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Can Forest Restoration Enhance the Water Supply to Respond to Climate Change?—The Case of North Korea

Hyun-Chul Yeo [1,2] and Chul-Hee Lim [1,2,*]

[1] College of General Education, Kookmin University, 77 Jeongneungro, Seongbukgu, Seoul 02707, Korea
[2] Future Korea Institute, Kookmin University, 77 Jeongneungro, Seongbukgu, Seoul 02707, Korea
* Correspondence: clim@kookmin.ac.kr

Abstract: North Korea is a representative country that should restore its forest ecosystem, which is vital for responding to climate change. In this study, we assessed the extent to which afforestation can reduce the climate change impact on water resources by adding an afforestation scenario to the variables used to estimate the forest water yield. We applied the InVEST seasonal water yield model and constructed a data ensemble of the SSP5–8.5 scenario for this simulation. In the projection of future forest water supply according to the SSP5–8.5 scenario, baseflow and local recharge decreased by approximately 25%, and quickflow increased by approximately 47%, compared to the baseline period. Under the three reforestation scenarios, the future water supply from the forests showed significant positive changes. The baseflow increased by approximately 4%, 15%, and 28% in the reforestation scenario of Level 1, Level 2, and Level 3, respectively. In a Level 3 scenario, most of the baseflow and local recharge, which had decreased owing to the impact of climate change, was recovered. The baseflow in Level 3 was 26,882 million $m^3\ y^{-1}$, which was approximately 98% of that in the baseline period. The Taedong River and Chongchon River, which are the major granary areas in North Korea, were directly affected by the climate change. However, it was confirmed that the water supply in these areas can be increased through forest restoration. These results indicate the deterministic role of forest restoration in increasing the water supply.

Keywords: forest water supply; North Korea; afforestation; climate change; InVEST seasonal water yield

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1. Introduction

Every year, record climatic disasters occur worldwide [1,2]. In 2020, the longest rainy season in the history occurred in the Korean Peninsula in East Asia, leading to significant flood damage [3]. In 2021, more than 200 people died in a summer torrential rain, never experienced before in developed European countries, such as Belgium, Germany, and the Netherlands [4,5]. In 2022, severe drought and heatwaves hit several countries around the world. Although these climatic events were overshadowed by the COVID-19 pandemic, the era of a climate crisis has truly begun.

Climate disasters are most represented as hydrological disasters. In the dry season, drought intensifies and in the rainy season, heavy rain and strong typhoons cause havoc. Even in the monsoon climate of East Asia, which has a high precipitation seasonality, hydrological changes are outstanding [6,7]. Recently, East Asia suffered excessive damage due to heavy rains and typhoons in the summer, and according to the Coupled Model Intercomparison Project (Phase 6) (CMIP6) simulated datasets, high precipitation is anticipated to increase by up to 30% or more in the second half of the twenty-first century [8]. Increasing evapotranspiration due to high temperatures as well as long meteorological drought periods are also foreseen for East Asia [9,10]. In the end, although greenhouse gas reduction is necessary for minimizing climatic disasters, adaptation is vital for hydrological changes that have already begun.

Forests play a critical role in countering climate crisis by being a carbon sink and are a major factor that influence climate-change-adaptation strategies [11,12]. In particular, forests are the largest water source on land, and thus have a major function in water resource management [13,14]. Healthy forests reduce direct runoff during torrential rains, preventing flooding as well as reducing landslides and soil loss [15,16]. In other words, forests are the most suitable nature-based solution for adapting to hydrological changes.

In East Asia, where hydrological changes are expected, prominent changes in forest dynamics are observed in North Korea [17]. In North Korea, the overall forest cover rapidly degraded from the 1990s to the 2000s [18], and various studies and policies for forest restoration began in the 2010s [19,20]. Despite extensive efforts, most of the forests remain hitherto unrestored, although a goal has been set to restore the forests to pre-deforestation levels by the 2040s [19]. Recently, a potential reduction in the available water resources as well as an increase in soil runoff by water due to deforestation was investigated in North Korea [14,21]. Moreover, the recent frequent floods and drought damage are also expected to be related effects. In other words, deforestation-related climatic changes are expected to be most noticeable in North Korea, and accordingly, the country needs to develop strong strategies to respond to climate change through forest restoration.

This study was conducted with the aim of confirming the amount of forest restoration required to maintain as well as enhance the water supply under extreme hydrological changes due to climate change, through a spatial model. In particular, we intended to confirm the change in the forest water supply due to climate change and forest restoration in North Korea, which is actively planning and promoting forest restoration. The effect of forest restoration was evaluated both spatially and numerically. Furthermore, afforestation scenarios are presented, in this paper, according to the intensity of forest restoration, and the effect of water supply according to the level of forest restoration is compared. Ultimately, our findings will contribute to recognizing the justification of forest restoration, and the suggested the positive effects of forest restoration are expected to aid in speeding up the restoration process.

2. Data and Methods

2.1. Study Area

The Korean Peninsula located in Eastern Asia corresponds to the mid-latitude region, and North Korea occupies the northern half of the peninsula. North Korea covers an area of approximately 122,000 km^2 and is located explicitly at 37.41° N–43.01° N and 128.17° E–130.41° E. Topographically, it has mountainous areas in the Northeast and plains in the Western part. The Baekdudaegan mountainous region runs from the north to the south along the eastern coast [22,23]. The Kaema Plateau, which is the highest region in the Korean Peninsula and the Baekdu mountains are situated in the Northern part of the country. Mountains and uplands cover approximately 80% of North Korea's land [17]. Because of these topographical characteristics, many streams flow westward, making large watersheds and giving rise to plains and basins that are suitable for agricultural activities. The Yalu river basin is the largest watershed, and the Taedong river basin and Chongchon river basin have the largest cropland (Figure 1a).

The annual average temperature and precipitation are 10 °C and 1000 mm, respectively [23]. Although North Korea has a temperate monsoon climate, it is highly influenced by the Asian continent due to its high latitude. Winters are cold and dry, and summer is characterized by high temperatures and heavy precipitations. According to the future climate projections, temperatures are expected to rise above the global average, and precipitation is also expected to increase drastically. However, the increase in rainfall intensity is expected to be more significant than the increase in precipitation; moreover, the winter and spring droughts are also expected to increase [9,24].

