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Planning Strategies of Wind Corridor Forests Utilizing the Properties of Cold Air

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Abstract: A wind corridor forest is defined as an urban forest for utilizing the functions of a wind corridor that allow "cool and fresh air (cold air)" generated in forests at night to flow to urban development areas. This study aims to provide planning strategies for implementing a wind corridor forest by analyzing current conditions in Haengbok City (HBC region), Sejong, South Korea. The HBC region had many wind-generating forests (WGF), wind-spreading forests (WSF), and wind-connecting forests (WCF), and secured the connections among the target areas of each wind corridor forest. Despite the favorable conditions for a wind corridor forest, cold air flow showed that there are regions with unfavorable wind conditions in the HBC region. In order to strengthen the functions of a wind corridor forests in the HBC region, four zones were distinguished according to the functional characteristics. Additionally, the planning strategies of a wind corridor forests suitable for each zone were provided, and the strategies for establishing a wind corridor forest were proposed. The results of this study can be used as the fundamental data for establishing guidelines for a wind corridor forest and utilized as resources for selecting regions suitable for a wind corridor forest.

Keywords: urban forest; ventilation corridor; forest planning; KALM; climate change

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1. Introduction

The outbreak of urban heat islands (UHIs) due to urbanization and population growth is threatening the heat conditions in urban areas [1–3]. UHI represents the temperature in urban dense areas being higher than in suburban areas [4]. The worsening of the urban thermal environment poses a biological threat to human health due to heat stress [5]. In South Korea, the number of heat-related illnesses caused by heatwaves reached the highest record of 4526 in 2018. Since the urban thermal environment continues to deteriorate, that number is expected to increase further in the future. In addition to the problem of the urban thermal environment, the increase in traffic and energy use in dense cities has led to an increase in fine dust emissions, resulting in atmospheric environmental problems [6]. Fine dust is a harmful substance that causes lung and heart diseases when exposed for a long time, possibly leading to death [7,8]. In 2019, the annual average concentration of $PM_{2.5}$ in South Korea was 24.8 $\mu g/m^3$, the worst among OECD countries [9].

It has become an increasingly important task to improve these urban environmental problems and manage urban climate [10]. The Korea Forest Service aims to improve the thermal and atmospheric environment in urban areas by creating urban forests utilizing the functions of wind corridors (i.e., urban ventilation corridors or cold air paths). Wind corridors play a role in improving air pollution and the thermal environment as urban ventilation corridors allow "cool and fresh air (cold air, commonly used in English in the term 'Kaltluft' originated in German)" generated in forests at night to flow into urban development areas where climate conditions are unfavorable [11]. Wind corridors operate by areas that create cold air, areas that cold air flows into, and the areas that connect the two [12]. Hence, wind corridor forests are classified into three categories according to the role of urban forests in and outside the city that create the wind corridor. Wind-generating forests (WGF) are urban forests that create cold air, mainly located on the city outskirts. Wind-spreading forests (WSF) are greenery areas that create thermal winds caused by differences in temperature between built-up and greenery areas, such as urban parks. Wind-connecting forests (WCF) are linear greenery areas that connect WGFs and WSFs. The main examples of WCF include greenery areas along the river and trees along the street, which function as a corridor that transports cold air through the topographical structure of rivers and roads.

Previous studies on wind corridors have focused on the relationship between urban structures and wind corridors and to improve climatic environment in terms of urban planning. Ren et al. [13] assessed wind corridor plans in order to improve the air exchange in different cities in China, investigated urban wind corridors, and applied them to urban master plans. Wong et al. [14] assessed city-level wind corridors using the concept of "building frontal area index" and identified major buildings that limit the flow of wind corridors through the analysis of the target area. Furthermore, they predicted wind corridors in the city and devised ways to identify the areas that benefit from wind corridors and the areas that supply cold air. Grunwald et al. [15] identified different types of wind corridors through the analysis of the data on the cooling rate using the cold-air analysis model of KLAM_21(Kaltluftabflussmodell_21), and analyzed wind corridors of the target area using the tool "Particle Track" (ArcGIS Software, ver.10.6). Furthermore, Grunwald et al. [16] devised a methodology to analyze wind corridors through regression analysis using the data from cold-air analysis of KLAM_21, land-use, topography, and buildings.

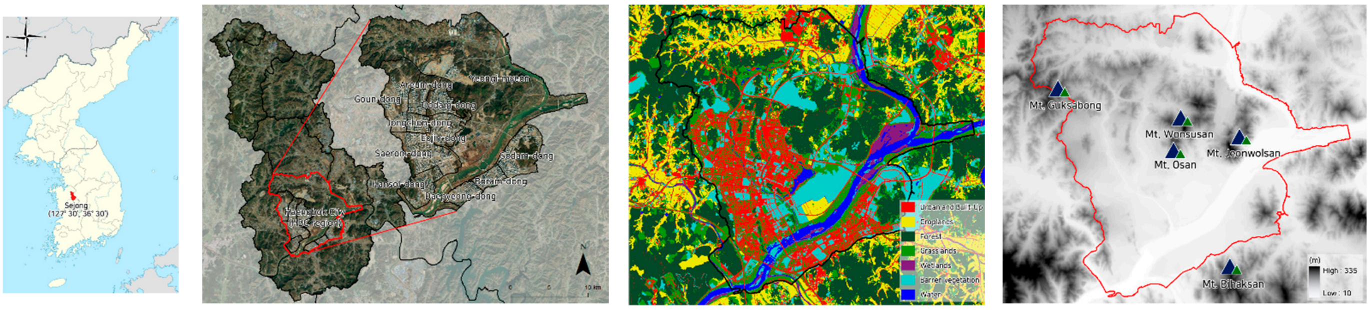
Unlike previous studies on wind corridors that analyzed their relationship with urban structures, this study focused on the relationship between wind corridors, urban forests, and greenery areas. Studies on wind corridor forests started in 2019 in South Korea. Eum et al. [17] explored the characteristics of wind corridor forests and classified urban forests and greenery areas based on three types of WGF, WSF and WCF in Daegu Metropolitan City. Jang et al. [18] identified meteorological, topographical, and land-use conditions of cold air generation and its transport to establish principles of creating wind corridor forests. Son et al. [19] analyzed the current conditions of wind corridor forests in a medium-sized city, Pyeongtaek in South Korea, and proposed strategies for establishing wind corridors. Although previous studies have established the basis for creating wind corridor forests targeting several cities in South Korea, there were limitations in providing planning strategies of wind corridor forests. This is because the existing cities in need of wind corridor effects are already under development at high density, so it is insufficient to implement an efficient planning of wind corridor forests.

In order to provide practical planning strategies for implementing wind corridor forests, Sejong Special Self-Governing City (Sejong) in South Korea was selected, where spaces have been secured to create urban forests and greenery. This study analyzes the current status of wind corridor forests and the cold air conditions. Based on them, it provides planning strategies for wind corridor forests according to the specific urban conditions of Sejong.

2. Materials and Methods

2.1. Study Area

Sejong City was selected as the target area of this study. Sejong is located at 127°30′ longitude and 36°30′ latitude, bordered by Cheongju City to the east, Gongju City to the west, Cheonan City to the north, and other cities, such as Daejeon Metropolitan City, to the south (Figure 1). The total geographic area is 465.2 km^2, and the administrative districts consist of 10 Dongs (neighborhood), 9 Myeons (townships), and 1 Eup (town). Sejong is a multifunctional administrative city with a new city center "Haengbok City (HBC region)" and a former city center, Jochiwon region. The new city center, the HBC region, was chosen as the target area for detailed analysis. The HBC region consists of 10 Dongs and 1 Myeon, surrounded by green corridors along the mountainous areas at a height of 251 m above sea level, such as Mt. Wonsu, Mt. Janggun, and Mt. Bihak. Geumgan River, flowing from east to west, is located in the south of the HBC region (Figure 1).



(**a**) (**b**) (**c**) (**d**)

Figure 1. Maps of study area: (**a**) location of Sejong City; (**b**) study area (HBC region); (**c**) land cover of HBC region; (**d**) topography of HBC region.

Figure 2 shows the wind environment analyzed with the combined data on wind velocity and wind direction over four years (2016 to 2019) using the observational data from five automatic weather stations (AWS) in Sejong. The prevailing wind direction was different depending on the location of observation stations. The important point is that the wind rose map showed high rates of calm winds (when the wind speed is lower than 0.3 m/s), ranging from 16.9% to 34.1%. The average wind speed measured across the five stations was lower than 1.1 to 2 m/s. This means that Sejong is an area with an unfavorable wind environment in general, and it is required to improve the wind conditions to achieve a favorable thermal and atmospheric environment.

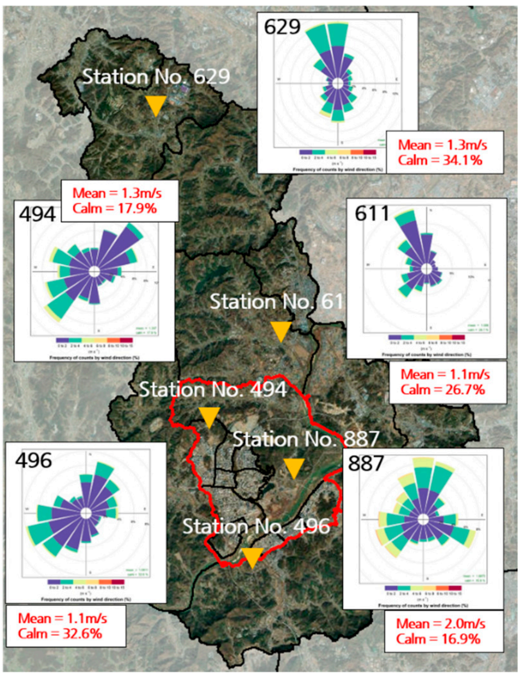


Figure 2. Wind rose map in study area.

