was the highest contributor of the decline in the carbon stocks. The changes of the agricultural land, grassland and wetland resulted in 1.1, 3.0 and 6.1 million t C of the carbon stocks decrease, respectively. On the contrary, 4.3, 5.9 and 5.4 million t C of the carbon stocks increased in the urban lands, barren lands and waters, respectively, due to the changes of the LULC. The 4.3 million t C represents the net increase of carbon stocks resulting from all LULC changes in urban lands between 1989 and 2009. It can be interpreted as changes in carbon stocks in places where the urban lands have been changed into forests, grassland (urban parks), and farmland (garden). The 5.9 million t C also means that the net increase in carbon stocks occurred over the last 20 years as the barren land changed to a different land type. Like urban areas, barren land has been transformed into parks and farmland. The 5.4 million t C represents the net increase of carbon stocks resulting from water to other LULC types. Waters have been changed to forests, farmland, grassland, and barren land through the waterway change or the reclamation project. In Korea, reclamation projects have been active in the last 20 years (1989–2009), mainly in the west and south sea coastal areas [36,43].

Table 3. Changed areas detected in the land use and land cover (LULC) map and change of the carbon stocks between 1989 and 2009 (Unit: km^2).

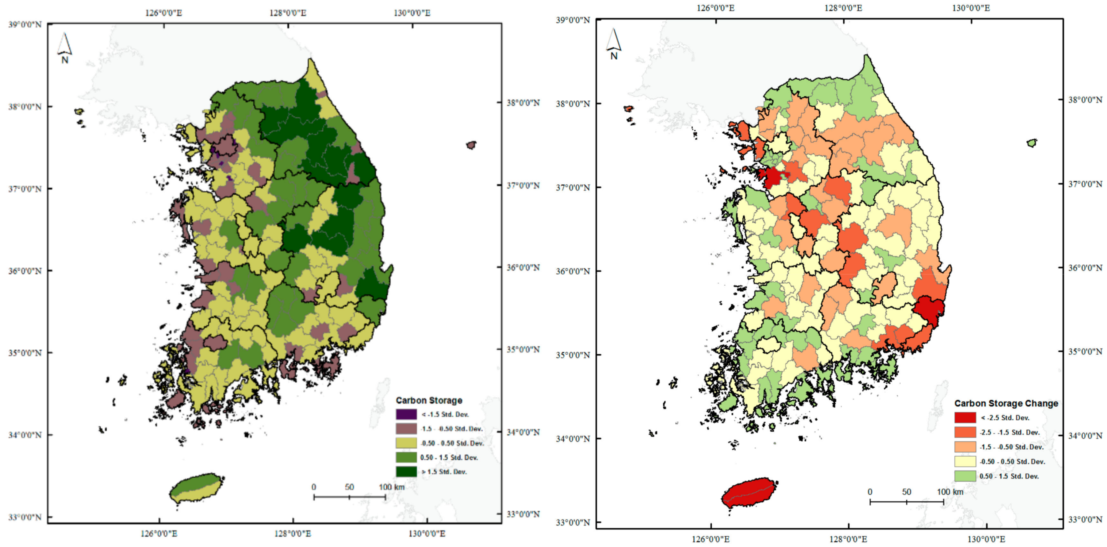
2009 \ 1989	Urban Land	Agricultural Land	Forest Land	Grass-Land	Wet-Land	Barren Land	Waters	Total
Urban land	1424.8	2752.0	1190.0	390.6	57.1	326.4	112.6	6253.6
Agricultural land	330.6	15,663.9	6476.5	1470.0	245.2	428.9	126.2	24,741.3
Forest land	85.2	3358.0	56,941.1	1323.7	45.9	132.0	109.1	61,995.1
Grassland	57.1	538.6	1176.5	369.8	29.2	57.9	40.1	2269.2
Wetland	37.7	302.7	149.5	43.7	221.9	72.1	215.5	1043.1
Barren land	106.0	605.2	586.3	94.6	68.4	148.3	157.8	1766.6
Waters	66.1	567.7	417.4	82.7	208.9	131.4	1353.9	2828.0
Total (class total)	2107.5	23,788.1	66,937.3	3775.2	876.6	1297.1	2115.2	100,896.9
Changes in LULC *	682.7	8124.2	9996.2	3405.4	654.7	1148.8	761.4	
Increase between 1989 and 2009	4146.1	953.2	−4942.2	−1506.0	166.5	469.5	712.8	
Changes in carbon stocks due to LULC change (million t C)	4.3	−1.1	−74.5	−3.0	−6.1	5.9	5.4	−69.1

* Total amounts of changes from original LULC type to another LULC type.