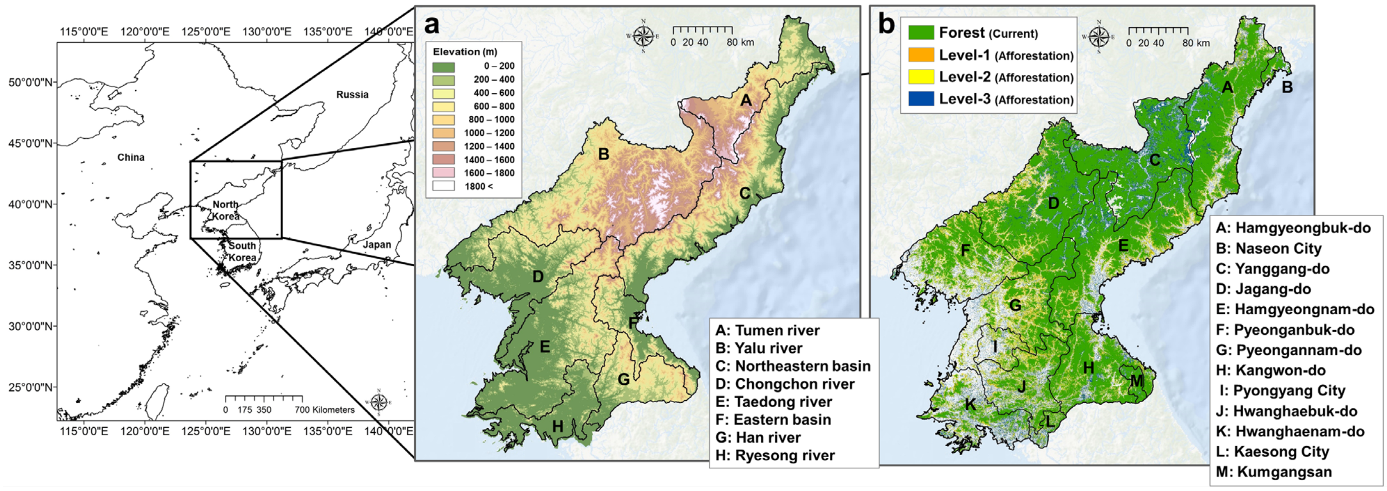

Figure 1. (**a**) Elevation of the study area with the main watershed boundaries and (**b**) forest cover and afforestation levels with administration boundaries.

In North Korea, deforestation has been rampant since the 1990s, and 25%–30% of forest land has been reclaimed for agricultural activities or has become mountains without trees [18,25] (Figure 1b). However, since the regime of Kim Jong-un, an active forest restoration policy has been framed, and forest restoration has been actively promoted in the country [19]. North Korea's forest policy aims to create 2.2 million ha of forest cover by the 2040s. This corresponds to restoring most of the area that was degraded since the 1980s.

2.2. Method

2.2.1. InVEST Seasonal Water Yield Model

The InVEST model is an effective toolset for spatially assessing ecosystem functions and services. Since its development by the Natural Capital Project in the United States [26], it has been widely used in many countries, including South Korea [13,27] and North Korea [14]. The InVEST model deals with diverse ecosystem services and includes dozens of sub-models, such as water yield, carbon sequestration, habitat quality, timber production, and marine water quality.

In this study, we used the seasonal water yield (SWY) sub-model of InVEST to estimate the water supply of the forests in North Korea. In previous studies in which the water yield in the Korean Peninsula was evaluated using the InVEST model, only the annual water yield model was applied for calculating the water flow. Although the InVEST annual water yield model enables the calculation of the total water yield for a grid or basin, in many regions an understanding of the associated seasonal flows, especially during the dry and rainy seasons, is mandatory. The InVEST SWY model can provide both the baseflow and quickflow (QF) by considering the seasonal hydrological systems [28]. In addition, the InVEST SWY model was successfully applied in various regions, such as India, Myanmar, and Peru [29,30]. In particular, the SWY model could be effective for assessing the situation in the Korean peninsula, where the seasonality of precipitation is extreme.

The InVEST SWY model produces various outputs, such as monthly and annual QFs as well as annual local recharge, baseflow, and cumulative streamflow for each indicator, as raster data, and for each watershed level, that aid in understanding the local hydrological systems. Among these, we used the annual QF, local recharge, and baseflow for this simulation. Here, seasonality according to monthly hydrological characteristics is reflected in annual QF, local recharge, and baseflow, unlike water yield in the existing water yield model.

The QF is calculated based on the curve number (CN), which uses the mean event depth, monthly precipitation, and number of rain events per month at a given pixel, and assumes an exponential distribution of the daily precipitation depths on days with rain [31].

A higher CN value indicates a higher potential runoff, and lower CN values indicate a higher probability of infiltration. Details of the QF calculation process are described in the model documentation [26].

The local recharge, which implies a potential contribution to baseflow, is computed from the local water balance. Precipitation that does not runoff as QF and is not evapotranspired by the vegetation on each grid can infiltrate the soil to become the local recharge. The local recharge indicator is calculated on an annual timescale, but the values derived from monthly water budgets are applied. The specific equation of local recharge is as follows.

$$L_i = P_i - QF_i - AET_i \tag{1}$$

where L is the local recharge, P is precipitation, QF is quick flow, AET is the actual evapotranspiration, and i refers to each spatial grid.

The baseflow indicator describes the water that reaches the stream during the dry season. A negative local recharge indicates that the spatial grid does not contribute to the baseflow, and therefore it becomes zero. Further, if the spatial grid contributes to groundwater recharge, then the baseflow is a function of the amount of flow leaving the grid and the relative contribution of this grid to the recharge. The baseflow can be directly derived from the ratio of the cumulative baseflow exiting cell i with respect to the available recharge to the upstream accumulative recharge:

$$B_i = max\left(B_{sum,i} \cdot \frac{L_i}{L_{sum,i}}, 0\right) \tag{2}$$

where B is baseflow, L is the local recharge, and i refers to each spatial grid.

2.2.2. Spatial Construction of the Afforestation Scenario

We set up North Korea's forest restoration scenario at three levels. We followed the land cover classification and afforestation target area of Kim et al. [25] and assumed that a maximum of 2.6 million ha is restored based on this. Kim et al. [25] classified the latest deforestation area in North Korea using the Sentinel-2 satellite image and deep learning techniques in 2018. Six priority levels for the afforestation target areas were classified based on the type of deforested land as well as the topographical factors. However, in this study, the six classified levels were merged into three stages. The current forest area is about 7 million ha out of which 550,000 ha in Level 1, 1.41 million ha in Level 2, and 2.61 million ha in Level 3 are reforested (Table 1). If the forest restoration in North Korea proceeds according to the current trend, then the reforested forest land is expected to be slightly larger than that in Level 1, and if the total forest construction plan is successfully implemented, then it is anticipated to be close to that in Level 3. Based on this data, the changes in the water yield according to North Korea's forest policy and restoration intensity can be confirmed.

Table 1. Classification of the afforestation scenario with its amount by implementation level.

