Optimizing Urban Green Space Planning for Enhancing Carbon Storage and Urban Ecosystem Connectivity

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1. Background

Urban green spaces not only serve as efficient carbon sinks but also perform broader ecological functions, acting as stepping stones for terrestrial species fragmented by urban development, supporting biodiversity, and promoting sustainable urban environments. Amid growing concerns about climate change, international agreements like the Paris Agreement urge countries to reduce greenhouse gas emissions. Aligning with these efforts, South Korea is focusing on the creation of new carbon sinks, with green spaces playing a key role, to achieve its 2030 emission reduction targets.

How to achieve Nature-positive and Carbon Neutral at the same time?
: The importance of consideration of "dual-goal" when planning green space

Targeting green space management plans toward a single objective risks underestimating the complexity and multifunctionality of green spaces. However, previous research primarily identifies spatial patterns of carbon and biodiversity hotspots independently, limiting the understanding of potential trade-offs in new green space allocations. This study aims to address these gaps by identifying optimal locations for new green spaces that achieve both carbon storage and ecological connectivity simultaneously, while analyzing potential trade-offs among multiple benefits.

2. Data and Study Area

Achieving national objectives requires concerted efforts at the local scale. Cheonan-si has developed a local plan to achieve South Korea's NDC goals by 2050, with our primary focus on the carbon sink sector. It includes initiatives that focus on extensive tree planting as part of its implementation strategies. We have selected *Quercus variabilis*, *Pinus densiflora* and *Liriodendron tulipifera*, following Korea Forest Service guidelines, due to their suitability for local conditions and efficiency in biomass production for carbon sequestration.

Goal for 2030	Budget for 2025	Implementation strategies
121,100 tCO2eq	2,500,000K KRW	Climate-responsive urban forests
		Urban forest development projects
		Eco-friendly pocket parks
		Community-centric forests

Table 1. Cheonan City's Basic Plan for Carbon Neutrality and Green Growth by 2050 (2023~2034)

Cheonan-si is undergoing a demographic shift, with a decline in working-age and youth populations and a growing elderly population. This shift has led to an increase in vacant areas, including fallow fields and underutilized urban spaces. However, these vacant areas offer opportunities to address environmental goals. In this study, we defined vacant land as any unused, permeable area suitable for tree planting to help achieve local government carbon neutrality goals.