3.3. The Carbon Stock and the Changes in the Carbon Stocks According to the LULC Change, Per City/County

Table 4 and Figure 6 show the results of the analysis of the carbon stocks and the carbon stock changes in 162 cities/counties. The top three administrative districts with high carbon stocks in year of 2009 are Hongcheon, Inje and Pyeongchang County. The top three local municipalities where the carbon stock changes were large due to the changes in the LULC between 1989 and 2009 were Seogwipo and Jeju City of Jeju Special Self-Governing Province, Hwaseong City in the Gyeonggi-do Province. The changes in the LULC, which had a large effect on the carbon stock changes, were 'forest land to agricultural land', 'forest land to urban land' and 'agricultural land to grassland'. Unlike other regions, Jeju City was the city where the changes of 'forest land to grassland' mainly contributed to the changes in the carbon stocks.

We examined whether the quantity of the carbon stocks correlate with the LULC change per region. The coefficient of determination derived from the fitting of the logarithmic changes of the carbon stocks of 162 cities/counties in 1989 and the changes of the carbon stocks between 1989 and 2009 into a simple linear regression model was approximately 48% (Figure 7). From the Spearman rank correlation analysis, there was a positive correlation between the carbon stocks of 1989 and the carbon stock changes between 1989 and 2009, with a correlation coefficient of 0.57 at the significance level of 0.01.



(**a**) (**b**)

Figure 6. The carbon stocks and the changes in the carbon stocks in 162 cities/counties between 1989 and 2009: (**a**) distribution of the carbon stocks in cities and counties in 2009; (**b**) distribution of changes in the carbon stocks in cities and counties between 1989 and 2009.

Table 4. Top 10 municipalities with high carbon stock in 2009 and top 10 municipalities with high carbon stock changes between 1989-2009, and main types of the LULC change.

Ranks	Top Cities/Counties with High Carbon Stocks (2009)	Top Cities/Counties with Greater Change in Carbon Stocks (1989–2009)	Types of LULC Change	
			1st	2nd
1	Hongcheon County	Seogwipo City	Forest land to agricultural land	Forest land to urban land
2	Inje County	Jeju City	Forest land to agricultural land	Forest land to grassland
3	Pyeongchang County	Hwaseong City	Agricultural land to urban land	Forest land to urban land
4	Andong City	Ulsan City	Forest land to agricultural land	Agricultural land to urban land
5	Jeongseon County	Cheongju City	Forest land to agricultural land	Forest land to urban land
6	Samcheok City	Yongin City	Forest land to urban land	Agricultural land to urban land
7	Bonghwa County	Incheon City	Agricultural land to urban land	Forest land to urban land
8	Sangju City	Busan City	Forest land to urban land	Agricultural land to urban land
9	Gyeongju City	Changwon City	Forest land to agricultural land	Agricultural land to urban land
10	Yeongwol County	Gimcheon City	Forest land to agricultural land	Forest land to urban land