2.2. Methods

In order to identify the target areas to create the wind corridor forests, the current conditions were analyzed for HBC region. The analysis consists of two parts. The first part, analysis of wind corridor forests was conducted to understand the current status of urban forests and the greenery areas located within the city. After the analysis, urban forests are classified into three types according to their functions for generating, spreading and connecting cold air as well as its effects. As the second part, characteristics of cold air flow representing important factors in wind corridor forest planning were analyzed to find places that need to be strengthened or supplemented with wind corridor. Based on the analysis of the first part, planning strategies are established for preserving the urban forests that perform the wind corridor and for selecting the areas that need to be complemented by wind corridor forests. The analysis was conducted throughout Sejong (analysis range: 45 km × 48 km, resolution: 30 m), and then a detailed analysis for HBC region (analysis range: 1.4 km × 1.2 km, resolution: 30 m) was carried out. The following presents the details of the analysis methods used in this study.

2.2.1. Classification of Wind Corridor Forest

In order to understand the distribution of urban forests and greenery areas, and to classify them according to three types of wind corridor forest, the analysis schemes used by Eum et al. [17] were modified. Figure 3 shows the modified schemes tailored to the properties of Sejong.

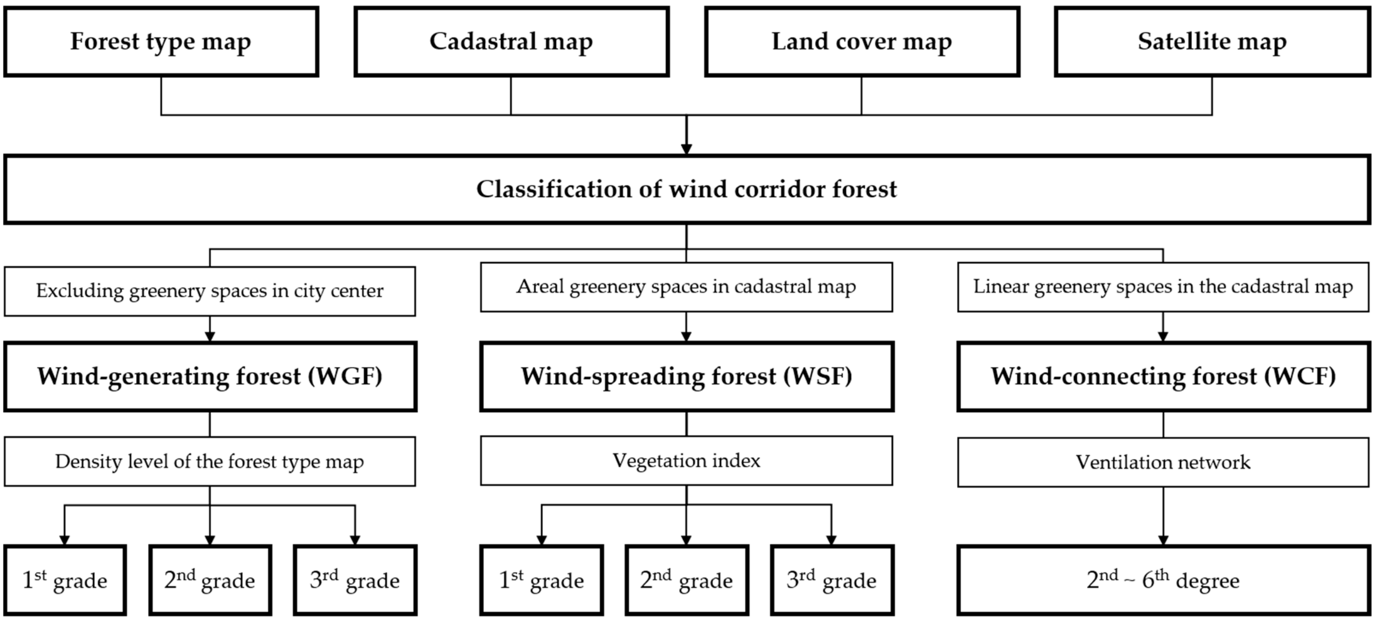


Figure 3. Analysis schemes for wind corridor forests in this study.

In order to analyze the current status of urban forests and greenery areas, the study mainly used the forest type map for 2015 released by the Korea Forest Service, and supplemented the urban green space data from the cadastral map for 2018 by the Ministry of Land, Infrastructure, and Transport, and the land cover map for 2018 by the Ministry of Environment, as well as satellite images. The forest type map is a representative map across the country and contains various property information on forest such as physiognomy, species, age group, and density. Since the forest type map was released in 2015, the map was complemented with urban green space data and land cover maps while comparing them with satellite images to accurately reflect the characteristics of the rapidly developing study area. For example, data corresponding to forest areas in the land cover map and green spaces such as plazas, parks, green areas, amusement parks, and public areas of the urban green space data were included in the forest type map to update the information on urban forests and greenery areas.

Using the updated forest type map, the study classified urban forests and greenery areas into three types of wind corridor forest. First, since the wind-generating forest (WGF) refers to a forest located outside the city center, the urban forest is classified as a WGF, excluding the urban green space planning data that classified parks and green areas located in the city center. In contrast, the wind-spreading forest (WSF) and wind-connecting forest (WCF) were green spaces located in the city center. WSF corresponds to areal greenery spaces such as squares, parks, public areas and facility green areas, while WCF corresponds to linear green spaces such as riverside and roadside trees.

In addition, three types of wind corridor forest were graded. WGF was classified into three grades according to the density levels of the forest type map. The higher grade has the better function for generating cold air, which means that it should be preserved instead of developed.

WSF was graded using the vegetation index. In order to identify the vegetation index, the normalized difference vegetation index (NDVI), which is the most commonly used vegetation index, was analyzed. NDVI is calculated using Equation (1): NIR is near-infrared spectral reflectance, and RED is visible red spectral reflectance. Green plants hold positive NDVI values because the reflected rate of the NIR is smaller than the RED [20]. The NDVI is strongly correlated with the density and vitality of the vegetation. A value of NDVI closer to 1 means better vitality and density of vegetation. In this study, satellite images were selected under the condition of less than 10% cloud volume during spring, summer, and autumn so that vegetation vitality is sufficiently displayed. As a result, the vegetation index was calculated using the Landsat TM 8 image on 8 June 2020, where the vivid image appeared. Then, the vegetation index within the analysis range was categorized into three grades using Natural Break methods of ArcGIS ver. 10.6.

$$NDVI = \frac{NIR - RED}{NIR + RED} \tag{1}$$

In the case of WCF, the analysis data on ventilation networks (Korea Research Institute for Human Settlements, 2018) was used to identify whether WCF can be utilized additionally. Since the ventilation networks were calculated considering the nocturnal cold air drainage based on topography and urban structures, areas on the ventilation networks were considered as available areas for wind corridor forests. The ventilation network was analyzed using the digital elevation model (DEM) provided by the National Geographic Information Institute based on ArcGIS hydrological modeling. Based on the 1-km grid, the height of buildings was estimated, and the plan area index, façade area index, zero-plane displacement, and roughness length were measured. The higher degree of ventilation network means a corridor with better flow, and two to six degrees out of a total eight degrees in the ventilation network was judged to be suitable for WCF of Sejong. Finally, the WCFs adjacent to the ventilation networks were selected as the main target sites.

2.2.2. Characteristics of Cold air Flow

Simulations using numerical models can be used to confirm the flow of cold air in complicated terrains [21]. Representative models for simulating cold air flow are KLAM_21 (Kaltluftabflussmodell_21) and KALM (Kaltluftabflussmodell). The KLAM_21 developed by the German Weather Service (DWD) is a two-dimensional, mathematical-physical simulation model for calculating cold air flow and accumulation in topographically structured terrain [22]. The KALM model calculates the evolution of the cold air flow and the height of cold air layer occurred on a clear and calm night (i.e., nocturnal drainage flow) [23]. It is specialized in analyzing the properties of cold air due to land cover and topographical characteristics [24,25]. To determine the overall wind corridors of Sejong with high rates of calm winds, KALM was selected for this study.

The KALM model is based on the shallow water equations, the vertically integrated form of fluid mechanics [23]. The main equation is shown as follows (Equation (2)):

$$\begin{gathered}\frac{\partial \mathrm{u}}{\partial \mathrm{t}} + \mathbf{u}\cdot\mathrm{grad}\ \mathbf{u} = -\tilde{\mathrm{g}}\mathrm{gradH} - \mathrm{cu}|\mathbf{u}| \\ \frac{\partial \mathrm{h}}{\partial \mathrm{t}} + \mathrm{div}(\mathbf{u}\mathrm{h}) = \mathrm{q}\end{gathered} \tag{2}$$

where **u** = (u, v) is the horizontal velocity vector of cold air, h is the height of the cold air layer, H is the height of the top of cold air layer, c is a friction coefficient, and q is the rate of generation of cold air. $\tilde{g} = g\Delta T/T_0$ is the amount of reduced gravity with T_0 and ΔT representing the ambient temperature and the deficit of a layer-averaged temperature. The layer-averaged horizontal velocity is expressed by u and v components. The KALM model provides value of the parameters for seven types of land use. Table 1 shows the land cover types categorized for KALM simulation and their parameters used in this study.

