Optimizing Urban Green Spaces Using a Decision-Support Model for Carbon Sequestration and Ecological Connectivity

Urban green spaces (UGSs) are multifunctional assets within urban environments that address a range of ecological, social, and health-related demands. As integral structural components, UGSs greatly influence the functionality of urban environments. They are critical for managing air pollution (Matos et al., 2019; Jaung et al., 2020), urban heat island effects (Yang et al., 2015; Zhang et al., 2015), and stormwater, among other environmental challenges (Zhang et al., 2017; Xiao et al., 2018; Xu et al., 2022). The growing emphasis on carbon neutral development has motivated the development of UGSs, owing to their capacity for capturing atmospheric CO_2 through carbon sequestration during photosynthesis (Park et al., 2021; Niemelä et al., 2010). UGSs are also crucial ecological corridors that promote wildlife movement by reconnecting fragmented habitats, thereby promoting gene flow, biodiversity, and overall ecosystem resilience (Wu et al., 2023; Zipperer et al., 2000). In addition to their environmental functions, UGS foster a stronger sense of community (Dwyer et al., 1992; Xiao et al., 2016; Piaggio, 2021) while also enhancing economic value by increasing the market appeal of properties near well-maintained green spaces (Conway et al., 2010). Moreover, UGS provide urban residents with opportunities for outdoor leisure and recreation, which contribute to improved physical health (Mitchell and Popham, 2008; Ward Thompson and Aspinall, 2011) and help reduce stress (Richardson et al., 2013).

This multi-functionality underscores the need for an integrated approach to urban planning that balances multiple objectives (Soto-Navarro et al., 2020). As urban greenery operates as a quasi-public good, it falls on local governments to develop and maintain appropriately designed green spaces (Li et al., 2022. For instance, the city of Suwon has established the 2030 Green Space Vision and Strategy, which prioritizes the development of urban forests to mitigate environmental challenges, including air pollution, extreme heat, and heavy rainfall, while enhancing urban resilience to natural disasters. At the same time, the initiative aims to improve accessibility to green spaces by promoting equitable distribution and integrating green corridors to strengthen ecological connectivity (Kim et al., 2018). Similarly, Melbourne, facing challenges associated with climate change, population growth, and urban heat, has acknowledged the increasing strain on its built environment, infrastructure, and residents (City of Melbourne, 2012a). The city introduced an evidence-based urban forest strategy to mitigate the urban heat island effect and enhance biodiversity, successfully planting 12,000 trees, demonstrating the effective role of multifunctional green spaces in sustainable urban development (Gulsrud et al., 2018). To effectively allocate resources and maximize benefits to the residents, it is important to maximize the multifunctionality of a UGS. However, the balancing of diverse objectives in urban planning is often complicated by constraints such as limited space and competing land use preferences (Hansen et al., 2019; Hauck et al., 2013; Korkou et al., 2023).

Over the years, the definition and scope of urban green spaces (UGS) have expanded to "all urban land covered by vegetation of any kind" (Anguluri et al., 2017). This includes parks, gardens, and recreational spaces, extending to informal green areas like riverbanks, historical site surroundings, and linear green spaces along railway and road corridors (Jabbar et al., 2022). Additionally, native vegetation and repurposed urban habitats, such as abandoned industrial sites and overgrown gardens, also fall within the category of UGS (Tzoulas et al., 2007; Venn & Niemelä, 2004). A more structured and spatially organized systems-based approach to UGS incorporates city-centric green infrastructure elements, such as greenbelts, green wedges, and artificially designed scenic areas, as key components (Lee & Maheswaran, 2011).

Since the adoption of the Paris Agreement, many nations, including South Korea, have implemented these UGS expansion as a strategy to enhance carbon sequestration and support their carbon neutrality commitments (Zhou et al., 2011; Chen et al., 2015). Contributing to South Korea's 2030 Nationally Determined Contributions (NDCs), the Third Comprehensive Plan for Enhancing Carbon Sinks focuses on expanding carbon sinks in urban and underutilized lands. This plan sets specific targets, including large-scale tree planting on unused land, with a goal of afforesting 4,000 ha annually by 2030, and the expansion of urban forests, aiming to cover 3,212 ha over five years (MOE, 2023). Ultimately, achieving these national objectives requires active efforts at the local level (Peters et al., 2010). Based on this national framework, local governments formulate and implement strategies such as urban forest development and park green space expansion, adapting these initiatives to their regional ecosystems and specific environmental conditions.