Class	Baseline	Afforestation Level 1	Afforestation Level 2	Afforestation Level 3
Afforestation area	-	551,839	1,416,051	2,610,308
Total Forest area	7,024,677	7,576,516	8,440,728	9,634,985

The temporal range is divided into a baseline period and a future period. In the baseline period, the climate data from 1981 to 2010 is used to indicate the current climate value, as well as the land classification information in 2018. For the future period, the climate data from 2041 to 2070 and an afforestation scenario (Level 1 to 3) according to the level of forest restoration in the 2040s are used. The North Korean afforestation plan referred to as the reference is until the 2040s, however, the effect of afforestation will be the largest 10–20 years later. Therefore, the future climate period was selected as 2041–2070.

2.2.3. Model Performance Evaluation

Data observation and access to quantitative water flow are not possible for North Korea. Therefore, we used the water supply potential (WSP) concept suggested by Kim et al. [13]. In several previous studies targeting North Korea, the flow rate verification was successful through WSP. The water supply potential can be defined as the difference between the annual precipitation and actual evapotranspiration (AET) [14]. The annual precipitation is the total amount of water input, and AET reveals the total amount of water used by the forest or each land use. Therefore, this gap refers to the maximum amount of water supply from the forests [13]. The accuracy of the water yield in forests was assessed using a determined coefficient (R^2) based on a simple linear regression analysis of the simulated water yield and WSP.

In addition, the performance of the model was evaluated by comparing the results obtained using this model with those reported previously for North Korea. Moreover, comparative verification of our results was performed with those obtained in similar previously verified studies. Lim et al. [14] simulated the changes in the water supply of North Korean forests in the 1980s and 2000s. Further, Lim [7] simulated changes in the forest water supply from 1981 to 2010 and used this simulated data to predict future climate change. In the case of model sensitivity, the sensitivity analysis result of Kim et al. [13] and Redhaed et al. [32] is followed. In particular, Kim et al. [13] conducted sensitivity analysis on South Korea, therefore no separate sensitivity analysis was performed in this study.

2.3. Data

2.3.1. Input Data for the InVEST Seasonal Water Yield Model

The InVEST SWY model requires six input data and several components as follows: monthly precipitation, monthly potential evapotranspiration (PET), land use, digital elevation model (DEM), soil hydrologic group, and area of interest (such as watersheds, biophysical table, rain event table, and several parameters). These data describe meteorological characteristics, topographical and soil conditions, and spatial features in each pixel.

The soil hydrologic group data was collected from the Oak Ridge National Laboratory (ORNL). HYSOGs250m of the ORNL-DAAC was utilized, which represents the global layers of the hydrologic soil group. The DEM data were obtained at 7.5 arc-second (approximately 250 m) resolution from the Global Multi-resolution Terrain Elevation Data of the United States Geological Survey. For the land-use data, land cover maps classified by Kim et al. [25] were used. This land cover map was produced through multi-spectral images obtained using the Sentinel-2 satellite and deep learning techniques in 2018. We used the forests and degraded areas indicated in these image data. All the spatial datasets were resampled to 1 km^2 by the nearest neighbor resampling method.

The biophysical table includes the K_c coefficient and CN by land use. For the forested areas, we adopted $K_c = 0.77$ based on the forest K_c coefficients published by the National Institute of Forest Science in South Korea [33]. This K_c coefficient was measured in the northern forests of Gyeonggi-do in South Korea adjacent to North Korea, therefore it has significant applicability to the North Korean forests. In addition, Lim et al. [14], Lim [7], etc. have been applied and verified in previous studies for this coefficient. The CN for each soil type and land use was set based on the USDA Natural Resources Conservation Service data [34].

For the rain event table, the data related to the number of days of precipitation in North Korea were provided by the Korea Meteorological Administration. This data was further processed into monthly data and then used in our simulation model-based analysis. In the case of future rain event, it was calculated through the precipitation days information of the SSP5–8.5 scenario. Furthermore, the InVEST-SWY model requires alpha, beta, and gamma parameters. The alpha parameter was deduced from the monthly precipitation contribution, which was calculated by considering the seasonality of precipitation in the Korean Peninsula. The future alpha parameter was re-calculated based on the SSP5–8.5 scenario. However, the beta and gamma parameters were set as representative values because of the spatial complexity of this study, which was focused on the entire country of North Korea.

2.3.2. Climate Data

For the climate data, the climatologies at high resolution for the Earth's land surface areas (CHELSA) dataset [35] for the baseline (1981–2010) and future periods (2041–2070) was used. The monthly precipitation was used directly, and the monthly average temperature, maximum temperature, minimum temperature, and solar radiation were applied to calculate the PET value. For the future periods, SSP5–8.5 scenarios, obtained from the representative Global Circular Model (GCM), were used. SSP5–8.5, the scenario in which the highest greenhouse gas concentration is responsible for the climate change, is a future climate scenario used in the CMIP6 system. Although various SSP climate scenarios exist, the effect of forest restoration was evaluated by selecting the SSP5–8.5 scenario with the largest hydrological change in the Korean Peninsula. Five types of GCM data were used: GFDL-ESM4, UKESM1-0-LL, MPI-ESM1-2-HR, IPSL-CM6A-LR, and MRI-ESM2-0. We created one monthly dataset as an ensemble of five of the GCM data. The CHELSA climate dataset provides up to 30 arc-second spatial resolution. Therefore, we reprocessed it to 1 km^2 using the nearest neighbor resampling technique.

The Hargreaves method was applied to calculate the PET of the baseline and future periods. The Hargreaves equation, which is an empirical equation based on temperature, was proposed in 1975 and then modified in 1985 [36]:

$$\mathrm{PET} = 0.0023 \times \mathrm{R_a} \times \mathrm{TD}^{0.5}\ (\mathrm{TC}\ + 17.8) \tag{3}$$

where TD represents the range of monthly temperatures based on the minimum and maximum temperatures (°C), TC is the monthly average temperature (°C), and R_a is the solar radiance (MJ m^{-2}). The details of the Hargreaves equation are reported in [10,36].

3. Results and Discussion

3.1. Evaluation of Model Performance for SWY of North Korea

The InVEST SWY model accurately estimated the forest water yield in terms of the coefficients of determination. The annual water yield was calculated by combining the QF and the baseflow, and plotted with the WSP, which was determined as the difference between the annual precipitation and the AET. The estimated water yield from the forest well fitted measured values. Despite the grid-level analysis, it showed high accuracy. The coefficient of determination for all of North Korea is 0.978 (Figure 2a).