Table 1. Land use types applied for the KALM model and their parameters used for this study.

Land Cover Type	Temperature Difference (k)	Cold Air Production Rate (m^3/m^2h)	Roughness Length (m)	Zero-Plane Displacement Height (m)
Suburb	4.0	0.0	0.441	2.0
Forest	8.0	30.0	1.070	5.0
Open land	10.0	15.0	0.100	0.0
City center	2.0	0.0	0.714	5.0
Water	4.0	0.0	0.001	0.0
Traffic areas, airports, etc.	4.0	0.0	0.010	1.0
Industrial areas	4.0	0.0	0.22	5.0

As major input data for analysis, the land cover map released in 2018 (the scale of 1:25,000) and the digital map by the Ministry of Environment were used. The 22 categories in the land cover map were reclassified into seven land use types (suburb, forest, open land, city center, water, traffic area, and industrial area) to apply to the KALM model. In addition, four parameters for each land use type were applied. For temperature difference and zero-plane displacement height, the values used in the KALM model were applied, and the values for surface roughness length and cold air production rate were taken from Eum [26] and Eum et al. [10], considering the structural properties of the cities in South Korea.

The analysis of characteristics of cold air flow consists of an overall analysis for Sejong (analysis range: 45 km × 48 km, resolution: 30 m) and a detailed one for the HBC region (analysis range: 1.4 km × 1.2 km, resolution: 30 m). As the results, simulation data on cold air flow and the height of cold air layer over six hours (360 min) were extracted. Then, the cold air speed and the height in each administrative area (unit: Dong) were compared.

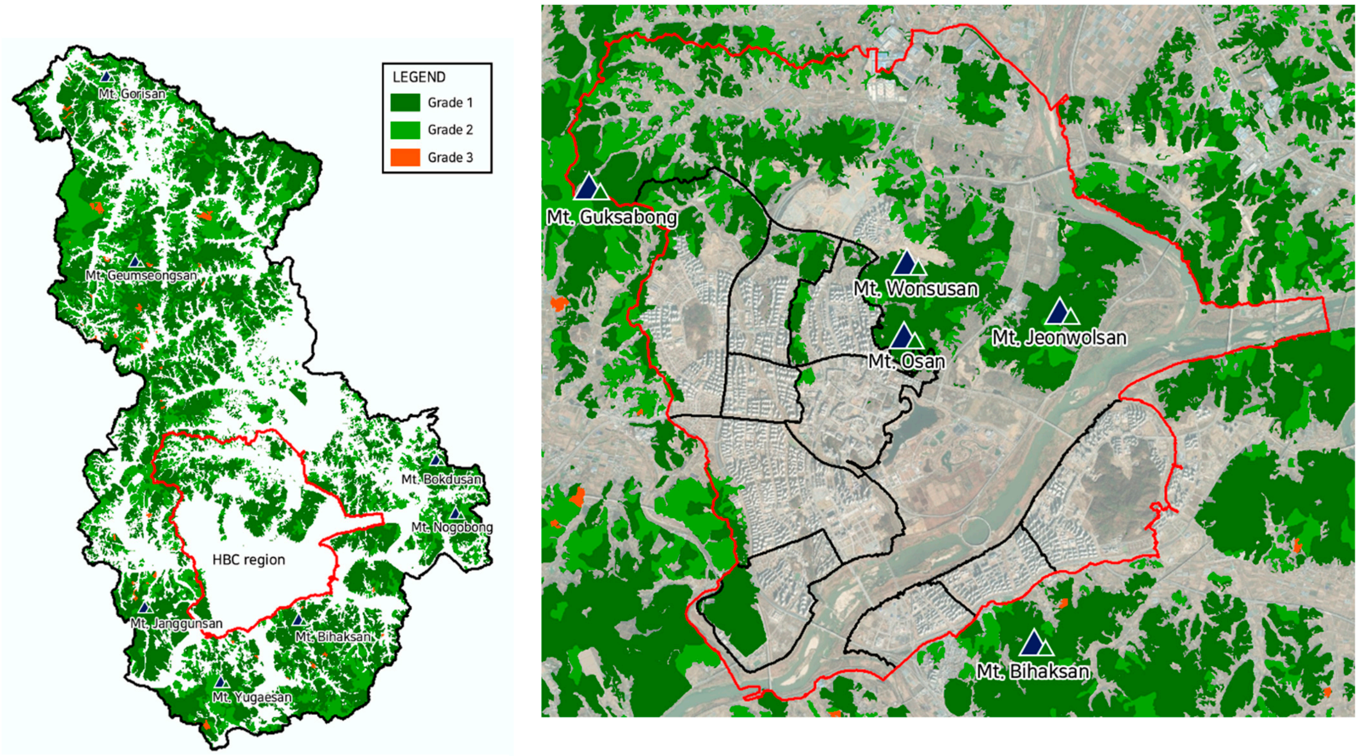
Since this study did not include the validation of cold air flow by KALM simulation, the previous studies comparing observation values and model results by KALM were reviewed. Son et al. [2,27] analyzed the characteristics of cold air using KALM in mountainous regions of South Korea and compared the observation data from several meteorological stations with the simulation results. The studies confirmed that the air temperature decreased significantly at night in the region where the cold air flow was analyzed to be favorable, and that the KALM model was affordable for simulating cold air flow in mountainous regions such as Sejong and the HBC region.

3. Results

3.1. Wind Corridor Forests

The distribution of wind-generating forests (WGFs) in Sejong is shown in Figure 4. The total area of WGFs is 241 km^2, accounting for 52% of Sejong City's total area. With Mt. Bokdusan and Mt. Nogobong in the east, Mt. Janggunsan in the west, Mt. Yuegaesan and Mt. Bihaksan in the south, and Mt. Gorisan and Mt. Geumseongsan in the north, the overall distribution of WGFs in Sejong is revealed to be even.

The area of WGF in HBC region is 54.82 km^2, and when graded according to the density of the forest type map, the area ratio of Grade 1 was the highest at 68.82%, followed by Grade 2 (30.41%) and Grade 3 (0.77%). WGFs surround the outskirts of the HBC region, and those in the north play a major role as they are adjacent to residential and commercial areas. The major WGFs are Mt. Guksabong, Mt. Ohsan, and Mt. Wonsusan. However, the forests in the north are fragmented due to urban development; thus, it is necessary to strengthen the function to produce cold air through forest management and restoration.



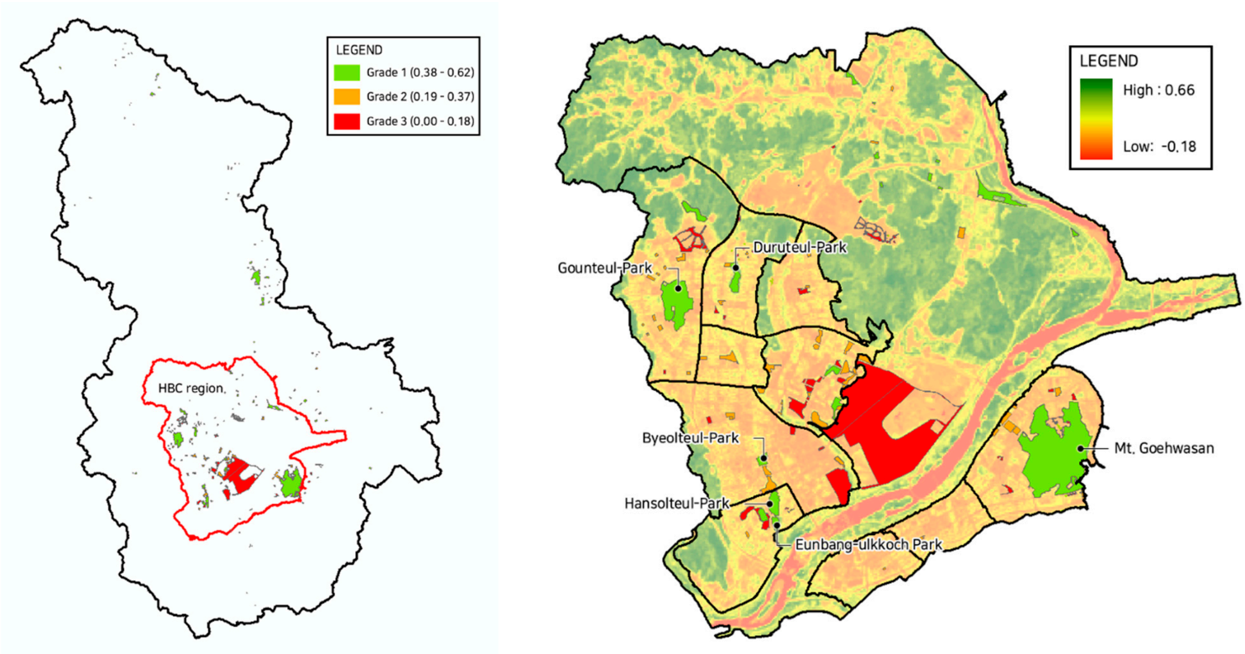
(**a**) (**b**)

Figure 4. Distribution of wind-generating forest (WGF): (**a**) Sejong; (**b**) HBC region.