However, investment in carbon storage alone through, for example, the planting of dense monocultures, can negatively impact ecological connectivity through habitat fragmentation (O'Brien et al., 2023), and compromise ecosystem functionality (Huang et al., 2023). For example, Qiu et al. (2023) demonstrated that fragmentation destabilizes ecosystem connectivity, which in turn reduces the effectiveness of carbon sequestration. Blindly planting trees without considering the structural layout of the green space network can lead to neglecting other factors (Wan et al., 2024). In contrast, the restoration of ecological networks holds significant potential to enhance carbon sequestration by stabilizing ecosystem linkages and facilitating more effective material cycling (Wan et al., 2024; Lu et al., 2024). For instance, Valentine et al. (2023) highlighted the importance of considering connectivity to support carbon storage management. Similarly, Saavedra-Hortua et al. (2023) demonstrated that ecosystems with stronger connectivity exhibit higher biomass productivity and carbon storage capacity compared to their isolated counterparts. By acknowledging and addressing the interplay between carbon storage and ecological connectivity, urban planners can develop more balanced and beneficial green spaces.

Various multi-objective approaches have been proposed in green space planning, utilizing mainstream software models or incorporating evaluation results to assess multiple ecosystem services (Pan et al., 2020; Evans et al., 2015; Xu et al., 2019; Wu et al., 2023). Additionally, some studies have employed scenario-based evaluations (Martin et al., 2022; Nyelele et al., 2021; Neema et al., 2010) to identify an optimal alternative for the maximization or minimization of specific objectives. While these studies aim to identify areas capable of delivering multiple benefits, the co-occurrence of ecosystem service hotspots remains rare (Martin et al., 2022), highlighting the need for a more flexible approach that can accommodate the complexities of multi-dimensional trade-offs, where competing priorities and synergies often conflict. While numerous studies have explored carbon sequestration and ecological connectivity independently, research that integrates both objectives within a multi-objective optimization framework remains in its early stages (Wan et al., 2024). Existing studies have employed various modeling approaches to address specific aspects of carbon and ecological planning. For instance, Liu et al. (2023) applied the MOP-PLUS coupling model to identify the optimal carbon sink maximization strategy for 2035, focusing on land-use-based evaluations. Similarly, Lu et al. (2024) utilized a source-node approach to determine key nodes influencing carbon stock value, highlighting spatial dependencies in carbon storage. Meanwhile, Huang et al. (2023) integrated circuit theory and complex network models to simulate ecological networks, complementing their approach with the InVEST model to assess carbon sequestration potential.

While the capacity of urban green spaces to provide multiple benefits is widely acknowledged, establishing UGS requires optimizing decision-making priorities while considering practical constraints (Chen et al., 2015), such as budget limitations and spatial availability. Thus, there remains a pressing need to generate diverse alternatives tailored to the specific objectives of different decision-makers, while instantly evaluating scenarios. In particular, from a carbon perspective, it is essential to not only establish green spaces but also estimate the carbon sequestration potential over time as trees grow and mature. Furthermore, while previous studies have primarily examined UGS planning at the regional scale, effective implementation at the local scale requires a more context-specific approach (Hein et al., 2006), highlighting the necessity of a grid-based spatial framework. In light of this context, our study aims to address the following key scientific questions:

1. Can a multi-objective approach generate a range of balanced alternatives while concurrently assessing trade-offs between objectives and incorporating scientific evaluations into allocation decisions?
2. How can urban green spaces be spatially configured to maximize both carbon storage and ecological connectivity while minimizing costs?

This study aimed to address the gaps in past research by developing an effective approach for identifying optimal locations for UGSs that achieve carbon sequestration and ecological connectivity goals while considering budget constraints. Utilizing a heuristic optimization approach, this study aimed to achieve a balance among the competing objectives while evaluating the trade-offs. This approach offers a range of solutions by enabling the rapid generation and evaluation of alternative strategies, allowing planners to balance diverse objectives and assess trade-offs in real time (Wang et al., 2020; Ozcelikkan et al., 2022). This study provides a sound scientific framework for planning UGSs that can serve as a decision-support tool for policymakers and environmental planners, promoting the identification of more balanced strategies for sustainable development.