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Analysis of the effect of environmental protected areas on land-use and carbon storage in a megalopolis

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A R T I C L E I N F O

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A B S T R A C T

Carbon storage in terrestrial ecosystems plays a vital role in climate control. However, urban expansion and damage to natural areas, especially the rise of megalopolises, have affected carbon storage. To mitigate this damage, various policies have been established by international, domestic, and local governments. This study focuses on the establishment and management of environmental protection areas and analyzes their impact on carbon storage. The study targets the cities of Gyeonggi-do province, South Korea, which make up a representative megalopolis, and the effectiveness of protected areas was analyzed by typifying the cities based on the proportion of available development areas and environmentally protected areas. In this study, the SLEUTH (Slope, Land-use, Excluded Area, Urban, Transportation, Hillshade) land-use change model was used to predict future land-use changes, and carbon storage was estimated using the InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) Carbon model. When operating the model, we tested a control group scenario that only preserves the water zone, a scenario that preserves the legally protected areas, and a scenario that protects the areas with high environmental value. There are two significant effects of setting up protected areas: First, the "development inhibition effect" of reducing the development area itself. Second, the "development replacement effect" of moving development to relatively low environmental value areas. These two effects differ depending on the availability of development areas, with "development replacement effects" prominent in areas with high development availability and "development inhibition effects" predominant in areas with low development availability. Future policies for setting up and managing protected areas can be used in megalopolis in conjunction with policies focusing on securing the area of carbon sinks.

1. Introduction

Carbon storage in terrestrial ecosystems is a critical indicator of ecosystem services and is essential for productivity and climate control (He et al., 2016). Many studies have been conducted to monitor and systematically manage terrestrial ecosystems as they play an essential role in the carbon cycle between the atmosphere and the soil as a significant source of carbon dioxide, potentially affecting global warming (Goetz et al., 2009; Fehrmann et al., 2008; Lyu et al., 2019; Zhao et al., 2019). The annual net carbon absorption of the world's terrestrial ecosystem is estimated to be between 2000 and 2500 Pg, 500 and 600 Pg in vegetation, and 1500 and 2300 Pg in soil (Zhao et al., 2019; Liang et al., 2021a; Liang et al., 2021b). Thus, carbon storage can be used as an ecological indicator of productivity and climate change (Liang et al., 2021a; Liang et al., 2021b). In addition, the cycle of sustainable carbon is linked to social and economic issues related to ecosystem services (Liang et al., 2021a; Liang et al., 2021b).

The intergovernmental panel on climate change (IPCC) suggests that land-use change is closely related to future climate change as a significant factor in increasing greenhouse gases in the atmosphere (Nj et al., 2000; Park and Ha, 2013). Changes in land-use types play an important role in carbon storage, with factors such as land-use type, vegetation, and soil all affecting carbon storage (Li et al., 2020). Factors that hinder carbon storage include climate change, deforestation, desertification, and urban expansion (Lyu et al., 2019). It is estimated that 35% of the amount of carbon dioxide in the atmosphere increased by humans over

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the past century because of changes in land use resulting from urban construction or road construction (Turner et al., 2007). Land use changes are essential for increasing greenhouse gas emissions by releasing carbon dioxide and decreasing vegetation and soil (Foley et al., 2005). They seriously affect ecosystems by changing their biodiversity and hydrologic characteristics (Foley et al., 2005).

Recent population growth and reduction in household size have led to the proliferation of urban areas and increasing challenges of urbanization (Brown et al., 2004; Kim and Park, 2015). Urban expansion means changing areas with strong natural characteristics, including agricultural area into cities, and the increase in urban areas due to industrialization and urbanization changes land use (Li et al., 2020). Especially in large megalopolis, a group of two or more approximately adjacent metropolitan areas, worldwide, cities are undergoing expansion and facing problems, such as urban issues, population issues, and environmental issues (Yadav et al., 2019). Urban expansion, which involves dramatic changes in land use, affects soil carbon storage and carbon balance, and degrades the ecosystem services of carbon absorption (Li et al., 2018). In the case of land-use changes, it has been suggested that it is essential to understand the status of carbon dioxide and potential reduction due to changes in future land-use because land-use can be controlled through regulations (Schulp et al., 2008).

To reduce and manage carbon dioxide emissions, it is necessary to have a deep understanding of carbon circulation mechanisms for ecosystems and quantify carbon emissions from humans and terrestrial ecosystems (Ito, 2008; Ohtsuka et al., 2005). To establish systematic measures for low-carbon development, it is crucial to comprehensively examine carbon dioxide emissions from development and changes in carbon dioxide reduction characteristics from land-use characteristics, technological development, and lifestyle changes (Gomi et al., 2007). Estimating carbon circulation using models and scenarios is an excellent means of determining the effects of policy on carbon absorption (Lyu et al., 2019). Reliable quantitative analysis of carbon absorption and emissions is a consistent methodology for agricultural land and forests, which are expected to have high absorption, and for comparative analysis considering characteristics by ecosystem type (Ceschia et al., 2010).