The studies on North Korea reported to date were focused on an approach similar to our InVEST SWY model. Comparative verification was possible using the total amount of water supply forecasted across North Korea based on the InVEST annual water yield model. In our case, the total annual water supply from the forests was 33,056 million m^3 y^{-1}. Lim et al. [14] found that the total forest water supply in North Korea was 34,840 million m^3 y^{-1} in the 1980s (pre-deforestation era) and 20,477 million m^3 y^{-1} in the 2000s (post-deforestation era) (Figure 2b), resulting in a decrease in the amount of supply due to a decrease in the forest area. The decrease in the water supply reported by Lim et al. [14] was more than that observed in this study because the deforestation area considered in our study was wider than that considered by Lim et al. Lim [7] suggested that the total forest water supply in North Korea was 30,189 million m^3 y^{-1} in the baseline period (Figure 2b), which was the same as that adopted in our study. Accordingly, we could compare our results with those of Lim [7] and verify them. Although the climate data processing method and model calculation procedure were different, they showed similar values in a broad framework. Our results were confirmed reasonable even in comparative verification of the existing verified studies.

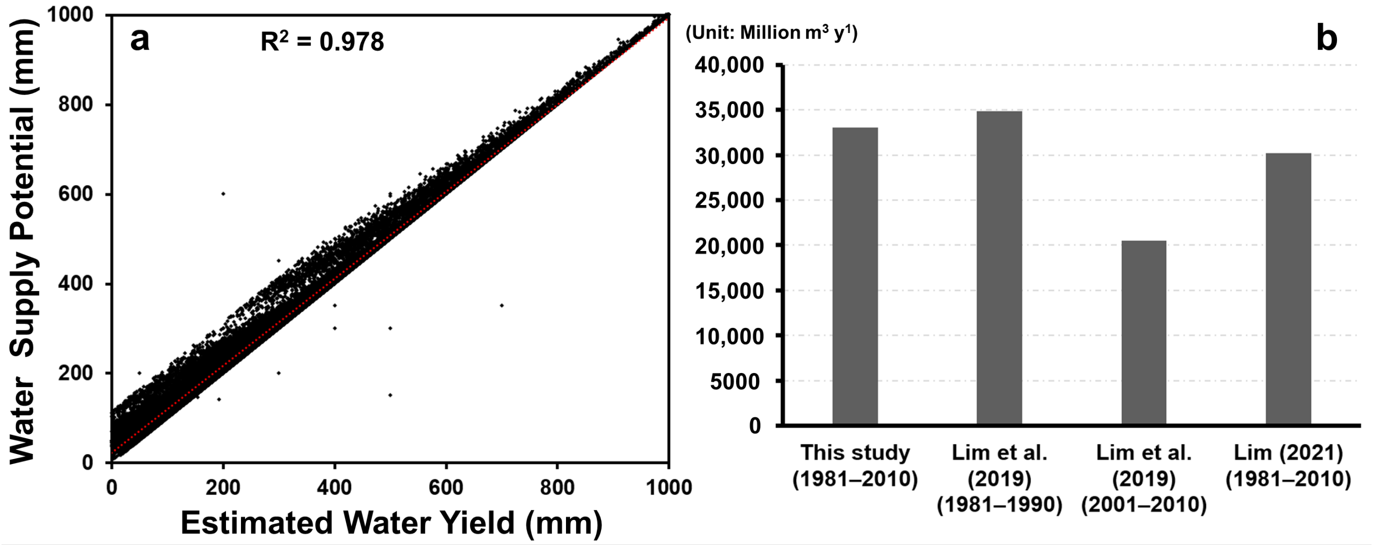

Figure 2. Evaluation of model performance (**a**): statistical evaluation with WSP, (**b**): quantitative comparison with previously reported models.

3.2. Estimating the Forest Water Supply of North Korea in the Baseline Period

In the baseline period, three indicators were estimated: QF, baseflow, and local recharge. First, baseflow and local recharge showed similar levels both quantitatively and spatially. In the central mountainous region and the Kangwon-do region, with many mountainous regions and high rainfall, the baseflow and local recharge were markedly higher. In the case of the Northeast region, the distribution was higher than the median value only in the high-altitude region, which is thought to be because of topographical precipitation and low evapotranspiration (Figures 3a and 4a). There was no significant difference in the numerical values of the total amount of baseflow and local recharge, and it was confirmed that the forests of North Korea are slowly supplying approximately 2700 million m^3 y^{-1} of water (Table 2).

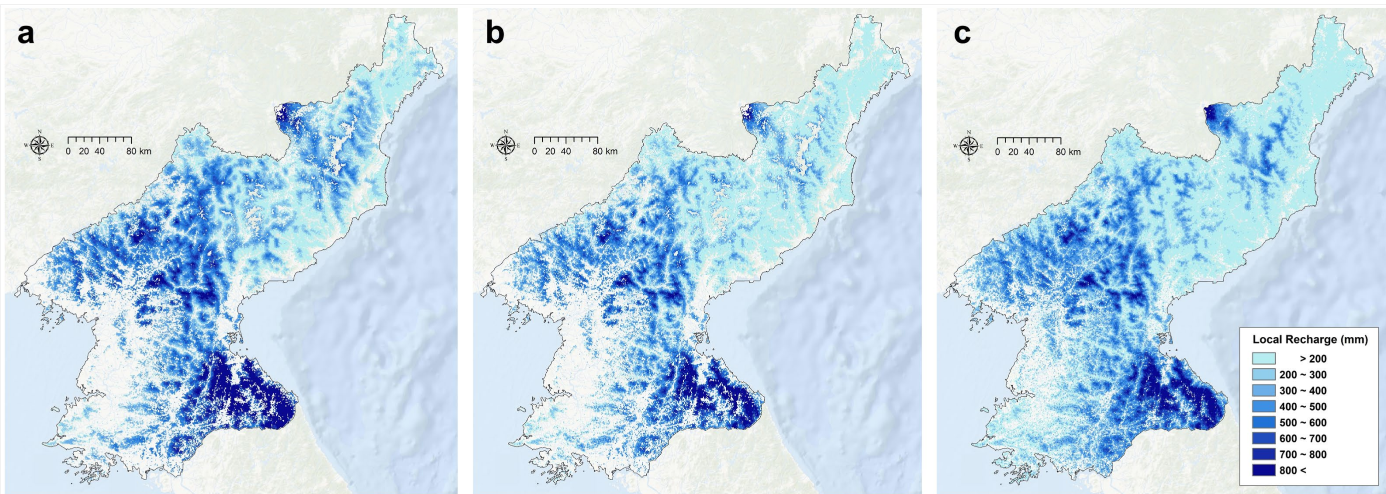

Figure 3. Spatial distribution of local recharge (L) in the forest area: (**a**) baseline period (1981–2010), (**b**) climate change (2041–2070), and (**c**) climate and afforestation scenario (Level 3, 2041–2070).