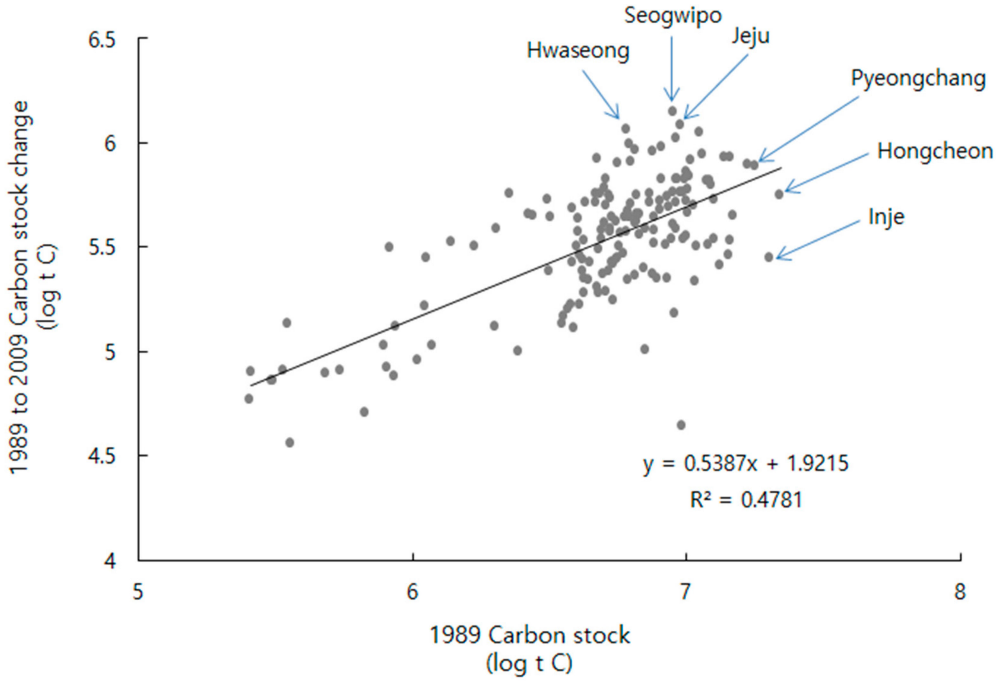


Figure 7. Simple linear regression model of the logarithmic changes in the carbon stocks of 162 cities/counties in 1989 and the changes of the carbon stocks between 1989 and 2009.

3.4. Evaluation of the Economic Value and Its Changes Made Between 1989 and 2009

The carbon sequestration services (about 1 billion t C of 2009) were estimated to be worth 68.36 trillion won (60,237 million USD) as of 2010 when evaluated with the Korean ETS average market prices of the first phase (2015–2017) (Table 5). Also, the loss of economic value of the changes in the carbon stocks (69.1 million t C) due to the LULC changes was estimated to be 4.7 trillion won (4159 million USD). In terms of the regions, the loss of the economic value of the carbon sequestration services from 1989 to 2009 due to the LULC changes was greater in Gyeonggi-do, followed by Gyeongsangbuk-do, Jeollanam-do, Gyeongsangnam-do and Gangwon-do (Table 6).

Table 5. The economic value of the carbon sequestration services based on market prices.

Category	Carbon Stocks		Economic Value of CARBON	
	Carbon Stocks 2009 (Million t C)	Carbon Stocks Change Between 1989 and 2009 (Million t C)	Carbon Sequestration Service in 2009 (100 Million Won)	Carbon Sequestration Service Change between 1989 and 2009 (100 Million Won)
Urban land	0	4.3	0	2937.0
Agricultural land	163.8	−1.1	111,879.8	−751.3
Forest land	782.0	−74.5	534,126.9	−50,885.5
Grassland	14.5	−3	9903.9	−2049.1
Barren land	0.2	5.9	136.6	4029.9
Freshwater and Marine *	40.5	−0.7	27,662.6	−478.1
Sum	1001.0	−69.1	683,573.1	−47,197.1

* Wetland is included in the freshwater and marine category.

Table 6. The changes in economic value of the carbon sequestration services by 16 provinces according to the LULC changes between 1989 and 2009.

Province	Changes of Economic Value (100 Million Won)	Province	Changes of Economic Value (100 Million Won)
Gyeonggi-do	−7722	Jeju Special Self-Governing Province	−1773
Gyeongsangbuk-do	−7441	Ulsan Metropolitan City	−770
Jeollanam-do	−5304	Busan Metropolitan City	−619
Gyeongsangnam-do	−5198	Daegu Metropolitan City	−452
Gangwon-do	−4501	Daejeon Metropolitan City	−416
Jeollabuk-do	−4131	Incheon Metropolitan City	−343
Chungcheongnam-do	−4090	Seoul Metropolitan City	−303
Chungcheongbuk-do	−3721	Gwangju Metropolitan City	−297

4. Discussion

4.1. Changes in the Carbon Stocks According to the LULC Changes: Similarities and Differences between the Country and Regions (Cities/Counties)

Even in countries experiencing rapid economic growth, development projects tend to be concentrated in specific regions. In other words, even if the LULC changes occur both in the national and regional level, there is a regional difference in development pressure. This trend was also confirmed in Korea. From 1989 to 2009, the LULC changes in Korea have been accelerated due to the implementation of the regional development projects and urban sprawl. At the national level, many forest and agricultural lands have been changed. After having analyzed the LULC map [19,20], it was found that between 1989 and 2009, the agricultural land increased by 0.9% (953.2 km^2) and the forest land decreased by 4.9% (4942.2 km^2). At the local level, however, The Jeju Special Self-Governing Province and Hwaseong City in the Gyeonggi-do Province, where many regional development projects were actively implemented, showed more LULC changes during the same period (1989–2009). In the Jeju Special Self-Governing Province, the urban and agricultural lands increased by 42.5% and 116.1% while the forest land decreased by 29.8% [44]. This means that changes in carbon stocks due to LULC changes may differ across national and regional levels. In addition, the amount of the LULC change and the type of the change vary according to the area, and the carbon stock change due to the LULC change varies greatly by region.