Wind-spreading forests (WSFs) in Sejong were mainly parks in the urbanization area and green spaces, mostly concentrated in the center of the HBC region. As the HBC region is a recently built planned city, WSFs were evenly distributed.

When the vegetation index was analyzed using satellite images (Figure 5), the forest parks with a large area, such as Duruteul Neighborhood Park and Gounteul Neighborhood Park, had the highest vegetation index. However, small parks located in residential and commercial areas showed a low vegetation index, because trees in the city have lower vitality due to the unfavorable growing environment. When WSFs in the HBC region are classified into three grades according to the vegetation index, the average value of WSFs was 0.3, equivalent to grade 2. Six of the major parks and urban forest in the HBC region were categorized as grade 1, which has a high vegetation index with the value of 0.4 or more, including Duruteul Neighborhood Park, Mt. Goihwasan, and Goeunteul Neighborhood Park (Table 2).

Wind-connecting forests (WCFs) of Sejong were well-established even in the city center, but there are some sections where WCFs are cut off. The major WCFs of the HBC region are Geumgang River, Jaechun Stream, Bangchukchun Stream, and roadside green areas with linear and wide forms (Figure 6).



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

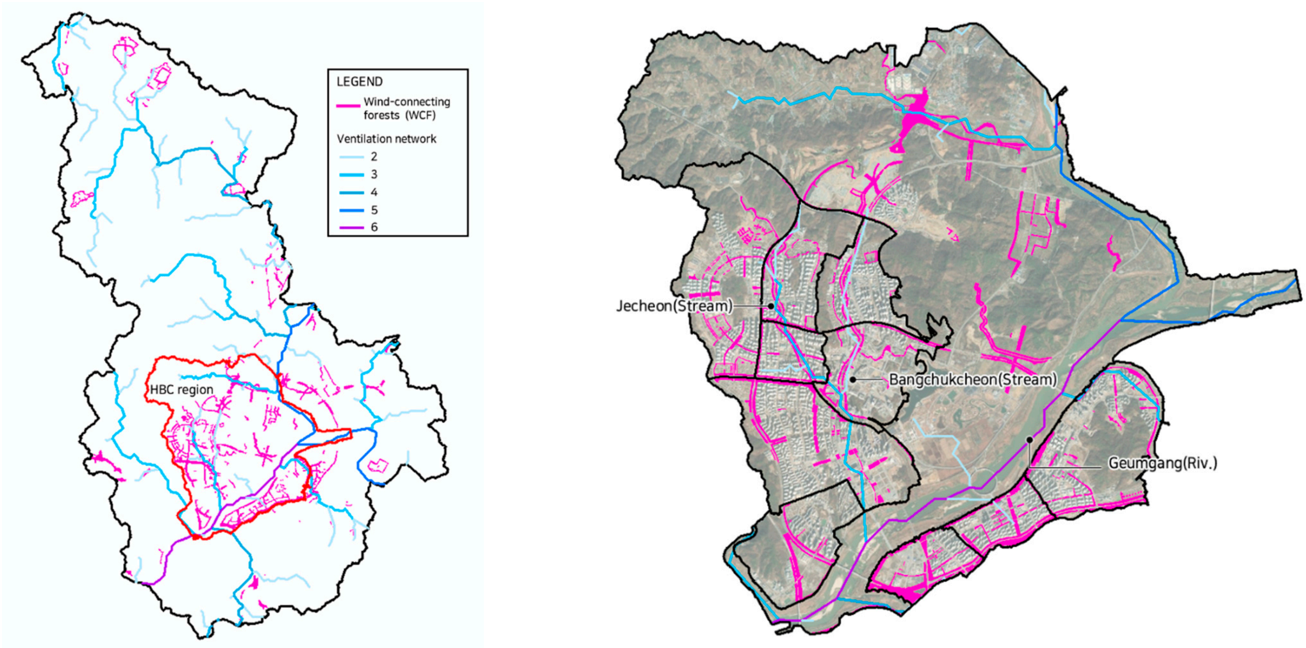
Figure 5. Distribution of wind-spreading forest (WSF): (**a**) Sejong; (**b**) HBC region (expressed with vegetation index).

Table 2. Grades and vegetation index of major wind-spreading forests.

Grade	Target Areas	
	Name	**Vegetation Index**
Grade 1 (0.38–0.62)	Duruteul Neighborhood Park	0.49
	Mt. Goihwasan	0.47
	Gounteul Neighborhood Park	0.45
	Hansolteul Neighborhood Park	0.43
	Byeolteul Neighborhood Park	0.42
	Lily of the Valley Neighborhood Park	0.42
	Gadeukteul Neighborhood Park	0.37
Grade 2 (0.19–0.37)	Choryeo Historical Park	0.34
	Jaechunteul Neighborhood Park	0.23
Grade 3 (0.00–0.18)	Sejong Central Park	0.2

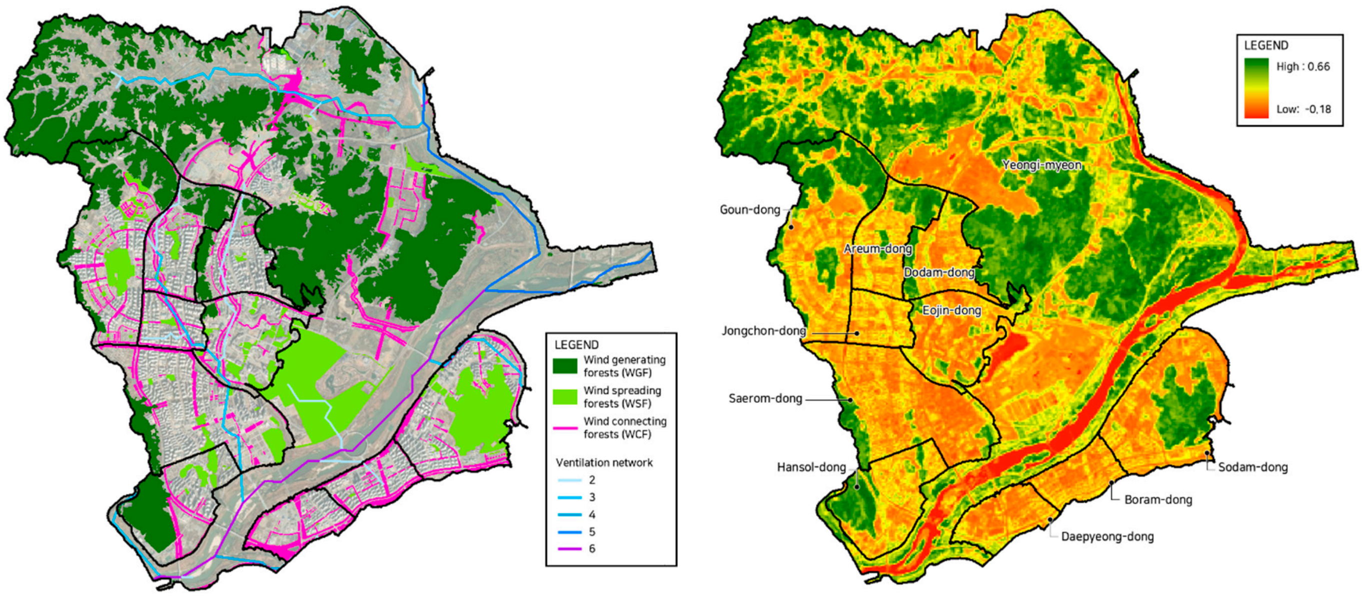
The ventilation network that is critical in selecting areas for utilizing WCF was formed along the river such as Geumgang River, Jaechun Stream, and Bangchukchun Stream. Although there are WCFs located on the ventilation network, there are also some WCFs that are disconnected.

According to the analysis of the overall conditions of wind corridor forests (Figure 7), the HBC region had many wind-generating, wind-spreading, and wind-connecting forests and secured the connections among the target areas of each wind corridor forest. Furthermore, ventilation networks were connected to the city center along the river. The vegetation indices were low in most of WSF and WCF; the average vegetation index of HBC region was 0.42, but the indices for WSF and WCF were 0.3 and 0.24, respectively, which were lower than the average. The index for WGF was 0.49 on average. WGF with a large proportion of 34.2% within the analysis range showed a high vegetation index, indicating its role in producing cold air in the HBC region. Although WSF and WCF occupy a small area in the HBC region, they are adjacent to residential and commercial areas. Hence, it is necessary to improve the vegetation index of these two types in order to increase the positive effect of cold air on the HBC region.



(a) (b)

Figure 6. Distribution of wind-connecting forest (WCF) and ventilation network: (**a**) Sejong; (**b**) major areas available for utilizing WCF in HBC region (expressed with satellite image).



(a) (b)

Figure 7. The overall conditions of wind corridor forests in HBC region: (**a**) wind corridor forests; (**b**) vegetation index of wind corridor forests.