Recently, the establishment and management of protected areas have been emphasized to preserve carbon storage (Dudley et al., 2010). This study identifies the impact of protected areas on land use and urbanization, and how this will affect carbon storage. In this study, the SLEUTH (Slope, Land-use, Excluded Area, Urban, Transportation, Hillshade) land-use change model and the InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) model for estimating carbon storage will be combined to simulate future land use and estimate changes in carbon storage in various scenarios. The scenarios will be established to analyze the impact of legally protected areas and integrated management using the environmental conservation value assessment map, which reflects the environmental value of land for land use and carbon storage.

2. Materials and methods

2.1. Study area

The Republic of Korea systematically establishes and manages protected areas. Separate protected areas are managed through legislation and regulations, and each region is systematically managed according to environmental information. Gyeonggi Province is an area surrounding Seoul, the capital of South Korea. The area is located on the mid-latitude on the latitude, and on the biome, it is located at Temperate Broadleaf and Mixed Forest Ecoregions. It is a representative megalopolis with the world's fifth-largest population and fourth-largest GDP (Joseph Parilla, 2015). It is also the area that emits the most greenhouse gases among metropolitan and provincial governments in the country (Ko et al., 2018). To understand the effectiveness of protected areas according to the characteristics of cities, cities in Gyeonggi-do were classified into taxonomies, and three cities in each taxonomy were designated as study sites.

In this study, two criteria were used to classify cities and determine the direction of future development according to the current usage characteristics of cities. The first classification criterion for cities is the area of the available development areas. Available development areas are defined as areas of the city which exclude the current urban area and legally protected areas. Sizeable available development areas can mean that the city's development potential is high, and small available development areas can mean low development potential.

The second criterion was the area of the legally protected area. The country establishes and manages protected areas for various purposes, such as environmental conservation. Even if it is the same available development area, it is difficult to expand the city if there are legally protected areas for development.

Cities were divided into four main types through cluster analysis. High available development, high legally protected areas (HAHP)-type has sizeable available development areas, and a sizeable legally protected area, while high available development, low legally protected areas (HALP)-type has a small area. The low available development, high legally protected area (LAHP)-type has a small available development area and a large legally protected area, while the low available development, low legally protected areas (LALP)-type has a narrow legally protected area (Table 1).

As a result of the classification, cities selected as study sites were: HAHP-type: Yangpyeong, Gapyeong, Gwangju; HALP-type, Yeoju, Pyeongtaek, Hwaseong; and LAHP-type: Uiwang, Hanam, Gwacheon; LALP-type: Bucheon, Suwon, Gwangmyeong (Fig. 1).

2.2. Model design

This study was conducted using two main processes. The SLEUTH land-use change model predicts future land use and the InVEST carbon model estimates future carbon storage for each scenario (Fig. 2).

2.2.1. Future land use prediction using SLEUTH model

Future land use was estimated using the SLEUTH land-use change model. The estimated year was set for 2030. The SLEUTH land use change model requires data on slope, land use, excluded areas, urban areas, transportation, and hillshade. Slope and Hillshade data were established using the DEM (Digital Elevation Model) data produced by the National Geographic Information Service. To build the slope and hillshade data, we used a topographic analysis tool within ArcGIS software. Land use, urban, and transportation data were established using a land cover map created by the Ministry of Environment. Land cover maps used mid-class land cover maps for 2002, 2007, 2009, and 2014. Land-use data were reclassified into land-use types corresponding to the carbon pool. Urban data were selected as built-up areas among land cover maps, and transportation data were produced by selecting transportation areas among land cover maps.

The SLEUTH model consists of three phases: testing, calibration, and prediction (Clarke et al., 1997). There are three main ways to build scenarios in the SLEUTH model (Osman et al., 2016): parameter values that affect urban growth rules (Leão et al., 2004), self-organization constraints, and controlling the excluded area (Oguz et al., 2007; Osman et al., 2016). In this study, we used a differentially weighted method of controlling the excluded area to adequately reflect the protected areas and environmental conservation value assessment map

Table 1
Regional Classification.