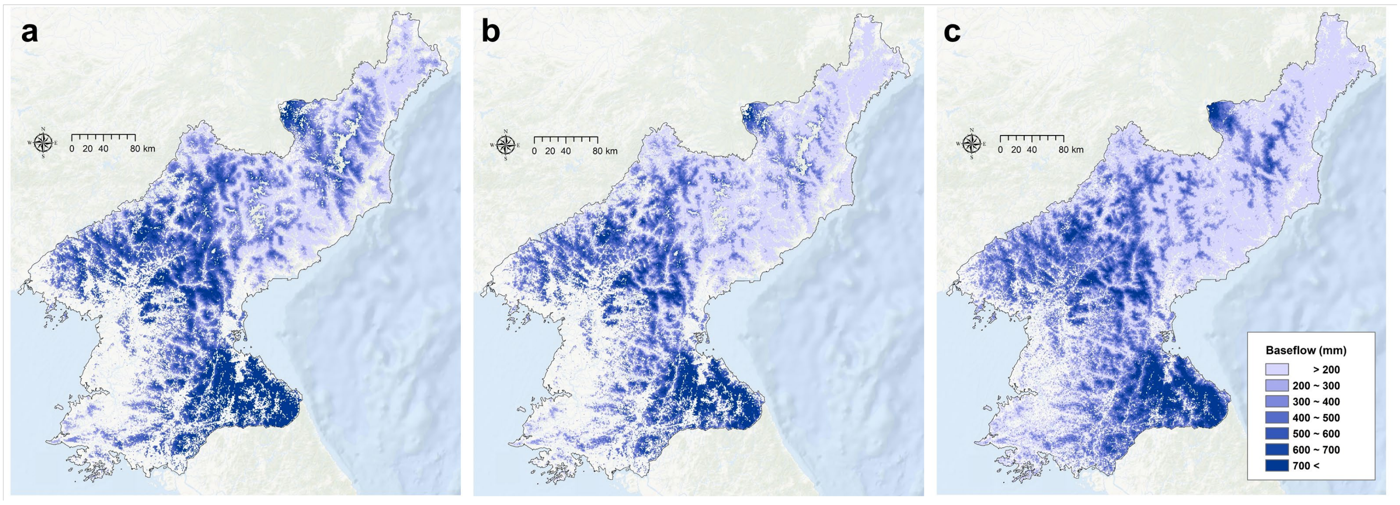

Figure 4. Spatial distribution of baseflow (B) in forest area: (**a**) baseline period (1981–2010), (**b**) climate change (2041–2070), and (**c**) climate and afforestation scenario (Level 3, 2041–2070).

Table 2. Water flow statistics of baseline period and future climate and each afforestation period (million m^3 y^{-1}).

Water Flow Category	Baseline	Only Climate Change	Afforestation Level 1	Afforestation Level 2	Afforestation Level 3
QF	5612	8210	8782	10,029	11,522
Local Recharge	27,169	20,629	21,333	23,582	26,206
Baseflow	27,444	20,972	21,762	24,103	26,882
Total water supply	33,056	29,183	30,544	34,132	38,404

Further, the central and western regions, centered at Kangwon-do, where the precipitation was high, exhibited relatively high QFs (Figure 5a). A higher precipitation resulted in an increased runoff. The Kaema Plateau and the Northeast region showed a low QF because of negligible torrential rains. According to the numerical total, approximately 5600 million m^3 y^{-1} of water is rapidly flowing out of the forests of North Korea (Table 2); this is 17% of the total annual forest water supply.

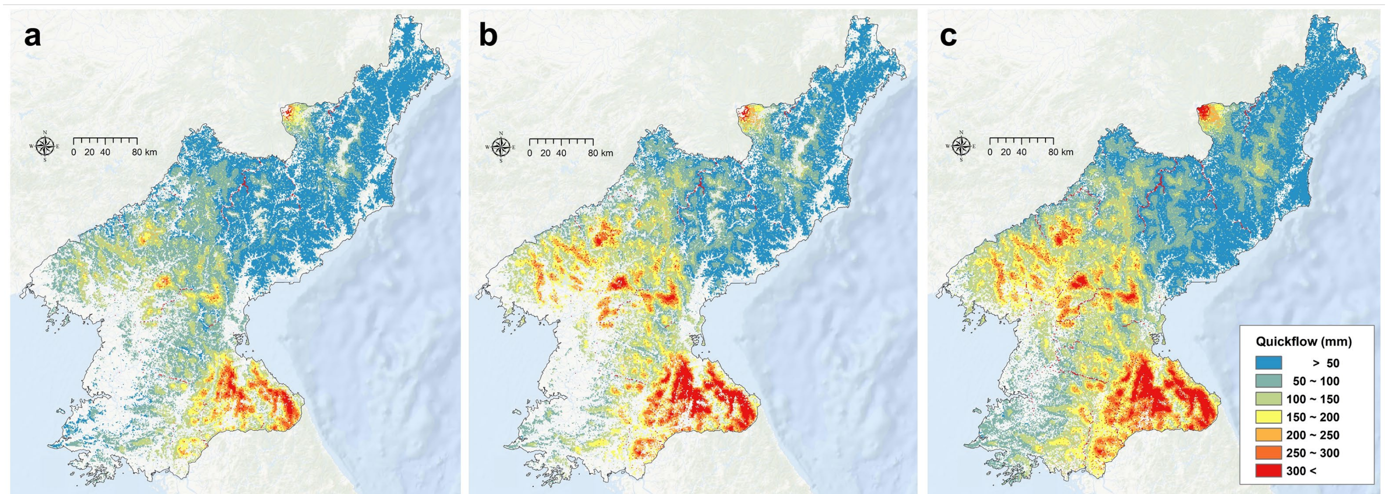

Figure 5. Spatial distribution of QF in forest area: (**a**) baseline period (1981–2010), (**b**) climate change (2041–2070), (**c**) climate and afforestation scenario (Level 3, 2041–2070).

3.3. Climate Change Impact on the Forest Water Supply of North Korea

In the prediction of future forest water supply according to the SSP5–8.5 scenario, the difference between the changes in the baseflow (local recharge) and QF was outstanding. Although the baseflow and local recharge decreased in most regions, they decreased only slightly in Kangwon-do, where precipitation was high (Figures 3b and 4b). However, there was a significant decrease in the mountainous regions of the northeast possibly because of a slight increase in the precipitation compared to that in the evapotranspiration. Moreover, the numerical values representing the changes in these indicators across the country were also large. During this period, the amount of water slowly supplied from the forest was approximately 20,000 million m^3 y^{-1} (Table 2), which is an approximately 25% reduction compared to the baseline period.

By contrast, the QF increased significantly in all the regions of North Korea, including Kangwon-do, where precipitation was high, as well as the central mountains and western plains (Figure 5b). This is because as the amount of precipitation increases, the intensity of precipitation will increase, which is expected in the future of the Korean Peninsula. This increase in precipitation intensity will eventually increase the QF. During this period, the amount of water that rapidly flowed from the entire forest was expected to be approximately 8200 million m^3 y^{-1} (Table 2), which corresponds to an increase of approximately 47% compared to the baseline period.