In Korea, where development pressure was high for the 20 years between 1989 and 2009, there have been similarities and differences in the changes of the carbon stocks according to spatial scales between countries and regions. As a common denominator, it was found that there were considerable changes in the carbon stocks when the LULC change was greater, at both the national and regional (cities/counties) level. At the national level, forest lands and agricultural lands were largely transformed into other LULC types and it resulted in a large loss of the carbon stocks (Table 3). At the regional level, cities and counties also experienced a larger loss of the carbon stocks due to the LULC changes in areas where the carbon stocks were high in 1989 (Figure 7). There were also differences between countries and regions. At the national level, LULC changes from forest land to agricultural land, urban land, and grasslands have had a significant impact on carbon stock changes. However, in the regions, the amount of the carbon stock changes (amounts) and change factors (types of LULC change) varied by region (Table 4, Figure 6). In terms of quantity, it can be observed that the carbon stocks have decreased much in the places where development projects are actively promoted (Seogwipo City, Jeju City, Hwaseong City, Ulsan City, Cheongju City, Yongin City etc.). For example, in Seogwipo, ranches, farms and recreational areas increased during this period. In Jeju, farms, ranches and golf courses increased. In Hwaseong, large-scale development projects constructing the residential, industrial and commercial areas were promoted due to the new town development policy of national government. However, in the areas where the carbon stocks were large but the development projects were less promoted (Inje County, Hongcheon County, Jungsun County, Andong City, Bonghwa County, etc.), the carbon stock changes were relatively small. At regional level, the types of the LULC change which are the cause of the carbon stock changes also varied from 'forest land → agricultural land', 'forest land → urban land', 'agricultural land → urban land', and 'forest land → grassland'.

4.2. Reduction of the Carbon Sequestration Services Due to the LULC Change by Region

Korea's carbon market is still in its infancy, and its market price is low, such as the prices in the carbon pricing mechanism of many other countries. Therefore, the Korean ETS market price applied in this study has limits to understanding how much the loss of carbon sequestration service is due to LULC change in Korea. Despite this limitation, the economic value of carbon sequestration services can be estimated relatively by region according to the LULC change. This information provides the data necessary for the policy-making process that leads to LULC change. In this study, the analysis shows that carbon sequestration services have declined over the past 20 years in all 16 regional provinces. In particular, as shown in Table 6, Gyeonggi-do and Gyeongsangbuk-do had many losses of carbon sequestration service. Using this information, many regional governments can make the policy to prevent the loss of carbon sequestration services and to maintain the sustainable carbon sequestration services.

As carbon prices rise globally, the decline in carbon sequestration services due to LULC changes will increase further in the future. Many countries are raising the carbon prices through implementation of policies such as the carbon price floor. In addition, the carbon prices are expected to climb steadily through reduction or abolishment of fossil fuel subsidies, and by corporate audits of climate-related fiscal crises driven by financial institutions. National and regional governments, therefore, are required to take policy countermeasures considering the LULC changes and the loss of the value in the carbon sequestration services due to the raise of the carbon prices.

In addition, given that the environmental and social value of the carbon is being reflected in the market prices, the loss of carbon sequestration services induced by LULC changes might increase in the future. In other words, the severity of the LULC change from forest land to agricultural land and urban areas will become higher. With the enforcement of policies which leads to the LULC changes, the amount that the country and local communities will have to pay as the opportunity costs for the carbon sequestration services may increase exponentially in the future.

4.3. Future Policy Directions to Sustain the Carbon Sequestration Services

The overall decline in the carbon stocks and the difference in the regional declines will continue without policy shifts. In Korea, analysis of the LULC map in 2014 [45] for the Gyeonggi-do Province, where the LULC changes were prominent during the study period (1989–2009), grassland increased by 210.5% in 2009–2014, and barren land also increased by 44.1%. On the other hand, agricultural land decreased by 20% and also forest land decreased by 3.5% during the same period. In the Jeju Special Self-Governing Province, agricultural land decreased by 12.9% in the same period, while urban area increased by 33.9%. In countries and regions, therefore, where development projects are expanded, such as Korea, the LULC changes and carbon value should be taken into consideration for the sustainable maintenance of the future carbon sequestration services.