Regions	High Available Development	Low Available Development
High Protected Area	HAHP	LAHP
Low Protected Area	HALP	LALP

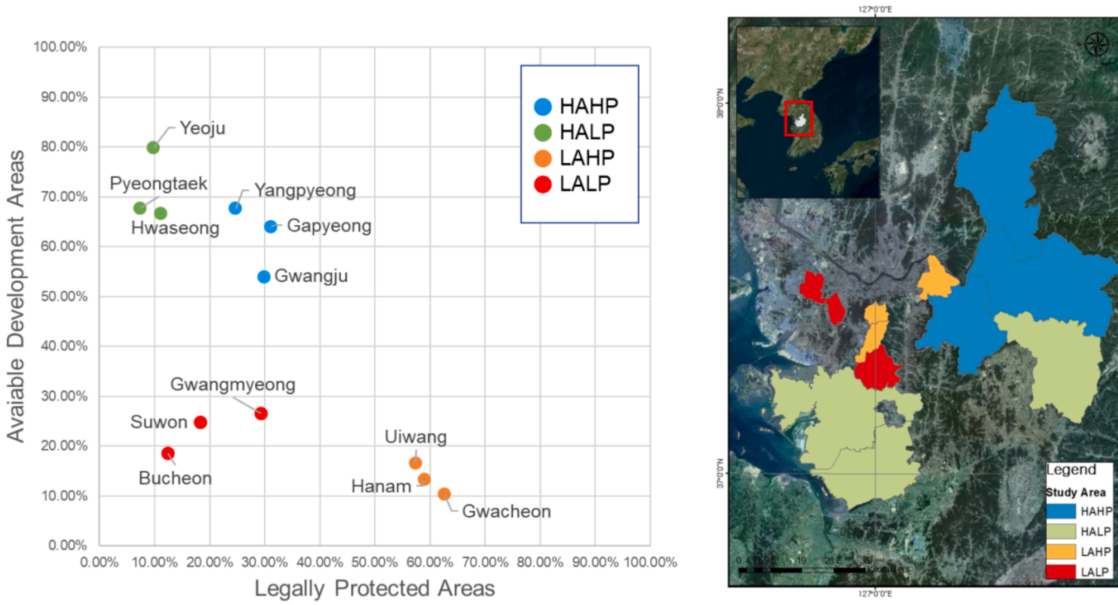

Fig. 1. Study Area.

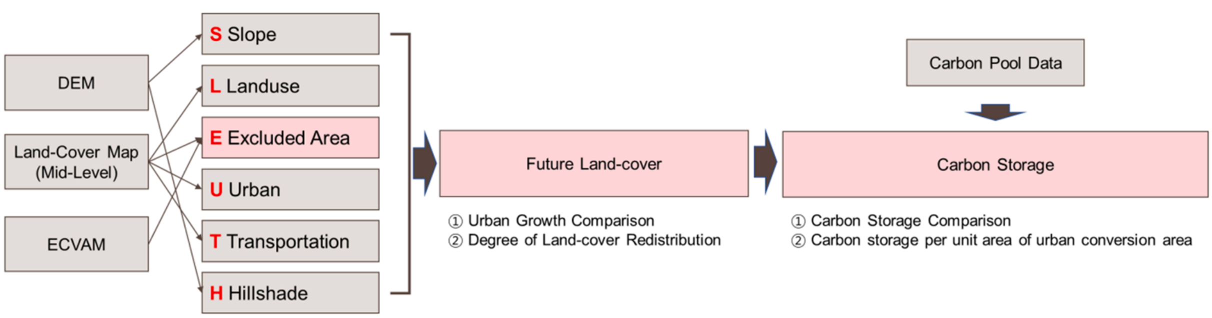

Fig. 2. Research Flow.

(ECVAM).

An ECVAM was used to prepare the excluded area. An ECVAM is a map, which was made by Korean Ministry of Environment, prepared by comprehensively evaluating various environmental information of the land, dividing the area into five grades according to environmental values, and displaying different colors (Ministry of Environment, 2008). The map includes legally protected legal evaluation items such as national parks, environmental ecological evaluation items representing environmental and ecologically valuable areas such as diversity and connectivity, and is evaluated in the form of ratings by overlapping each layer. (Ministry of Environment 2008). Areas with higher environmental value have grades closer to one, whereas areas with more development have grades closer to five.

Three scenarios were tested in this study. The scenarios were differentiated by setting different weights for layers of the excluded area. First, in the control scenario, only development in watershed areas was restricted. In the LAW scenario, development restrictions were imposed on legally protected areas and weight was given by utilizing the legal evaluation items of the ECVAM. A legal evaluation items include the protected area of the Korea such as National Park, the Development Restricted Zones, Water Supply Source Protection Zones and the number a total of 62. In the ECV scenario, the results of the ECVAM were directly utilized to give weights, reflecting the results of the integrated management of environmentally and ecologically valuable areas in addition to legally protected areas (Table 2).