3.2. Cold Air Flow

The cold air produced at night was analyzed using the KALM model to understand the overall properties of the wind corridor in Sejong (Figures 8 and 9). The time series analysis of the average speed of cold air flow showed a high value (0.48 m/s) at the initial time (60 min) when cold air was produced, but the value decreased (0.44 m/s) until 180 min. The highest value of 0.49 m/s appeared from 240 to 360 min (Figure 10a). This indicates that the cold air flow was strong in the initial period when the cold air was created in WGFs, but then it gradually stabilized. The wind speed of cold air around Geumgang River became stronger over time. At 360 min after the simulation began, the highest value was 2.15 m/s, appearing at Sejong Lake Park.

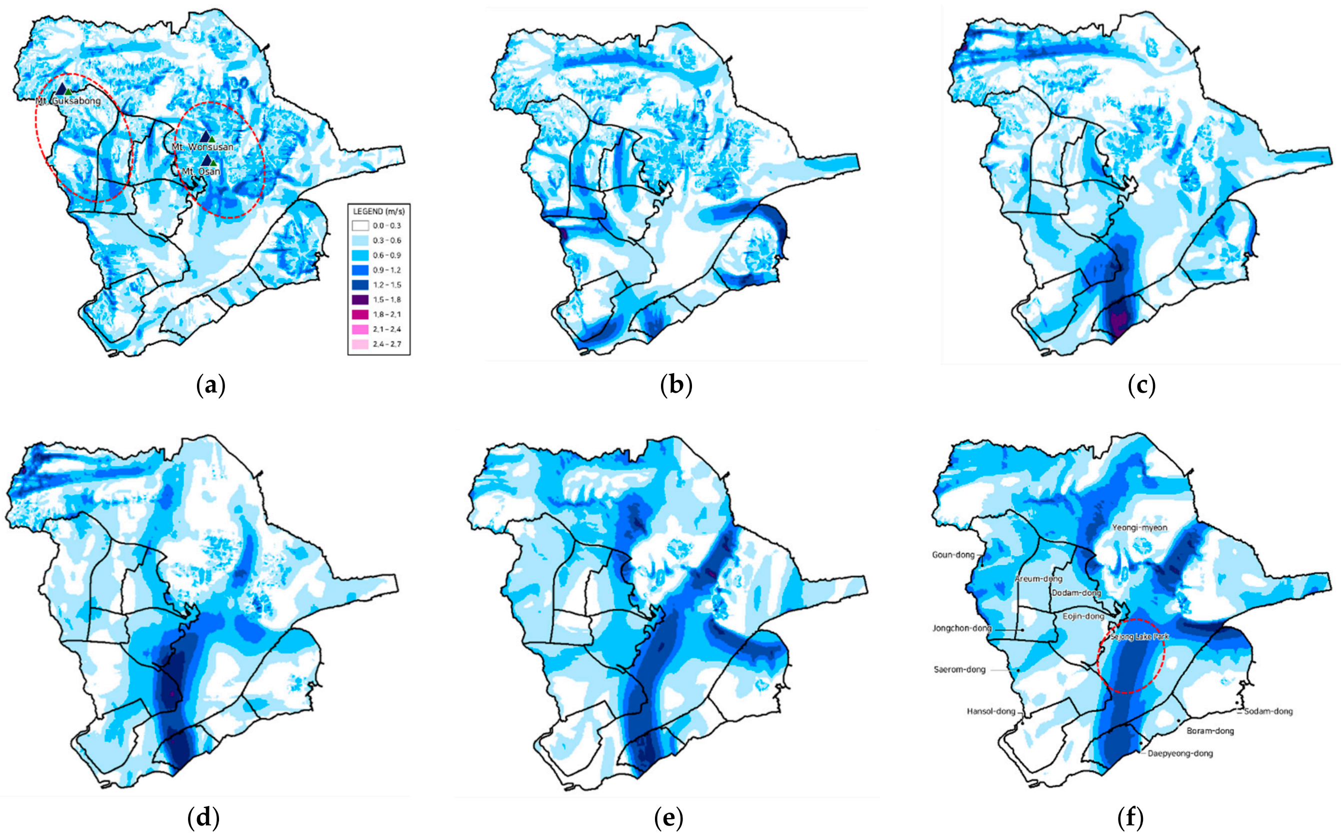


Figure 8. The speed of cold air flow by minute after the start of cold air generation in HBC region: (**a**) 60 min; (**b**) 120 min; (**c**) 180 min; (**d**) 240 min; (**e**) 300 min;(**f**) 360 min.

Regarding the height of the cold-air layer, it was confirmed that the cold-air layers were piling up through valleys in major areas of WGF, such as Mt. Guksabong, Mt. Ohsan, and Mt. Wonsusan, at the initial time of cold air production (60 min). Then, the cold-air layers increased over time and were widely distributed throughout most of HBC region. When comparing the height of cold-air layer by time, the highest and average heights 360 min after the simulation began were 182 m and 115.07 m, respectively. In particular, the generated cold air was piled up high at Sejong Lake Park located in the southeastern part of HBC region (Figure 10b).

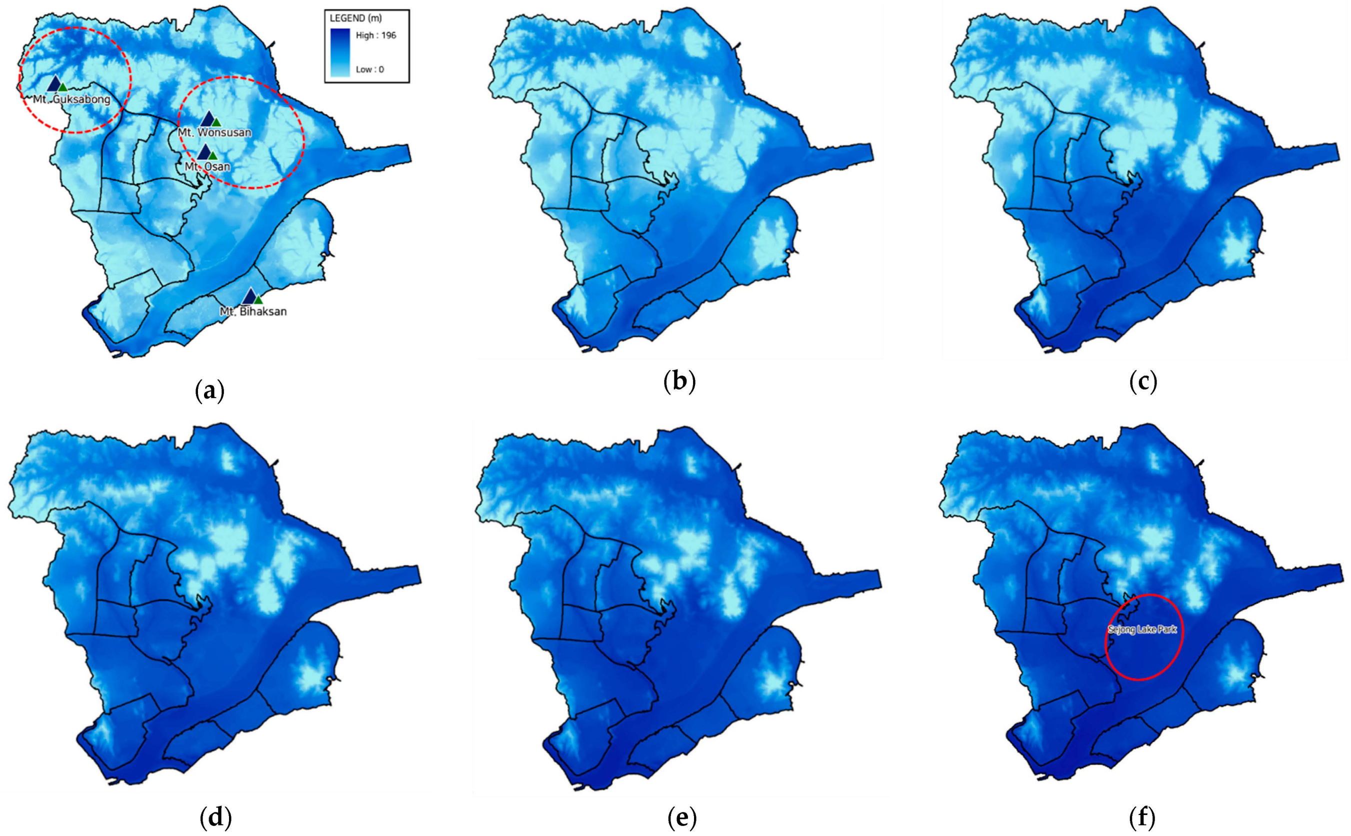


Figure 9. The height of cold air layer by minute after the start of cold air generation in HBC region: (**a**) 60 min; (**b**) 120 min; (**c**) 180 min; (**d**) 240 min; (**e**) 300 min; (**f**) 360 min.