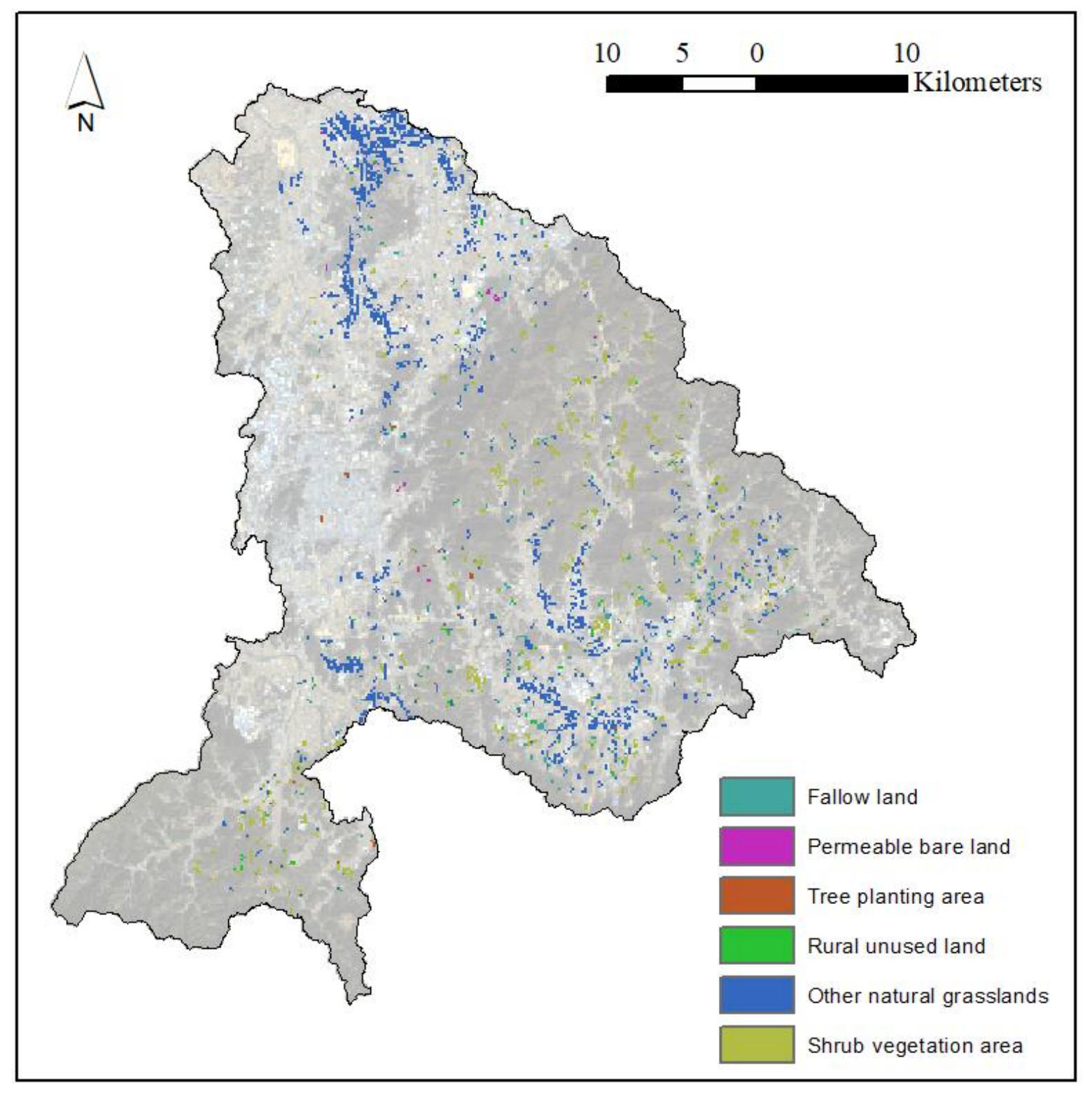
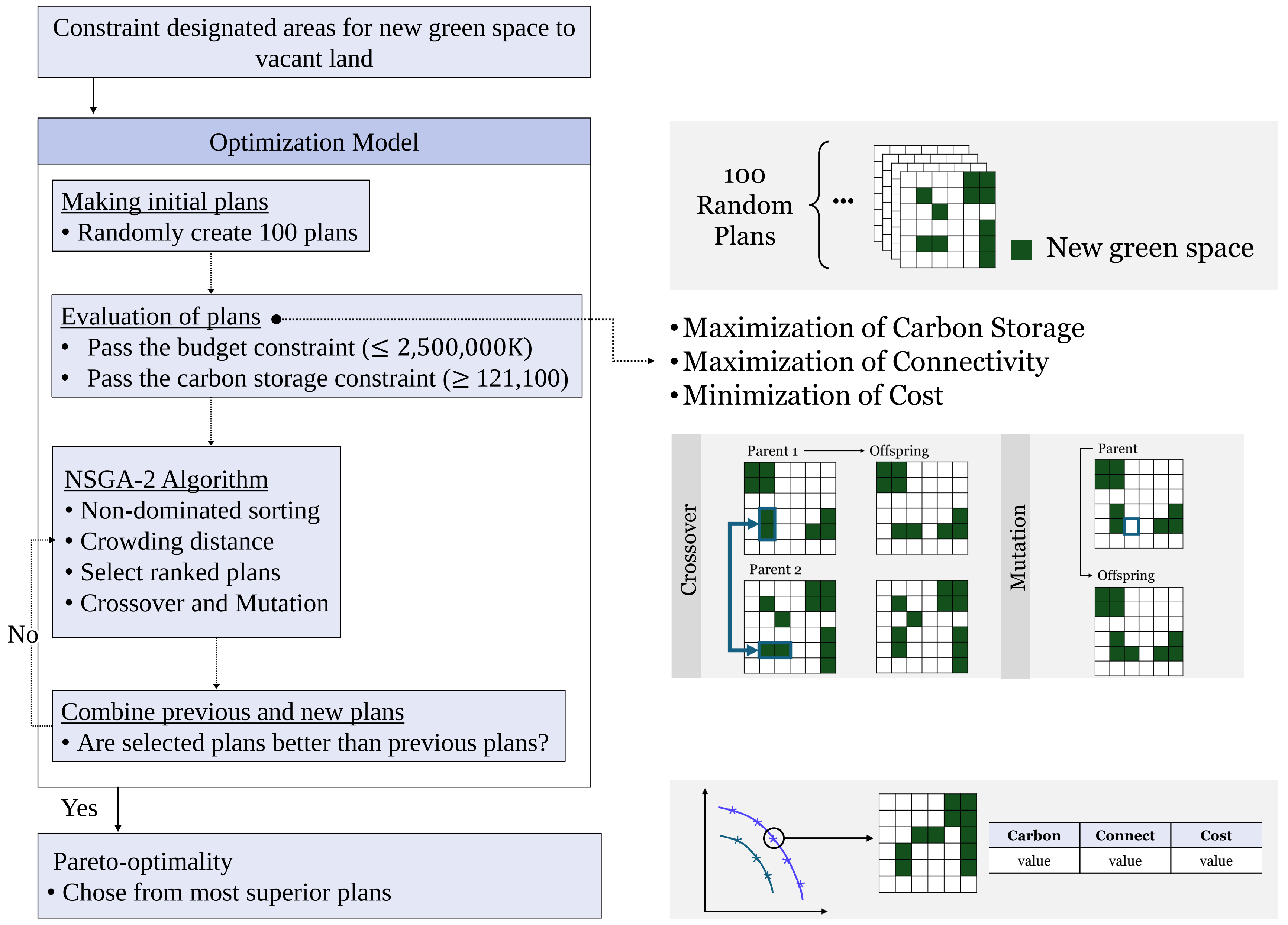