Two aspects were analyzed after simulating the scenario-specific land-use changes. First, the amount of change in urban areas showed a degree of development. The urban growth inhibition rates in the LAW and ECV scenarios were compared to the control scenario for each city type. Second, land cover was analyzed in non-urban areas that were converted into urban areas within the study period. An analysis of the degree of redistribution of the land cover was conducted for each scenario application, and the effect of alternating development to other regions instead of environmentally valuable areas was analyzed. The degree of redistribution into other land types was quantified using the following formula (Eq. (1), Eq. (2)). The denominator 5 is the number of land-use types, meaning Farmland, Forest, Grassland, Wetland, and Bareland:

Table 2
Scenario-specific weights for the excluded area of the SLEUTH land-use change model.

Scenario	Weight by Region				
Control	Water 100				
LAW	Water 100	LAW 1st 100	LAW 2nd 75	LAW 3rd 50	LAW 4th 25
ECV	Water 100	ECVAM 1st 100	ECVAM 2nd 75	ECVAM 3rd 50	ECVAM 4th 25

$$R_{LAW} = \sqrt{\frac{\Sigma\left(p_{i,LAW} - p_{i,Control}\right)^2}{5}} \tag{1}$$

$$R_{ECV} = \sqrt{\frac{\Sigma\left(p_{i,ECV} - p_{i,Control}\right)^2}{5}} \tag{2}$$

The larger the value, the greater the effect of inducing development into other land covers.

2.2.2. Estimation of future carbon storage using InVEST carbon model

The following is an estimate of future carbon storage by scenario using the InVEST carbon model. Time-to-time land-use data and carbon pool data are required for InVEST to estimate carbon storage. For land-use data, simulated land cover maps and scenario-specific data were used. Carbon pool data from other studies on South Korea and neighboring regions were used for the carbon pool data (Table 3). (Kim et al., 2016; Chung et al., 2015; Tomasso and Leighton, 2014). Because the InVEST Carbon model is aimed at estimating carbon storage in local areas, data from local areas were used. Each land use classification was based on the classification group of level 2 land cover maps in Korea and was integrated into one classification group when the amount of carbon held by each land use was similar.

The total amount of carbon storage in the area is calculated by multiplying the sum of the carbon densities of aboveground biomass, belowground biomass, soil carbon, and dead organic matter per unit area by land type. The corresponding formula is as follows (He et al., 2016.) (Eq. (3), Eq. (4)).

$$C_i = C_{above} + C_{below} + C_{soil} + C_{dead} \tag{3}$$

$$C_{Total} = \Sigma C_i \times A_i \tag{4}$$

(i: Land Type, C_i: Carbon Density per unit area of land type, C_{above}: Aboveground Biomass, C_{below}: Belowground Biomass, C_{soil}: Soil Carbon, C_{dead}: Dead Organic, C_{Total}: Total Carbon Storage, A_i: Area per Land Type).

As with the analysis of the results of land-use changes, an analysis was conducted on the effect of inhibiting the reduction of carbon storage for each scenario along with the amount of carbon storage changes. In addition, an average carbon storage analysis was conducted on non-urban areas converted into cities to analyze the development of alternative effects of carbon aspects.

3. Results

3.1. Analysis of future land-use changes according to scenarios

3.1.1. Estimating changes in land-use

In order to show the measure of development, the predicted increase in urban area was estimated through the SLEUTH model. As of 2030, we predicted an average increase of 4.06% in control scenario, 3.48% in LAW scenario, and 3.37% in ECV scenario from 2013. The urban growth inhibition rate refers to the ratio of urban growth to the control group that is suppressed when each scenario is applied. The urban growth inhibition rate compared to the control scenario was 14.28% for the LAW scenario and 17.05% for ECV scenario. Overall, urban growth was inhibited by approximately 2.77% by integrally conserving environmentally valuable areas, compared to only restricting development on legally protected areas.

The urban growth inhibition rates were analyzed for each scenario. First, we analyzed the low available development area (LA) regions: in LAHP areas with many protected areas, 85.71% of the urban growth inhibition rate was observed when applying LAW scenario and 85.71% when applying ECV scenario. In LALP regions with relatively small protected areas, the inhibition rate was 18.82% for the LAW scenario application and 21.76% for the ECV scenario application, which was significantly lower than that in LAHP regions.

Second, we analyzed high available development area (HA) regions, and a different trend was observed. In HALP regions with relatively small protected areas, the inhibition rate of urban growth was 16.82% when applying LAW scenario and 18.40% when applying ECV scenario. On the other hand, in HAHP regions with relatively large protected areas, the urban growth inhibition rate was not significant for areas with sizeable available development areas, with 3.89% for LAW scenario application and 9.42% for ECV scenario application (Fig. 3).