Under the SSP5–8.5 scenario, it was confirmed that climate change has a negative impact on the water supply of the forests in North Korea. As precipitation increases, the ability of the forests to slowly supply water and retain water in the catchments diminishes, and the amount of runoff rapidly increases. Thus, it can be concluded that the increase in evapotranspiration, with the increasing temperature and rainfall intensity, affects the effective water supply.

3.4. Effect of Afforestation on the Forest Water Supply of North Korea

When the three reforestation scenarios were applied, the future water supply from the forests showed significant positive changes. Irrespective of the intensity of afforestation, both the baseflow and local recharge increased; however, the increase in the QF was comparatively less in all of the scenarios. In the afforestation scenario of Level 1, the baseflow and local recharge increased by approximately 4%, and in Level 2, it increased by 15%. In the Level 3 stage, most of the baseflow and local recharge were recovered with an increase of 28%, which had decreased due to the impact of climate change (Table 2). The baseflow of Level 3 was 26,882 million m^3 y^{-1}, which is approximately 98% of the baseline period. Numerically, the QF also significantly increased, but it was the total amount that increased due to the increase in the forest area. From the gridded point of view, the QF decreased compared to the existing land use.

Spatially, baseflow and local recharge per unit area decreased according to the climate change, but the increase in the forest area offset this decreasing phenomenon. When all the areas that were previously forests are restored, water can be supplied from a wide-area forest, as shown in Figures 3c and 4c. This is even more pronounced when viewed at the watershed level. The baseflow and local recharge decreased in all watersheds due to climate change at the main watershed level in North Korea (Figures 6 and 7). In particular, there was a significant decrease in baseflow and local recharge at the Taedong River and Chongchon River basins, which are the major granary regions in North Korea. Numerically, the baseflow and local recharge decreased in all the watersheds, and the largest drop was confirmed in the Tumen River and the Northeastern Basin in the Northeast region of North Korea, where the effects of climate change were significant (Table 3). These negative effects of climate change were improved in most watersheds via forest restoration, and sufficient recovery was expected in the Level 3 reforestation scenario. In particular, the baseflow and local recharge at the Taedong River, which includes the capital Pyongyang and is the largest granary region, showed an increase of 15% compared to the baseline period. These indicators also increased in the Chongchon River and Ryesong River basins, which are granary regions. This is because the afforestation target area has appeared widely in these watershed. However, despite forest restoration, it was confirmed that the water supply by forests in the watersheds of the Northeast region, such as the Tumen River and Northeastern Basin, significantly decreased. The region can be considered as an area requiring additional adaptation to climate change.

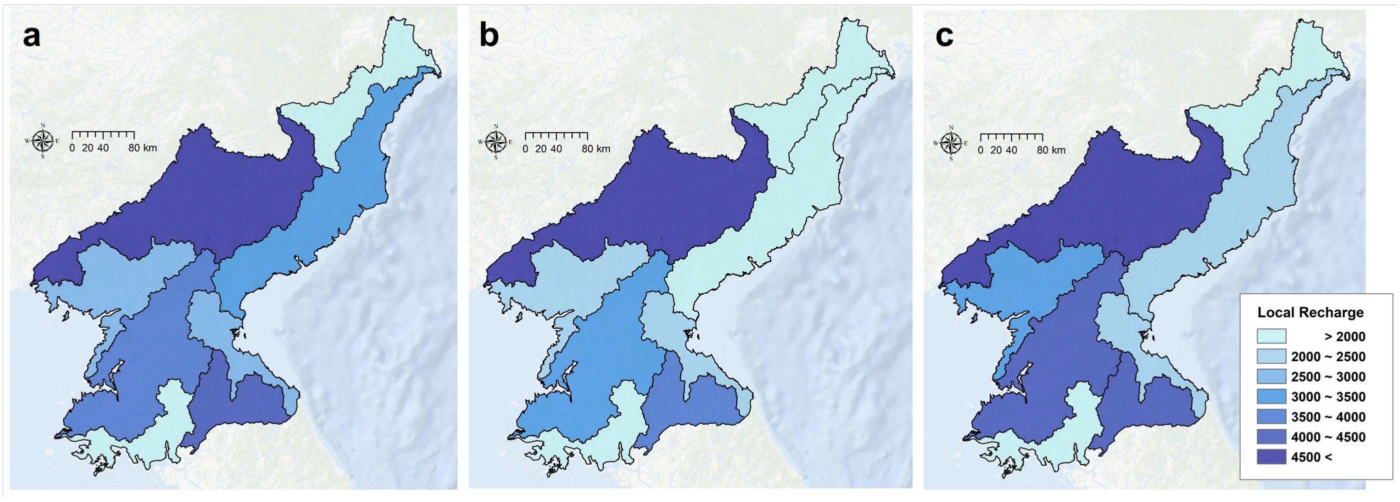

Figure 6. Local recharge amount at the main watershed level: (**a**) baseline period (1981–2010), (**b**) climate change (2041–2070), and (**c**) climate and afforestation scenario (Level 3, 2041–2070).

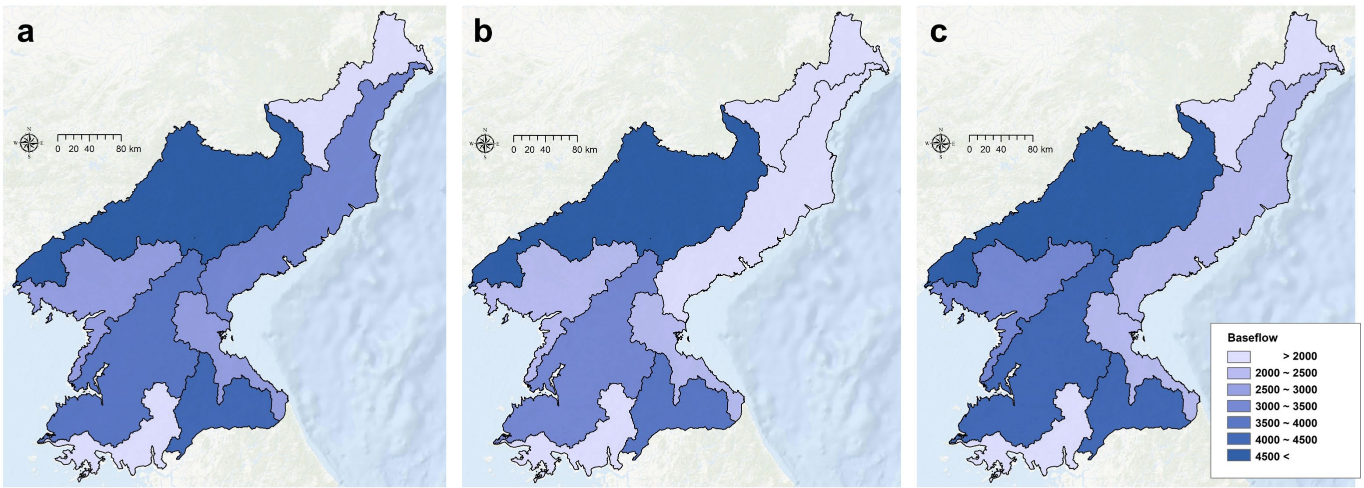

Figure 7. Baseflow amount at the main watershed level: (**a**) baseline period (1981–2010), (**b**) climate change (2041–2070), and (**c**) climate and afforestation scenario (Level 3, 2041–2070).