Fig 1. Study site and Location of Vacant Land

3. Methodology

Application of Multi-objective Optimization Method

Optimization was conducted using a non-dominated sorting algorithm(NSGA-II) where optimality of plans were determined by decision variable – new green space.



Constraint designated areas for new green space to vacant land

Optimization Model

Making initial plans
- Randomly create 100 plans

Evaluation of plans
- Pass the budget constraint (≤ 2,500,000K)
- Pass the carbon storage constraint (≥ 121,100)

NSGA-2 Algorithm
- Non-dominated sorting
- Crowding distance
- Select ranked plans
- Crossover and Mutation

Combine previous and new plans
- Are selected plans better than previous plans?

No

Yes

Pareto-optimality
- Chose from most superior plans

100 Random Plans

🟩 New green space

- Maximization of Carbon Storage
- Maximization of Connectivity
- Minimization of Cost

Fig 2. Study Flow

- Maximization of Carbon Storage

In this study, we calculated the carbon storage capacity per tree by assuming planting in 2025 and projecting the storage capacity for 2030. This involved assessing DBH changes relative to tree age, starting with trees that are 1-2 years old at the time of planting, reflecting the growth over this period.

$$Carbon\ storage_{plan_k} = \sum_{j=1}^{J} (Biomass_{Tree\ species} \cdot n_j)$$

$Biomass_{tree\ species}$
$= biomass\ of\ each\ individual\ tree\ species$
$n_j = number\ of\ trees\ in\ each\ location$

Equation
$DBH_{\text{Coniferous}} = 3.490 \cdot AGE^{0.460}$
$DBH_{\text{Broadleaf}} = 4.458 \cdot AGE^{0.363}$

Table 2. DBH growth by year (Kim et al., 2011)

Equation	Tree Species	*a*	*b*
$y = aD^b$	Quercus variabilis	0.186	2.184
	Pinus denisflora	0.235	2.071
	Liriodendron tulipifera	0.042	2.587

Table 3. Coefficient for calculating biomass (National Institute of Forest Science (2023))

- Maximization of Connectivity

We selected the PC index for its ability to identify critical areas for connectivity by integrating species dispersal mechanisms, thus strategically prioritizing the placement of green spaces.

$$Connectivty_{plan_k} = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} a_i \cdot a_j \cdot p_{ij}^{*}}{A_L^2}$$

$a_i, a_j = areas\ of\ patches\ i\ and\ j$
$d_{ij} = shortest\ Euclidean\ distance\ between\ patches$
$\alpha = rate\ at\ which\ the\ probability\ of\ movement\ decreases$
$A_L = landscape\ area$

- Minimization of Cost

$$Cost_{plan_k} = \sum_{j=1}^{J} (Cost_{tree\ species} \cdot n_j)$$

$Cost_{tree\ species} = cost\ of\ each\ tree\ species$
$n_j = number\ of\ trees\ in\ each\ location$

Tree Species	Tree Age	Cost (KRW/ha)
Quercus variabilis	1-0	1,254,000
Pinus denisflora	1-1	1,227,000
Liriodendron tulipifera	1-1	2,028,000

Table 4. Cost for implementing each tree species (Korea Forest Service (2023))

4. Results & Discussion

Optimization result for achieving objective function

- Despite having the highest number of plantings, the 80th plan falls short in terms of connectivity .
- The 61st plan, aimed at maximizing connectivity, presents an interesting alternative for decision-makers who seek to enhance ecological connectivity while maintaining reasonable levels of carbon sequestration and cost.
- Plan 51, although the most cost-effective, provides the lowest carbon storage and connectivity. This plan could be suitable for scenarios where cost-saving is a priority.