3.1.2. Degree of land-cover redistribution

We analyzed non-urban areas that were converted into urban areas. Our analysis demonstrated the effect of developing protected areas into areas with relatively minor environmental value compared to high environmental value due to restrictions on establishing and developing protected areas. In the case of the control scenario in the entire region, 25.05% of urban transition areas were forest areas, 51.43% were farmland, 12.72% were grassland, 3.44% were wetlands, and 7.36% were barelands. In the LAW scenario, 16.82% of urban transition areas were forest areas, 59.29% were farmland, 12.69% were grasslands, 2.06% were wetlands, and 9.13% were bare lands. In the ECV scenario, 10.95% of urban transition areas were forested, 64.25% were farmland, 13.66% were grasslands, 1.34% were wetlands, and 9.79% were bare lands. Regarding land cover, it was confirmed that the proportion of forests decreased, whereas the proportion of farmland and bare land increased when development restrictions were applied to protected areas.

The average redistribution rate across all regions was 5.19% in the LAW scenario and 8.65% in the ECV scenario. Fig. 4 shows the redistribution rates of the different scenarios.

When analyzing the Degrees of Redistribution by each region, it showed high values in the HAHP area and LAHP area, where there were

Table 3
Carbon Pool Table for InVEST Model (Unit: Mg of C/ha/yr)

LU_Code	LULC_Name	C_above	C_below	C_soil	C_dead
10	Built-up	0.00	0.00	0.00	0.00
21	Rice Paddies	0.00	0.00	69.90	0.00
22	Field	0.00	0.00	62.20	0.00
23	Facility Cultivation site	0.00	0.00	45.90	0.00
24	Fruit Farm	0.00	0.00	51.00	13.00
25	Other Cultivation site	0.00	0.00	45.90	0.00
31	Broadleaf Forest	64.31	23.15	55.68	10.13
32	Coniferous Forest	42.87	11.57	38.75	13.45
33	Mixed Forest	53.59	17.36	47.22	11.79
41	Natural Grassland	4.17	16.69	88.20	0.00
42	Artificial Grassland	1.15	4.58	11.50	0.00
51	Inland Wetland	35.24	9.18	88.00	0.00
52	Artificial Wetland	1.30	1.30	240.00	0.70
60	Bare Land	0.00	0.33	0.33	0.00
71	Inland Water	0.00	0.00	0.00	0.00
72	Ocean Water	0.00	0.00	0.00	0.00

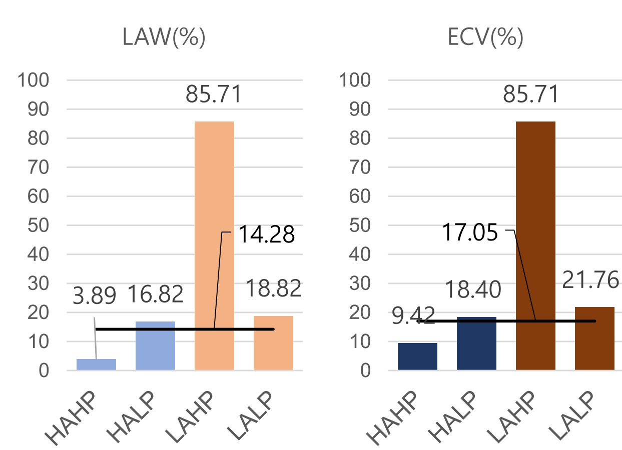

Fig. 3. Urban Growth Inhibits by scenario.

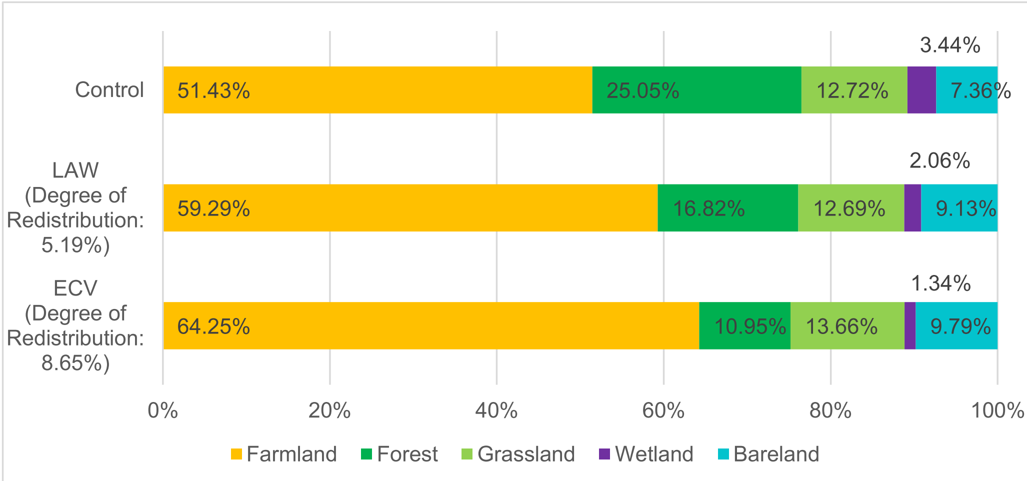

Fig. 4. Distribution of Land Cover in Urban Transition Areas by Scenario.

relatively many protected areas. In the LAW scenario, the HAHP region was 11.50% and the LAHP region was 14.33%, higher than the average of 5.19%, and in the ECV scenario, the HAHP region was 16.89% and the LAHP region was 17.58%, higher than the average of 8.65%.