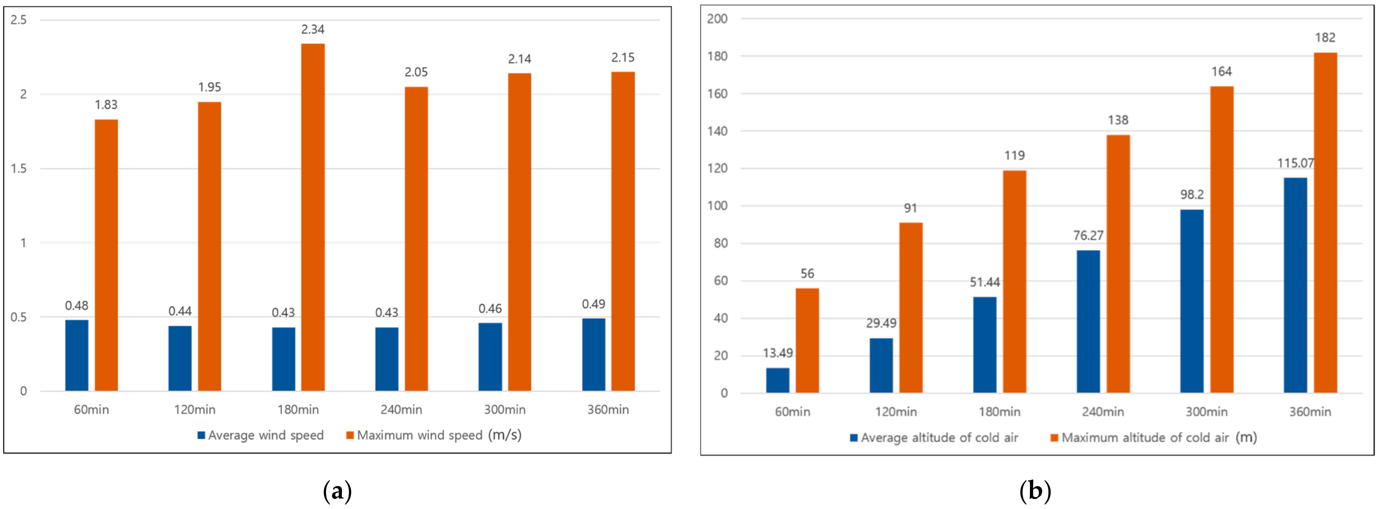
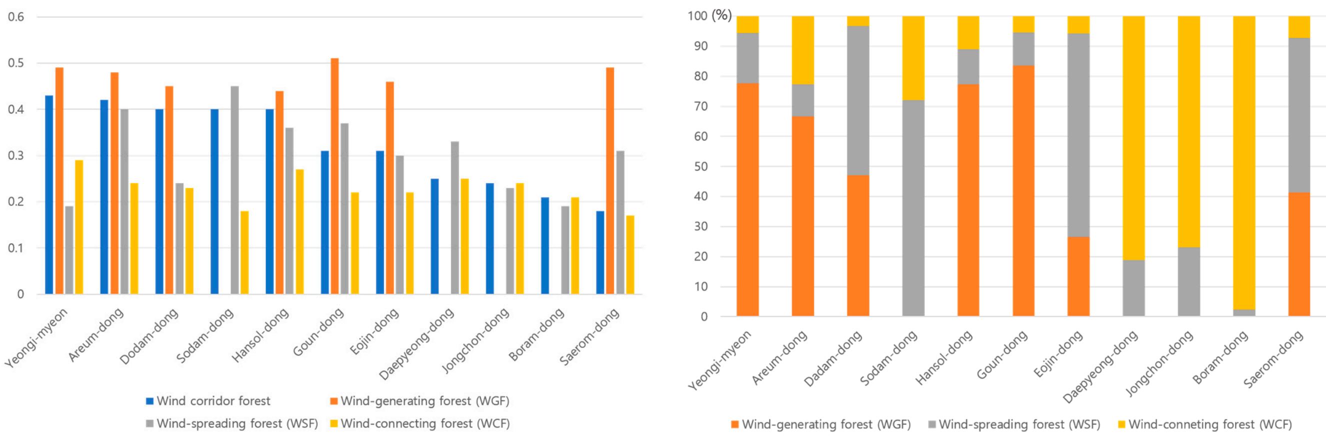


Figure 10. Comparison of cold-air properties by minute after the start of cold air generation: (**a**) changes in cold-air wind speed by time; (**b**) changes in cold-air layer height by time.

3.3. The Comprehensive Analysis of Wind Corridor Forests in HBC Region

According to the analysis of wind corridor forests and cold air flow, it was judged that the HBC region has abundant wind corridor forests and favorable conditions available for cold air flow. However, there were differences in the current status of each region, so detailed analysis is required for each administrative district to suggest a strategy for wind corridor forest planning.

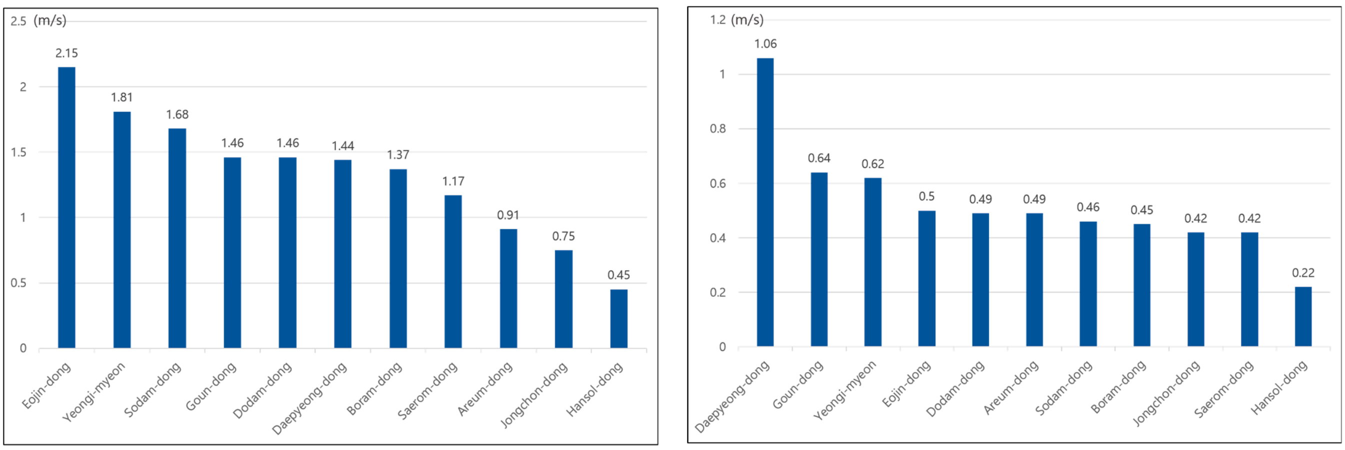
When comparing vegetation index by administrative districts (Figure 11), Yeongi-myeon (0.43) and Areum-dong (0.42) had high values, while Boram-dong (0.21) and Saerom-dong (0.18) had low values. Except for Yeongi-myeon, the indices in the other districts were lower than the average vegetation index of wind corridor forest. Thus, the planning of additional wind corridor forests is critical in order to increase the vegetation index across all regions. We also compared the vegetation index of three types of wind corridor forest according to the administrative district. In order to complement and strengthen the types with lower values, we analyzed the most critical type for each district. The districts where WGF is important are Yeongi-myeon, Goun-dong, and Areum-dong, and those where WSF in needed in advance are Yeongi-myeon, Dodam-dong, Jongchon-dong, and Boram-dong. WCF should be established first in the rest.



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

Figure 11. Comparison of wind corridor forest properties by administrative districts: (**a**) vegetation index of wind corridor forests; (**b**) proportion of three types of wind corridor forest.

When comparing the highest speed of cold air flow by administrative districts (Figure 12), Eojin-dong and Yeongi-myeon had high values, whereas Jongchon-dong and Hansol-dong had low values. The average speed of cold air flow was high in Daepyeong-dong and Goun-dong, and low in Saerom-dong and Hansol-dong. Hansol-dong had the lowest value of both the highest and average speeds. The difference of the average values between Hansol-dong and Daepyeong-dong, which has the highest value of cold air flow, was 0.84 m/s.



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

Figure 12. Comparison of speed of cold air flow by administrative districts at 360 min after the start of cold air generation: (**a**) highest value of cold air flow; (**b**) average value of cold air flow.

4. Planning Strategies for Wind Corridor Forest

Based on the analysis of wind corridor forests and cold air flow in the HBC region, the following presents the strategies to plan for implementing wind corridor forests. According to the consideration of the geographical location and each important type of wind corridor forest in each administrative district, four zones are distinguished: zone A, with Goun-dong, Areum-dong, and Jongchon-dong; zone B, with Dodam-dong and Eojin-dong; zone C, with Hansol-dong and Saerom-dong; and zone D, with Daepyeong-dong, Boram-dong, and Sodam-dong (Figure 13). In zone A, WGFs surround the outskirts, and large areas of WSFs are distributed adjacent to the residential areas. In addition, Goun-dong and Areum-dong are districts with the highest average value of cold air flow. Moreover, Jongchon-dong was also favorable. The wind corridor forests of zone A should strengthen the cold-air flow by securing the connection with WGFs surrounding them and complement the existing WGFs and WSFs. In zone B, there are large WGFs, such as Mt. Ohsan and Mt. Wonsubong, in the northeast of the residential area, and Bangchukchun Stream and major roads cross the residential areas. Furthermore, Eojin-dong is the administrative district with the highest value of cold air flow and also ranks on the top tier in the comparison of average values. For the wind corridor forests of zone B, the function to generate cold air should be strengthened by complementing large WGFs and the WCFs of rivers and roads should be enhanced in consideration of the cold-air flow from the north. Zone C is the zone where the effect of WGFs is weak, but WSFs and WCFs play an important role. Moreover, the districts in zone C have a relatively low speed of cold air flow, especially in Hansol-dong, where the value is considerably low compared to other administrative districts. The wind corridor forests of zone C require planning of WSFs in as many regions as possible as well as WCFs using rivers and major roads connected to zone A. Lastly, zone D has WGFs located in the south of the residential area and a large area of WSFs such as Mt. Goihwasan. In addition, the Geumgang River, which serves as a wind corridor, is adjacent, so the highest speed of cold air flow is considered to have been high in Daepyeong-dong. The average value of zone D is placed in the mid-range. The wind corridor forests of zone D should strengthen the cold-air flow by securing the connection with WGFs and implement WCFs to allow cold air that flows along Geumgang River into the city (Figure 14).