3.5. Implications and Limitations

Because the Korean Peninsula has a temperate monsoon climate and the seasonality of precipitation is traditionally high, it was necessary to predict into consideration of seasonal factors in hydrological indicators. In particular, because the seasonality of precipitation is expected to increase owing to climate change, seasonal factors are important in hydrology simulation [37,38]. However, in the existing InVEST water yield model, the annual precipitation and evapotranspiration were used as basic input data, limiting the consideration of precipitation seasonality [7,14,32,39]. In this study, by newly applying the InVEST-SWY model based on monthly data to North Korea, it was possible to predict the hydrological factors, considering the seasonality of precipitation [29,30]. In particular, in the study by Lim [7], it was predicted that the future water supply by forests would increase with precipitation increasing. However, through this study, the actual supply excluding QF was predicted to decrease, which was indicative of seasonality applied results. Overall, this case expressed technically improved results for water supply estimation.

Table 3. Local recharge and baseflow statistics of baseline period and future projection at the main watershed level (million $m^3\ y^{-1}$).

Main Watershed	Baseline Period		Only Climate Change		Climate Change with Afforestation (Level 3)	
	Local Recharge	Baseflow	Local Recharge	Baseflow	Local Recharge	Baseflow
Tumen River	1691	1706	991	1009	1414	1449
Yalu River	8176	8248	6095	6170	7168	7309
Northeastern Basin	3160	3171	1884	1926	2155	2233
Chongchon River	2630	2634	2246	2251	3190	3226
Taedong River	3770	3809	3119	3160	4273	4386
Eastern basin	2538	2544	2028	2034	2419	2434
Han River	4363	4382	3614	3634	4315	4359
Ryesong River	1063	1067	847	850	1421	1442
Total	27,392	27,560	20,823	21,035	26,356	26,838

3.6. Implications and Limitations

Because the Korean Peninsula has a temperate monsoon climate and the seasonality of precipitation is traditionally high, it was necessary to predict into consideration of seasonal factors in hydrological indicators. In particular, because the seasonality of precipitation is expected to increase owing to climate change, seasonal factors are important in hydrology simulation [37,38]. However, in the existing InVEST water yield model, the annual precipitation and evapotranspiration were used as basic input data, limiting the consideration of precipitation seasonality [7,14,32,39]. In this study, by newly applying the InVEST-SWY model based on monthly data to North Korea, it was possible to predict the hydrological factors, considering the seasonality of precipitation [29,30]. In particular, in the study by Lim [7], it was predicted that the future water supply by forests would increase with precipitation increasing. However, through this study, the actual supply excluding QF was predicted to decrease, which was indicative of seasonality applied results. Overall, this case expressed technically improved results for water supply estimation.

Forest restoration in North Korea is one of the representative policies of the Kim Jong-un regime and is being promoted from various angles through international cooperation projects [40,41]. However, due to sanctions against North Korea and the COVID-19 pandemic, the planned restoration speed has not been achieved. Although a social response is needed to speed up the restoration, the results of this study suggest the importance of forest restoration; therefore, the justification for restoration could be presented once again through the results of this study. In particular, the effect of forest restoration, efforts on which were previously focused on carbon absorption, was also confirmed in terms of water resources this time [42]. Forest restoration can be an important factor that can offset the negatively changing water supply due to climate change. Like the improvement of water supply suggested in this study, forest restoration has comprehensive value in terms of ecosystem services as well as natural ecosystems and carbon absorption. North Korea's forest restoration is highly desirable from the point of view of ecosystem services, and these indicators can lead to more exhaustive forest restoration policies to drive forest restoration efforts [19].

Water resources supplied from forests decreased in many watersheds due to climate change. However, through forest restoration, the water in the Taedong River, Cheongcheon River, and Yesong River recovered to their current levels or increased further. This area contained numerous target areas for forest restoration, such as reclaimed forest areas and unstocked forests, and accordingly, the effect of reforestation was noticeable in this area [25]. However, in the Northeast Basin and the Tuman River Basin, there were few forest restoration targets, and the water balance was negative because of climate change; therefore, the effect of reforestation was limited. For these areas, forest restoration alone is not sufficient and additional diversified adaptation methods, such as reservoir management and irrigation systems, should be devised as well [43,44]. In particular, the Northeast region may be more vulnerable to drought and floods as there are no major rivers, except the Tuman River.

In this study, we simulated the water supply of North Korea's forests using a new model and attempted to enhance the validity of the forecasts by using climate data with reduced uncertainties; nevertheless, some limitations do exist. First, because the InVEST-SYW model is based on a simplified simulation, a high-complexity hydrological system was not biophysically calculated. Biophysical estimation using daily weather data and detailed soil information can be more accurate. However, the overall water flow is at a significant level compared with that in the biophysical model, and our model has the advantage of predicting the spatial water flow as well. In addition, the collection of accurate measurement data was limited as the study was conducted for North Korea, which is a closed space. In particular, there was no water flow measurement information. Therefore, there was no choice but to verify the estimated water yield by an indirect method. This could cause uncertainty in estimating water yield amount by forests. Moreover, sensitivity analysis by all parameters was not conducted in this study. It is necessary to investigate the effect of each parameter, and it is hoped that it will be conducted in future studies. In predicting the impact of climate change, only the SSP5–8.5 scenario in which the highest level of greenhouse gas emission is considered, was applied, and the effects of greenhouse gas reduction could not be compared. However, this study focused on the effect of forest restoration and used only one climate scenario because the reforestation scenarios were diversified. In future investigations, application of various scenarios, comparison between scenarios, and evaluation of greenhouse gas reduction effects can be attempted.