The values were relatively low in the HALP area and LALP area, which were lower than the average of 5.19% when applying the LAW scenario, with 3.34% in the HALP area and 3.84% in the LALP area. In the ECV scenario, the HALP area was 7.07% and the LALP area was 5.94%, lower than the average of 8.65%.

Regardless of the rate of development availability, the redistribution effect in areas with higher rates of protected areas was higher than in areas with lower rates of protected areas (Fig. 5).

3.2. Analysis of carbon storage changes by scenario

3.2.1. Estimating changes in carbon storage

The amount of carbon storage according to future land-use changes was analyzed. Estimating the change in average carbon storage by scenario over the entire region showed average reductions of 0.14%, 0.04%, and 0.02% for the control, LAW, and ECV scenarios, respectively. The following formula was used to analyze the carbon storage conservation effect for each scenario (Eq. (5), Eq. (6)):

$$Effect_{LAW} = \frac{(\Delta CS_{LAW} - \Delta CS_{Control})}{|\Delta CS_{Control}|} \tag{5}$$

$$Effect_{ECV} = \frac{(\Delta CS_{ECV} - \Delta CS_{Control})}{|\Delta CS_{Control}|} \tag{6}$$

(Effect of scenario for carbon storage, CS: carbon storage).

These values quantify the effect on carbon storage when applying scenarios. Analysis of the carbon storage conservation effect showed 69.25% for LAW scenario and 85.51% for ECV scenario. In other words, 16.26% of the additional effect was identified when integrated protection was made outside the legal protection zone.

The carbon storage conservation effect was analyzed by scenario. Depending on the availability of development, the effect of protected areas on carbon storage differed, and the effect was significant in areas where development availability was low.

In LA areas, we demonstrated 37.87% effectiveness in LAW scenario application and 43.46% in ECV scenario application in the LALP areas. In LAHP areas, the effect was 87.69% for LAW scenario application and 89.51% for ECV scenario application, showing significantly more carbon storage conservation effect than LALP scenarios.

On the other hand, HA areas showed different patterns to LA areas. In HALP areas, the effect was 23.52% in the LAW scenario application and 27.28% in the ECV scenario application. In HAHP areas, the effect was 10.22% for LAW scenario application and 17.23% for ECV scenario application, showing a lower carbon storage conservation effect than HAHP areas (Fig. 6).

3.2.2. Comparison of carbon storage per unit area by scenario

The average amount of carbon storage in urban transition areas was

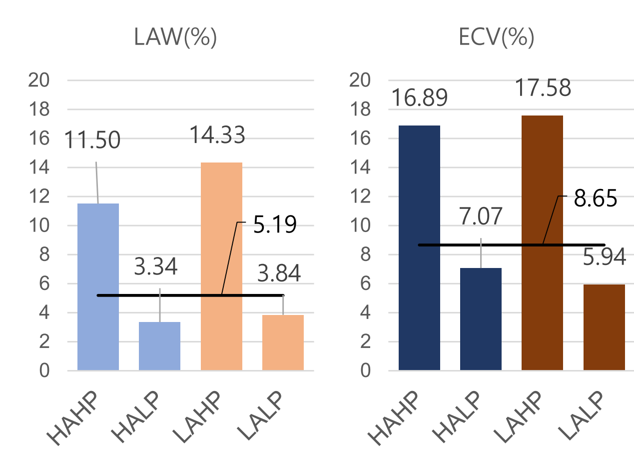

Fig. 5. Degree of Redistribution by scenario.