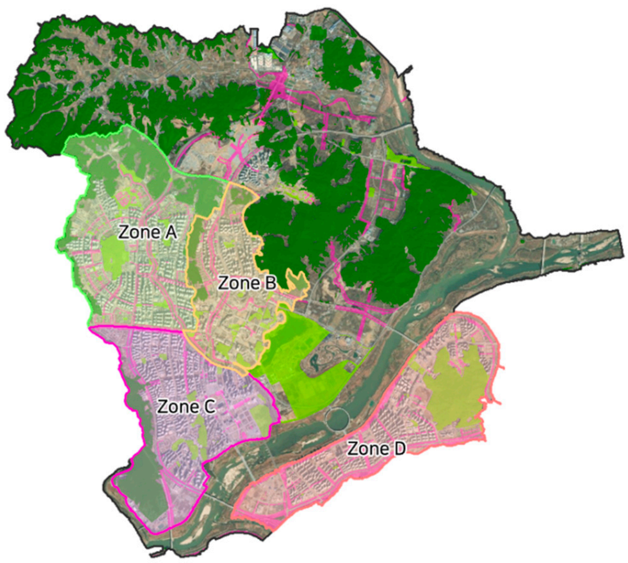
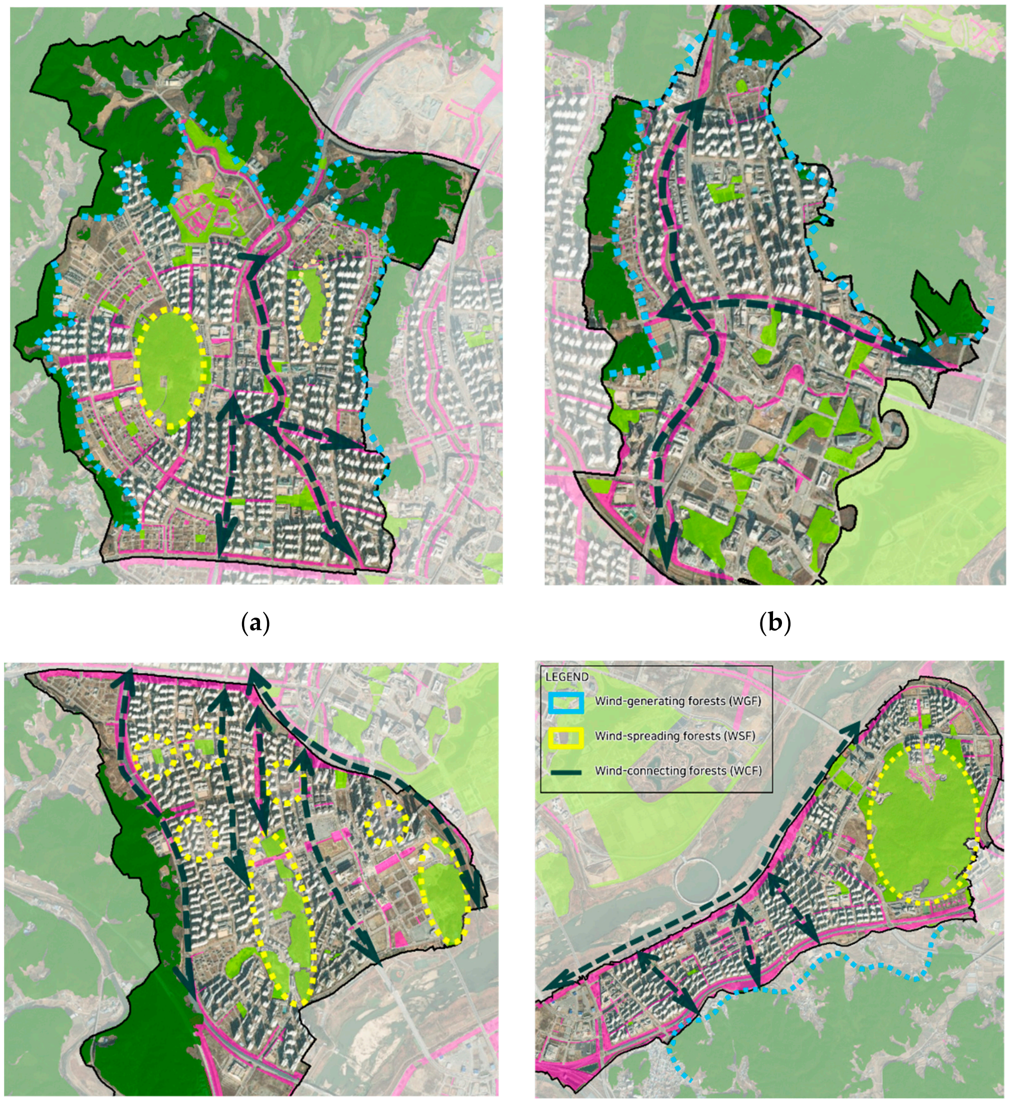


Figure 13. Division of zones for wind corridor forest implantation in HBC region based on administrative districts.



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

(**c**) (**d**)

Figure 14. Strategies for wind corridor forest planning by zone: (**a**) zone A; (**b**) zone B; (**c**) zone C; (**d**) zone D.

Finally, the strategies for planning by three types of wind corridor forests are suggested. WGSs should strengthen the function of wind production through changes in forest structure and vegetation in existing mountainous neighborhood parks. The vegetation index may be increased through dense planting, while decreasing the density of the peripheral areas of WGF so that the generated wind can circulate well. To create forests, the species suitable for climate and soil properties of the target areas should be identified. Damaged forests should be managed and restored to increase their vegetation index. Furthermore, WSFs should be planned in vulnerable districts of cold air flow by creating new urban parks as well as improving existing ones. By complementing planting in the existing urban parks, the production functions of cold air should be enhanced. In addition, the improvement and expansion of green spaces in the existing public institutes and schools should be implemented. Through various green projects, such as green parking lots and demolition of walls, the small area with the function of WSFs should be secured in each administrative district. To allow WSFs to expand the flow of cold air to the surrounding areas, low-rise plants should be planted along the boundaries of WSFs. The land cover of natural pastures, such as grass, should be maintained to secure cold air production functions, and impermeable paving should be removed. WCFs should enhance the function of wind flow connection using roadside trees and riverside green spaces. In the case of roads, the forest planning may be implemented according to guidelines of street tree planting in consideration of the surrounding land use and building structures as well as the conditions of roads such as widths of driveways and sidewalks. Old street trees with a low vegetation index should be replaced, and tree shading should be strengthened by adding a row of new street trees to prevent a rapid increase of surface temperature on the road during the day. In the case of rivers, the ground surface may be covered with grasslands to allow maintaining the function of generating cold air better.

5. Conclusions

This study aims to provide practical planning strategies for implementing wind corridor forests utilizing the properties of cold air with a study area of Sejong recently founded in South Korea. To achieve this goal, the study investigated the current conditions of wind corridor forests and cold air flow across regions in Sejong and carried out a detailed analysis in the HBC region. After dividing the HBC region into four zones based on the analysis results, the study provided strategies for different plans in each zone and set out planning strategies by three types of wind corridor forests.

The HBC region was surrounded by the wind-generating forests (WGF) on the outskirts of the city, and there were major WGFs, such as Mt. Guksabong, Mt. Ohsan, and Mt. Wonsusan, in the north. The WGFs were graded according to the forest density; grade 1, which is classified as forests advantageous for generating cold air, occupies the largest proportion at 68.82%, followed by grade 2 (30.41%) and grade 3 (0.77%). Wind-spreading forests (WSF) were evenly distributed in the form of neighborhood parks. WSFs were graded according to the vegetation index; the mountainous parks with large area were classified as grade 1, and small parks were generally classified as grade 2. The wind-connecting forests (WCF) were well-established in the HBC region, but some areas were disconnected. The ventilation network analysis was carried out to complement the disconnected WCFs. As a result, the study identified available areas where WCFs can be utilized around river areas, such as Geumgang River, Jaechun Stream, and Bangchukchun Stream. The study also identified unfavorable types of wind corridor forests that should be implemented for each administrative district.