The United Nations predicts that 90% of the urban growth will occur in low-income countries in Asia and Africa by 2050 [46]. These urbanization and development projects will frequently occur in natural areas, such as mangroves, rain forests, farmland which operated with traditional knowledges, and tropical and temperate wetlands. But once destroyed, the ecosystem will take a long time to return to its previous state and to restore its carbon storage capacity and value. Forests take a long time, usually 20 to 200 years, to recover naturally after a disturbance [47]. Even after restoration, its ecological value is never the same [47–49]. Therefore, in developing countries or regions where development projects occur locally, it is necessary to consider the value of carbon sequestration services as an important factor when making policy decisions that bring LULC changes in forest land, agricultural lands, wetlands, and other natural ecosystems.

The sustainable carbon storage capacity and carbon sequestration service management policies, which take into account the LULC changes and carbon price, can be implemented both jointly and separately by the national and local governments. The joint management policy can be suggested as follows. First, there is a need for a continuous monitoring on the LULC changes for the ecosystem types with high carbon stocks. Second, if the policy which induces the LULC changes would not be avoidable, it is necessary to shift to the LULC type that may have less impact on the carbon stocks. For instance, when implementing national policies or regional development projects, it is necessary to consider the transition types from forest land into agricultural lands, grassland and wetland rather than to the urban land. Third, both state and local governments should consider the carbon storage capacity and the opportunity costs that the project sites have as a carbon pool when establishing development policies for forest lands and agricultural lands.

The followings are the carbon storage capacity and carbon sequestration service management policies that need to be differentiated according to the characteristics of the country and region. Nationally, it is important to implement policies that focus on deforestation, urban expansion and agricultural land reclamation projects. In addition, when there is a LULC change, the state should recognize the opportunity costs that the carbon pools such as forests and agricultural land will lose as social costs and internalize them into the market prices. Locally, it is necessary to enforce policies that are appropriate to the characteristics of each region, taking the size and pattern of the carbon stock changes into account. For example, in this study, the Jeju Special Self-governing Province, in which the carbon stocks are greatly reduced due to the decrease in forests, needs a policy that allows them to designate the remaining forests as protected areas. In addition, since the rank one of the LULC change is from forests to agricultural lands, a policy to reduce agricultural land expansion is required. On the other hand, the Jeju City needs measures to reduce the LULC changes from forests to grassland, and Seogwipo City needs measures to reduce LULC changes from forests to urban areas.

5. Conclusions

This study analyzed the changes in the carbon stocks and the economic values caused by the LULC changes between 1989 and 2009, when the development pressure was accelerated in the urban surrounding areas and local regions in Korea. This study is valuable to show the difference in carbon storage loss caused by LULC changes and its economic value loss in countries and regions where development projects occur frequently. In particular, it helps to establish regionally-differentiated policies according to the size and type of LULC changes in countries and regions that promote carbon sequestration service management policies. But this study has some limitations. Since there was no LULC map established nationwide since the 2010s, it did not reflect recent LULC changes. The carbon price is based on the Korean ETS price, but not a stable carbon price.

We, therefore, suggest follows as the future studies: Research is needed to propose future policy directions for the management of carbon storage services in local municipalities using the latest LULC change data and future LULC change scenarios. This can reflect various socioeconomic conditions and regional policy changes, which will lead to more realistic implications for policy makers. It is also necessary to conduct research on the economic value of carbon storage services that apply the social cost of carbon so that the social and environmental values of carbon can be reflected in policy decisions.

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Appendix A

Table A1. Carbon stocks in carbon storage per ecosystem type and unit area (Unit: t C/ha) (2009).