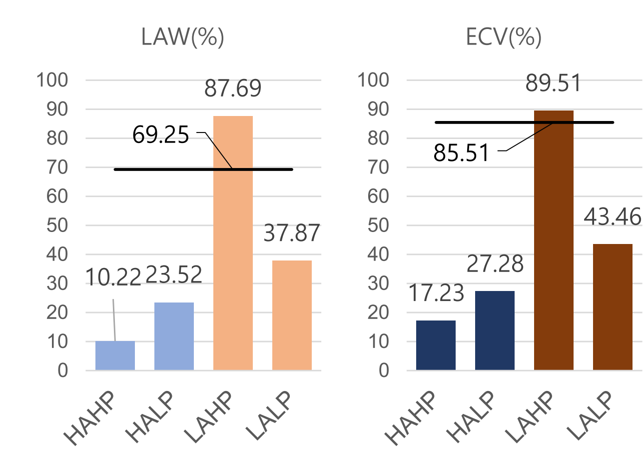

Fig. 6. Carbon storage effect by scenario.

analyzed. Our analysis shows that the setting of protected areas affects the transformation of development into areas of low environmental value and carbon storage. The average carbon storage for the entire urban transition zone was 78.02 Mg C/ha/yr in the control scenario, 68.73 Mg C/ha/yr in the LAW scenario, and 62.42 Mg C/ha/yr in the ECV scenario. Regarding the scenario-specific effect of average carbon storage per unit area of urban transition areas compared to the control, it was 11.91% decrease for LAW scenario and 19.99% decrease for ECV scenario.

Effectiveness of the average carbon storage per unit area of the urban transition zone by scenario was analyzed by city type. First, in HA areas, the effect of protected areas was 15.49% and 23.78% for LAW and ECV scenario application, respectively, in HAHP regions. In HALP regions, the effect were 6.08% and 12.88% for LAW and ECV scenario application, respectively.

Of LA areas, LAHP areas had effects of protected areas of 26.84% for LAW scenario application and 30.30% for ECV scenario application whereas LALP areas were 19.07% for LAW scenario and 29.03% for ECV scenario.

Regardless of the ratio of available development area, we found that the proportion of protected areas was relatively large, and that it was larger in highly protected areas (HP) than low protected areas (LP) (Fig. 7).

4. Discussion

4.1. Development inhibition effects and development replacement effects

The establishment and management of protected areas affect land use, and changes in land use are linked to carbon storage. There are two major effects of land use change on carbon storage considering the establishment of protected areas. The first effect is reducing the amount of urban development due to the establishment of protected areas (development inhibition effect). Decrease in development leads to conservation of carbon sinks, which serve to store more carbon. Therefore, the loss of carbon sink is prevented. The second effect is that the establishment of protected areas changes the area being developed. This inhibits the development of areas of high environmental value, and instead encourages development in other alternative regions (development replacement effect).

The two effects of protected area on land use vary depending on the type of city. There is little difference in the development inhibition effects between the two types in the LAW and ECV scenarios. In other words, the extent to which the amount of development decreased was similar. On the other hand, comparing the development replacement effects between the two types, the development of alternative effects in HAHP areas was larger than in HALP areas. There is not much difference

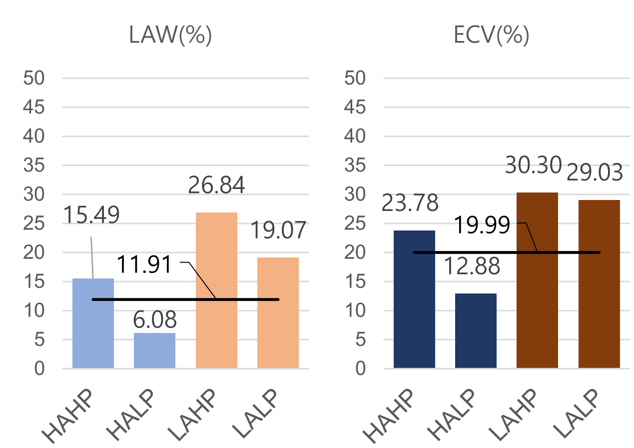

Fig. 7. The effectiveness of the average carbon storage per unit area of the urban transition zone by scenario.

in the development replacement effects for LA, but the development inhibition effect in LAHP areas is noticeable. Accordingly, the impact of protected areas on urban development varies depending on the ratio of urban availability and protected areas, which can be linked to carbon storage.

Our results confirmed that for the above two effects, ECV scenario using ECVAM had a greater effect than LAW scenario, which protected legally protected areas. This shows that integrating and managing areas of environmental ecological value would be more effective in terms of carbon storage than only preserving legal management areas.

4.2. Protected areas and carbon storage

In this study, we analyzed the effect of protected areas on land use, which is not a direct effect of protected areas themselves, but rather a ripple effect on the surrounding areas due to the establishment and management of protected areas. However, previous studies have reported the direct effect of carbon reduction on the protected area itself.