The analysis of cold air flow using the cold air analysis model, KALM, was carried out by focusing on the speed of cold air flow and height of cold air layer. Each analysis confirmed the time-series change of value. The height of the cold air layer gradually increased over time, but the speed of the cold air flow increased and decreased repeatedly. In addition, the highest and average speed of cold air flow were compared by administrative district. Eojin-dong and Daepyeong-dong showed high values, while Hansol-dong was the administrative district with low values.

According to the functional characteristics of the HBC region, four zones were distinguished, and the planning strategies suitable for wind corridor forests in each zone were provided. Zone A should strengthen the connection between WGFs surrounding the outskirts and WSFs in the city center. Zone B should complement large WGFs and enhance WCFs of major roads and Bangchukchun Stream. Zone C has disadvantageous wind, and hence, it should secure WSFs and implement WGFs connected to zone A. Lastly, zone D should secure a connection between WGFs located in the south and the Geumgang River located in the north and thus enhance the cold-air flow.

Moreover, the planning strategies for three types of wind corridor forest were also presented. The strategies strengthen each function of wind corridor forests—the wind production of WGF, wind diffusion and generation of WSF, and wind flow connection of WCF. WGFs should be changed in forests' structures and vegetation. WSFs should be planned by creating new urban parks and complement existing urban parks. WCFs should be implemented by using roadside trees and riverside green spaces.

The results of this study can be used as the fundamental data for implementing wind corridor forest projects and utilized as resources for selecting regions to establish wind corridor forests. Moreover, it is expected that the suggestions for planning strategies provided in this study contribute to providing directions for practical planning for wind corridor forests.

This study offered planning strategies for wind corridor forests based on the analysis of wind corridor forests and cold air flow in a target area. However, as the application strategies may differ depending on the target city, it is suggested that the analysis of the properties of the city should be carried out when the strategies are to be made for another region. It is expected that the accumulation of various case studies will lead to creating a guideline for wind corridor forest planning that can be commonly applied for any region. In addition, since the analysis of wind corridor forest in the study is based on the results of simulation, the verification of planning effects is lacking. Thus, future studies should verify the reliability of wind corridor forest analysis using various methods, such as satellite images and field studies. In particular, since the KALM model used for this study analyzed cold air flow occurred from topographical properties and land use conditions on a calm night, it may be different from the actual wind environment of Sejong. In a trailing study, a cold air simulation model that can reflect the synoptic wind conditions will be used to analyze various wind flows for the study area.

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References

1. Eum, J.H.; Scherer, D.; Fehrenbach, U.; Köppel, J.; Wang, J. Integrating urban climate into urban master plans using spatially distributed information—The Seoul example. *Land Use Policy* **2013**, *34*, 223–232. [CrossRef]
2. Son, J.M.; Eum, J.H.; Kim, D.P.; Kwon, J. Management strategies of thermal environment in urban area using the cooling function of the mountains: A case study of the Honam Jeongmaek areas in South Korea. *Sustainability* **2018**, *10*, 4691. [CrossRef]
3. Eum, J.H.; Kim, K.; Jung, E.H.; Rho, P. Evaluation and utilization of thermal environment associated with policy: A case study of Daegu Metropolitan City in South Korea. *Sustainability* **2018**, *10*, 1179. [CrossRef]
4. Kolokotroni, M.; Giridharan, R. Urban heat island intensity in London: An investigation of the impact of physical characteristics on changes in outdoor air temperature during summer. *Sol. Energy* **2008**, *82*, 986–998. [CrossRef]
5. Zhao, L.; Lee, X.; Smith, R.B.; Oleson, K. Strong contributions of local background climate to urban heat islands. *Nature* **2014**, *511*, 216–219. [CrossRef] [PubMed]
6. Koh, B.; Kim, E.A. Comparative analysis of urban road dust compositions in relation to their potential human health impacts. *Environ. Pollut.* **2019**, *255*, 113156. [CrossRef]
7. Kwon, M.Y.; Lee, J.S.; Park, S. The effect of outdoor air pollutants and greenness on allergic rhinitis incidence rates: A cross-sectional study in Seoul, Korea. *Int. J. Sustain. Dev. World Ecol.* **2019**, *26*, 258–267. [CrossRef]
8. Kim, H.; Hong, S. Differences in the Influence of Microclimate on Pedestrian Volume According to Land-Use. *Land* **2021**, *10*, 37. [CrossRef]
9. IQAir. 2019 World Air Quality Report Region & City Pm2.5 Ranking. Available online: https://www.greenpeace.org/static/planet4-thailand-stateless/2020/02/91ab34b8-2019-world-air-report.pdf (accessed on 10 March 2021).
10. Eum, J.H.; Scherer, D.; Fehrenbach, U.; Woo, J.H. Development of an urban landcover classification scheme suitable for representing climatic conditions in a densely built-up Asian megacity. *Landsc. Urban Plan.* **2011**, *103*, 362–371. [CrossRef]
11. Verein Deutscher Ingenieure. Environmental meteorology-local cold air. In *VDI Guideline 3787, Part 5*; Beuth: Berlin, Germany, 2003; Volume 85, pp. 14–29.
12. Sievers, U.; Kossmann, M. The cold air drainage model KLAM_21-Model formulation and comparison with observations. *Weather Clim.* **2016**, *36*, 2–24. [CrossRef]
13. Ren, C.; Yang, R.; Cheng, C.; Xing, P.; Fang, X.; Zhang, S.; Wang, H.; Shi, Y.; Zhang, X.; Kwok, Y.T.; et al. Creating breathing cities by adopting urban ventilation assessment and wind corridor plan–the implementation in Chinese cities. *J. Wind. Eng. Ind. Aerodyn.* **2018**, *182*, 170–188. [CrossRef]
14. Wong, M.S.; Nichol, J.E.; To, P.H.; Wang, J. A simple method for designation of urban ventilation corridors and its application to urban heat island analysis. *Build. Environ.* **2010**, *45*, 1880–1889. [CrossRef]

15. Grunwald, L.; Kossmann, M.; Weber, S. Mapping urban cold-air paths in a Central European city using numerical modelling and geospatial analysis. *Urban Clim.* **2019**, *29*, 100503. [CrossRef]
16. Grunwald, L.; Schneider, A.K.; Schroeder, B.; Weber, S. Predicting urban cold-air paths using boosted regression trees. *Landsc. Urban Plan.* **2020**, *201*, 103843. [CrossRef]
17. Eum, J.H.; Oh, J.H.; Son, J.M.; Kim, K.; Baek, J.B.; Lee, C.Y. Analysis Schemes of Wind Ventilation Forest Types-A Case Study of Daegu Metropolitan City. *J. Korean Assoc. Geogr. Inf. Stud.* **2019**, *22*, 12–23. (In Korean)
18. Jang, G.S.; Eum, J.H.; Son, J.M.; Baek, J.B.; Sung, W.J.; Kim, J.E.; Kim, S.H. *Application of Wind Ventilation Corridor Model in Urban Forest Planning and Management*; National Institute of Forest Science: Daejeon, Korea, 2019; pp. 1–82. (In Korean)
19. Son, J.M.; Eum, J.H.; Sung, U.J.; Baek, J.B.; Kim, J.E.; Oh, J.H. A Proposal of Direction of Wind Ventilation Forest through Urban Condition Analysis-A Case Study of Pyeongtaek-si. *J. Korean Assoc. Geogr. Inf. Stud.* **2020**, *23*, 101–119. (In Korean)
20. Goldblatt, R.; Adda, A.; Crull, D.; Maghrabi, A.; Levin, G.G.; Rubinyi, S. Remotely sensed derived land surface temperature (LST) as a proxy for air temperature and thermal comfort at a small geographical scale. *Land* **2021**, *10*, 410. [CrossRef]
21. Sachsen, T.G.; Schneider, C. The effect of vegetation on suburban ventilation paths: Studies on cold air drainage in the city of Aachen. *RWTH Aachen Univ.* **2014**, *229*, 229472. (In German)
22. Sievers, U. *Das Kaltluftabflussmodell KLAM_21: Theoretisch Grundlagen, Anwendung und Handhabung des PC-Modells*; Deutscher Wetterdienst: Offenbach, Germany, 2005.
23. Schädler, G.; Lohmeyer, A. Simulation of nocturnal drainage flows on personal computers. *Meteorol. Zeitshrift* **1994**, *3*, 167–171. [CrossRef]
24. Eum, J.H.; Son, J.M. Management of the Nakdong-Jeongmaek based on the characteristics of Cold Air–Focused on Busan, Ulsan, Pohang. *J. Korean Inst. Landsc. Archit.* **2016**, *44*, 103–115. (In Korean) [CrossRef]
25. Eum, J.H. Management Strategies of Local Cold Air in Jeongmaek for utilizing urban Ventilation Corridor—A Case Study of the Nak-nam Jeongmaek. *J. Korean Assoc. Geogr. Inf. Stud.* **2019**, *22*, 154–167. (In Korean)
26. Eum, J.H. Integration of Climate Information into Spatial Planning in Seoul, South Korea. Ph.D. Thesis, Technische Universität Berlin, Berlin, Germany, 14 April 2008.
27. Son, J.M.; Eum, J.H. Analysis and management strategies of the cold air characteristics in Hannnamgeumbuk-jeongmaek and Geumbuk-jeongmaek. *J. Korean Assoc. Geogr. Inf. Stud.* **2019**, *22*, 152–171. (In Korean)