Plan		Carbon Storage	Connectivity	Cost
Maximization of Carbon Storage	80th	227325	0.20338	2415939000
Maximization of Connectivity	61st	180957	0.021107	1934919000
Minimization of Cost	51st	122145	0.019491	1352751000

Table 3. Fitness Values of Selected Plans

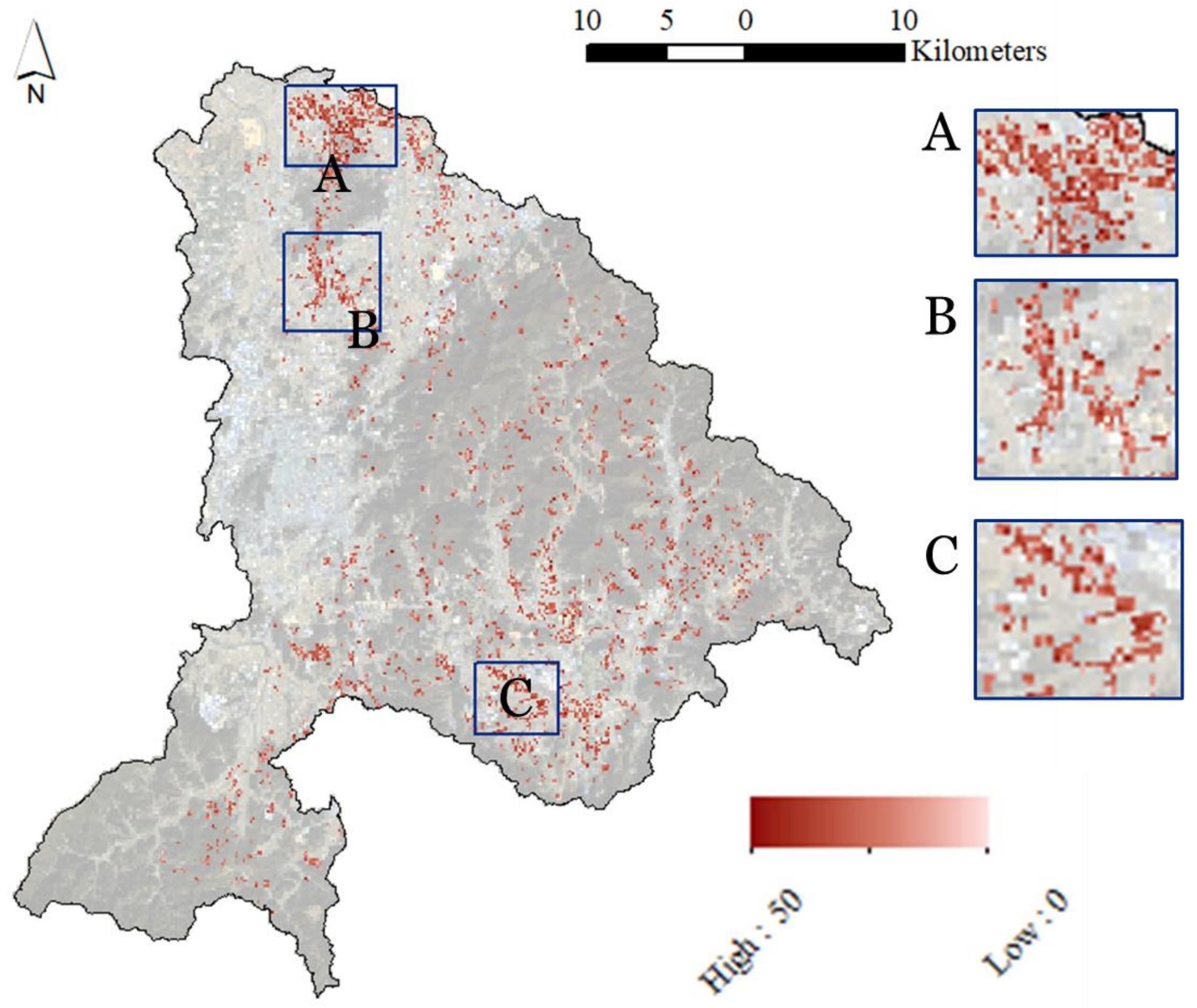


Fig 4. Result of Frequency Analysis

- We conducted a frequency analysis, which revealed that green spaces were mainly concentrated in the northernmost section **(A)**, enhancing connectivity through clusters.
- Additional green spaces were also found in the southernmost region **(C)** and the northern intermediate area **(B)**.
- This pattern suggests that connecting these areas could create a more cohesive and robust ecological network.