Ecosystem Type		Above Biomass	Belowground Biomass	Soil Carbon	Litter Layer/ Dead Tree	Total
Urban land (Built-up areas)	Residential areas	0	0	0	0	0
	Culture, sports and recreation area	0	0	0	0	0
	Public facilities area	0	0	0	0	0
Agricultural land	Rice paddy	0	0	69.9	0	69.9
	Field	0	0	62.2	0	62.2
	Cultivation facilities	0	0	45.9	0	45.9
	Orchard	0	0	51	13	64
	Others	0	0	45.9	0	45.9
Forest land	Broadleaf forest	64.31	23.15	55.68	10.13	153.27
	Coniferous forest	42.87	11.57	38.75	13.45	106.64
	Mixed forest	53.59	17.36	47.22	11.79	129.96
Grassland	Natural grassland	4.17	16.69	88.2	0	109.06
	Artificial grassland	1.15	4.58	11.5	0	17.23
Barren land	Barren land	0	0.33	0.33	0	0.66
Freshwater	River	0	0	0	0	0
	Lakes	0	0	0	0	0
	Inland wetland	35.24	9.18	88	0	132.42
Marine	Marine water	0	0	0	0	0
	Coastal wetland	1.3	1.3	240	0.7	243.3

Source: [33–36].

Table A2. Amount of growing stock of above and belowground biomass per unit area (2010).

Forest Type	Amount of Growing Stock Per Unit Area (m^3/ha)
Coniferous forest	130.33
Broadleaf forest	125.26
Mixed forest	133.18

Source: [32].

Table A3. Carbon storage coefficient per forest type (2015).

Forest Type	Basic Wood Density	Biomass Expansion Factor (BEF)	Root-Shoot Ratio	Carbon Fraction
Broadleaf forest	0.68	1.51	0.36	0.5 (IPCC default value)
Coniferous forest	0.46	1.43	0.27	
Mixed forest	0.57	1.47	0.32	

Amount of growing stock of above and belowground biomass (t C) = amount of growing stock × basic wood density × biomass expansion factor × (1 + root − shoot ratio) × carbon fraction (Source: [33]).

Table A4. Growing stock accumulation and biomass carbon stock and discrepancy per ecosystem type in 16 regional metropolitan municipalities (Unit: million t C).

Regional Metropolitan Municipality	KFS Growing Stock Basis	2009 LULC Map Ecosystem Type Basis	Discrepancy (%)
Seoul Special City	1.1	1.2	10.1
Busan Metropolitan City	2.6	2.3	−10.5
Daegu Metropolitan City	3.3	3.2	−3.3
Incheon Metropolitan City	2.6	2.5	−5.1
Gwangju Metropolitan City	1.1	1.1	0.4
Daejeon Metropolitan City	1.9	2.0	2.6
Ulsan Metropolitan City	5.0	4.7	−6.3
Gyeonggi-do Province	36.7	38.4	4.8
Gangwon-do Province	109.4	96.9	−11.4
Chungcheongbuk-do Province	32.7	35.0	7.1
Chungcheongnam-do Province	25.5	27.2	6.9
Jeollabuk-do Province	29.8	28.3	−5.2
Jeollanam-do Province	33.8	42.0	24.2
Gyeongsangbuk-do Province	88.6	90.8	2.5
Gyeongsangnam-do Province	47.9	46.5	−3.1
Jeju Special Self-Governing Province	5.7	4.3	−24.6
Average	26.7	26.7	−0.7

Mean absolute deviation = 8.0%, RMSE (Root mean square error) = 3.9.

Table A5. Carbon stocks (2009) and level of contribution per ecosystem type (Unit: million t C, %).

Ecosystem Type (7)	Carbon Stock	Ecosystem Type (20)	Carbon Stock
Urban land (Bulit-up areas)	0 (0.0%)	Residential areas Culture, sports and recreation area Public facilities area	0.0 (0.0%) 0.0 (0.0%) 0.0 (0.0%)
Agricultural land	163.8 (16.4%)	Rice paddy Field Cultivation facilities Orchard others	96.0 (9.6%) 55.4 (5.5%) 2.1 (0.2%) 8.6 (0.9%) 1.7 (0.2%)
Forest land	782.0 (78.2%)	Broadleaf forest Coniferous forest Mixed forest	267.3 (26.7%) 296.5 (29.6%) 218.2 (21.8%)
Grassland	14.5 (1.4%)	Natural grassland Artificial grassland	5.8 (0.6%) 8.7 (0.9%)
Barren land	0.2 (0.0%)	Bareland	0.2 (0.0%)
Freshwater	9.4 (0.9%)	River Lakes Inland wetland	0.0 (0.0%) 0.0 (0.0%) 9.4 (0.9%)
Marine	31.1 (3.1%)	Marine water Coastal wetland	0.0 (0.0%) 31.1 (3.1%)
Total: 1001.0 (100%)			

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