One of the most common policy tools for reducing forest loss is the establishment of reserves, such as national parks, that include highly regulated forms of protection for harvesting activities (Collins and Mitchard, 2017). The establishment of protected areas reduces habitat loss and devastation due to deforestation, agricultural and urban expansion, exotic or unsustainable species exploitation, energy development, and mining (Juffe-Bignoli et al., 2014; Shi et al., 2020). Protected areas can also reduce greenhouse gas emissions, especially carbon dioxide (Zarate-Barrera et al., 2015; Shi et al., 2020). This suggests that protected areas have a greater ability to capture and store carbon than non-protected areas (Zarate-Barrera et al., 2015; Shi et al., 2020). Ecological carbon storage in land-protected areas accounts for approximately 20% of all ecosystem carbon storage (Melillo et al., 2016; Shi et al., 2020). Campbell et al. (2009) stated that it is crucial to preserve protected areas to reduce greenhouse gases that come from land-use change. The original purpose of protected areas was biodiversity conservation, however we now know that they store terrestrial carbon which is an important secondary purpose (Campbell et al., 2009). Consequently, there has been growing interest in the ability of protected areas to provide a wide range of environmental services in recent years (Durán et al., 2013; Resende et al., 2021).

There has been a debate over the amount of carbon stored in protected areas. As the forest level in most protected areas increases, the carbon absorption capacity decreases, and it is believed that the carbon absorption capacity could be increased by changes in forest management and cutting age, rather than by protecting additional areas (Gundersen et al., 2021; Kim et al., 2021; Ryu et al., 2016; Kim et al., 2017). However, this is a plan to increase the absorption of carbon per unit area while our study is a quantitative study based on the land cover area of carbon sinks according to protected areas. Therefore, further research is required to provide evidence for this.

4.3. Limitations and complementary directions of research

A limitation of this study is related to the weights assigned for each of the excluded areas. In this study, we assigned separate weights, decreasing in equal rate, according to each ECVAM's class. There is no logical difficulty in assigning equal weights to the areas of the same grade. This is because regions of the same grade are understood to have the same degree of environmental value. However, the weights differing among grades need to be considered. The difference between grades should be quantified through methods such as surveys by experts.

Finally, there is a limitation to the carbon pool table used in the study. The estimated values of carbon stored in each LULC type was assumed to be constant, without consideration of spatio-temporal characteristics. Qualitative management of land-use-specific areas can improve carbon pools, that is, increase the carbon storage capacity per unit area. In order to deepen this study, the estimation of carbon storage, which reflect more detailed land-use and forest feeding, should be conducted.

5. Conclusions

In this study, we estimated future land-use changes and carbon storage changes by scenario following the establishment and management of protected areas. The estimation shows that the establishment and management of protected areas is a net function of carbon storage. In addition, we identified that integrated management using ECVAM is more effective for carbon storage than protection of legal areas. This study analyzed the effectiveness of protected areas in terms of carbon storage in two ways. First, the presence of protected areas inhibits the amount of development itself, which prevents a reduction in carbon storage (development inhibition effect). Therefore, it inhibited the reduction in carbon storage. Second, protected areas lead to urban development of areas with relatively low environmental values (development replacement effect) compared to areas with high environmental values. Consequently, forest areas, which account for most of the protected areas, are less likely to be developed. Therefore, the amount of carbon storage per unit area is reduced. These two effects were especially evident when the environmental protection standards of the national standard of ECVAM were established, rather than when only legally protected areas were established.

There were also differences according to the type of city. When establishing protected areas, areas with high development availability tended to induce development in regions that have low environmental value, rather than reducing the amount of development itself. In other words, the development replacement effect was more potent than the development inhibition effect. For areas with low development availability, there was a tendency to reduce the amount of development when establishing protected areas, and there was also a development replacement effect.

In this study, the designation and management of environmentally protected areas may lead to the securing of carbon storage, although they differ from their original designation purposes. In addition, it has been shown that managing not only legally protected areas but also integrated environmentally valuable areas will bring about net functionality in terms of carbon. Therefore, the establishment and management of protected areas and differential land management, along with existing policies such as expanding the area of carbon sinks in the city, can be used as a means of policy in megalopolis.

This study simulates land use and carbon storage in Megalopolis, Gyeonggi-do, Republic of Korea. This area is located in the mid-latitude and Temperate broadleaf and mixed forests biome areas and is expected to be highly utilized as other Megalopolis because many large cities around the world are located in similar areas. However, since there are differences in urban expansion policies by city size and region, a more precise approach is needed for application to individual cities.

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CRediT authorship contribution statement

Jinhoo Hwang: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Visualization. **Yuyoung Choi:** Conceptualization, Methodology, Writing – review & editing. **Yoonji Kim:** Writing – review & editing. **Lim No Ol:** Writing – review & editing. **Young-Jae Yoo:** Methodology. **Hyo Jin Cho:** Methodology. **Zhemin Sun:** Investigation. **Seongwoo Jeon:** Funding acquisition, Project administration, Supervision.

Declaration of Competing Interest

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

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