Synergy and Trade-off between multiple benefits

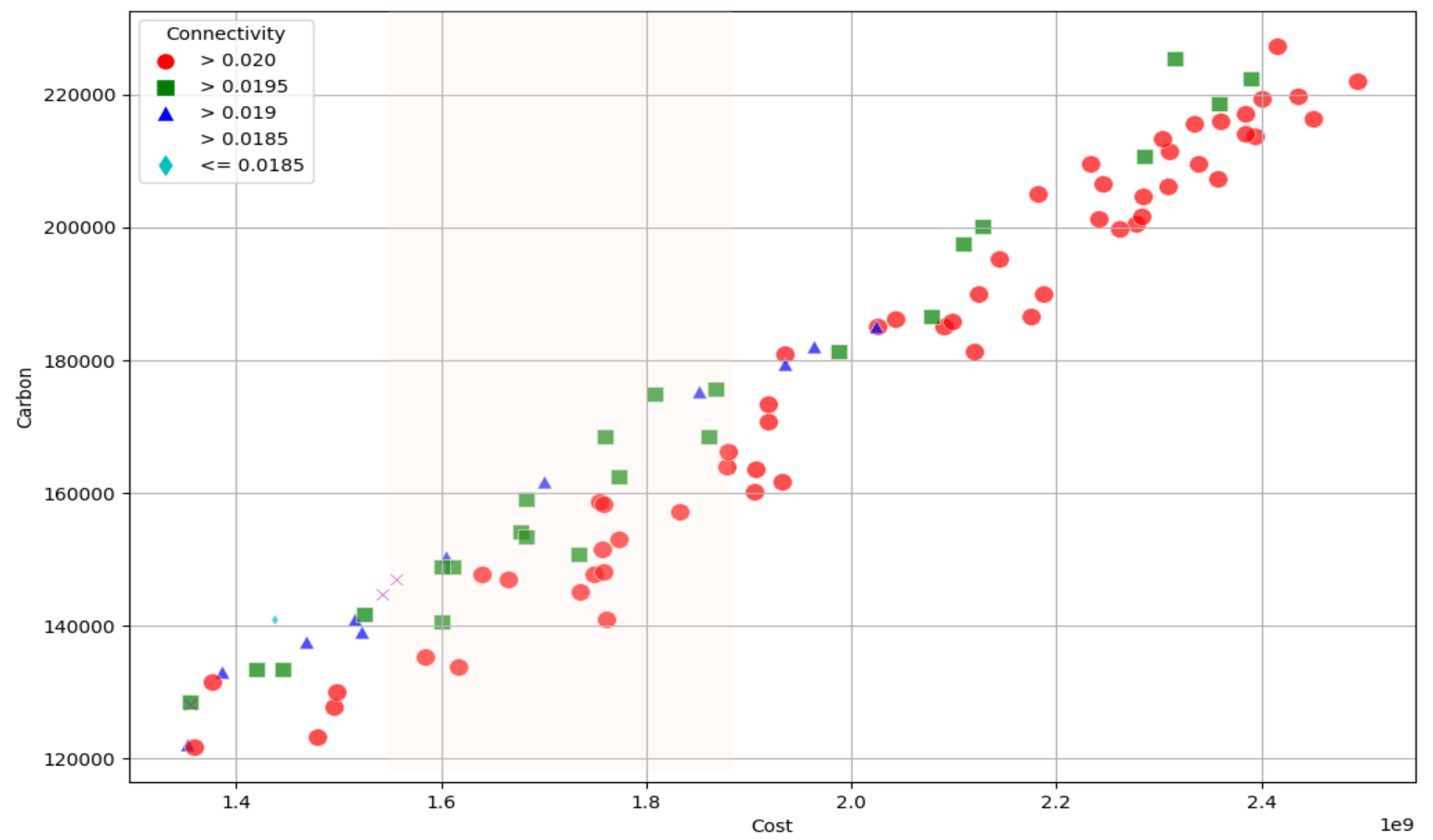


Fig 5. Relationship between Carbon and Cost

- As the graph shows, higher costs generally lead to increased carbon storage, reflecting a trade-off between cost and storage capacity.
- However, within the same cost range, significant variations in carbon storage emerge depending on connectivity levels.
- **Example:** Within the 1.8×10⁹ cost range, plans with higher connectivity achieve superior carbon storage, indicating that optimizing connectivity can enhance carbon storage outcomes without increasing costs, demonstrating a potential synergy.
- This emphasizes the need to integrate connectivity into planning strategies to enhance cost-effectiveness by balancing trade-offs and maximizing synergies.