4. Conclusions

A thorough spatial assessment of the effect of afforestation has significant implications for forest restoration and can facilitate the implementation of forest policy. In this study, we attempted to assess the extent to which afforestation can reduce the climate change impact on water resources by adding an afforestation scenario to the variables that have been used to estimate forest water yield. In the forecast of future forest water supply according to the SSP5–8.5 scenario, the difference between the changes in the baseflow and QF was outstanding. The baseflow and local recharge decreased by approximately 25%, whereas the QF increased by approximately 47%, compared to the baseline period. This indicates that the total precipitation increased, but the amount of water lost significantly increased. The future water supplied by forests, under the three reforestation scenarios, showed significant positive changes. In the reforestation scenarios of Level 1 and Level 2, the baseflow increased by approximately 4% and 15%, respectively. In the case of Level 3, the baseflow increased by 28%, and most of the baseflow, which had decreased because of the impact of climate change, was recovered. The baseflow in Level 3 was 26,882 million m^3 y^{-1}, which was approximately 98% of that in the baseline period. Although the Taedong River and Chongchon River, which are the major granary areas in North Korea, were directly affected by the climate change, it was confirmed that the water supply could be increased through forest restoration. However, despite the restoration of forests, supply in the northeast regions, such as the Tumen River and the Northeastern Basin, significantly decreased, which can be seen as areas requiring additional adaptation to climate change. In our study, we applied the InVEST-SWY model to North Korea and successfully predicted the hydrological factors by considering the precipitation seasonality. Further, the importance of forest restoration in increasing the water supply was justified as a suitably strategy to circumvent climate crisis. We expect that in the future, comparative studies between the future scenarios will be conducted by applying various climate and socioeconomic scenarios.

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References

1. Diffenbaugh, N.S.; Singh, D.; Mankin, J.S.; Horton, D.E.; Swain, D.L.; Touma, D.; Rajaratnam, B. Quantifying the influence of global warming on unprecedented extreme climate events. *Proc. Natl. Acad. Sci. USA* **2017**, *114*, 4881–4886. [CrossRef]
2. Korea Meteorological Administration (KMA). *Extreme Climate Report 2021*; KMA: Seoul, Korea, 2021.
3. Park, C.; Son, S.W.; Kim, H.; Ham, Y.G.; Kim, J.; Cha, D.H.; Lim, B. Record-breaking summer rainfall in South Korea in 2020: Synoptic characteristics and the role of large-scale circulations. *Mon. Weather. Rev.* **2021**, *149*, 3085–3100. [CrossRef]
4. Fekete, A.; Sandholz, S. Here Comes the Flood, but Not Failure? Lessons to Learn after the Heavy Rain and Pluvial Floods in Germany 2021. *Water* **2021**, *13*, 3016. [CrossRef]
5. Kreienkamp, F. Rapid attribution of heavy rainfall events leading to the severe flooding in Western Europe during July 2021. *World Weather. Attrib.* **2021**, *2*, 8732135.
6. Lee, M.H.; Im, E.S.; Bae, D.H. A comparative assessment of climate change impacts on drought over Korea based on multiple climate projections and multiple drought indices. *Clim. Dyn.* **2019**, *53*, 389–404. [CrossRef]
7. Lim, C.-H. Water-centric nexus approach for the agriculture and forest sectors in response to climate change in the Korean Peninsula. *Agronomy* **2021**, *11*, 1657. [CrossRef]
8. Korea Meteorological Administration (KMA). *Climate Change Outlook for Korean Peninsula 2020*; KMA: Seoul, Korea, 2021.
9. Lim, C.-H.; Kim, S.H.; Chun, J.A.; Kafatos, M.C.; Lee, W.-K. Assessment of Agricultural Drought Considering the Hydrological Cycle and Crop Phenology in the Korean Peninsula. *Water* **2019**, *11*, 1105. [CrossRef]
10. Lim, C.-H.; Kim, S.H.; Choi, Y.; Kafatos, M.C.; Lee, W.-K. Estimation of the Virtual Water Content of Main Crops on the Korean Peninsula Using Multiple Regional Climate Models and Evapotranspiration Methods. *Sustainability* **2017**, *9*, 1172. [CrossRef]
11. Choi, Y.; Lim, C.H.; Chung, H.I.; Kim, Y.; Cho, H.J.; Hwang, J.; Kraxner, F.; Biging, G.S.; Lee, W.K.; Chon, J.; et al. Forest management can mitigate negative impacts of climate and land-use change on plant biodiversity: Insights from the Republic of Korea. *J. Environ. Manag.* **2021**, *288*, 112400. [CrossRef]
12. Choi, Y.; Lim, C.H.; Krasovskiy, A.; Platov, A.; Kim, Y.; Chung, H.I.; Jeon, S.W. Can a national afforestation plan achieve simultaneous goals of biodiversity and carbon enhancement? Exploring optimal decision making using multi-spatial modeling. *Biol. Conserv.* **2022**, *267*, 109474. [CrossRef]
13. Kim, G.S.; Lim, C.-H.; Kim, S.J.; Lee, J.; Son, Y.; Lee, W.-K. Effect of National-Scale Afforestation on Forest Water Supply and Soil Loss in South Korea, 1971–2010. *Sustainability* **2017**, *9*, 1017. [CrossRef]
14. Lim, C.H.; Song, C.; Choi, Y.; Jeon, S.W.; Lee, W.K. Decoupling of forest water supply and agricultural water demand attributable to deforestation in North Korea. *J. Environ. Manag.* **2019**, *248*, 109256. [CrossRef]
15. Bhattacharjee, K.; Behera, B. Does forest cover help prevent flood damage? Empirical evidence from India. *Glob. Environ. Change* **2018**, *53*, 78–89. [CrossRef]
16. Lim, C.-H.; Kim, H.-J. Can Forest-Related Adaptive Capacity Reduce Landslide Risk Attributable to Climate Change?—Case of Republic of Korea. *Forests* **2022**, *13*, 49. [CrossRef]
17. Lim, C.-H.; Yeo, H.-C. Understanding the Long-Term Vegetation Dynamics of North Korea and Their Impact on the Thermal Environment. *Forests* **2022**, *13*, 1053. [CrossRef]
18. Choi, W.; Kang, S.; Choi, J.; Larsen, J.J.; Oh, C.; Na, Y.G. Characteristics of deforestation in the Democratic People's Republic of Korea (North Korea) between the 1980s and 2000s. *Reg. Environ. Change* **2017**, *17*, 379–388. [CrossRef]
19. Lim, C.-H.; Choi, H.-A. Ecosystem service-based economic valuation of forest restoration in North Korea. *Korean J. Environ. Biol.* **2021**, *39*, 225–235. [CrossRef]
20. Choi, H.-A.; Lim, C.-H. Forest cooperation with North Korea based on analysis of the characteristics of North Korea's forest Research. *Rev. North Korean Stud.* **2021**, *24*, 88–111.

21. Lim, C.H.; Choi, Y.; Kim, M.; Jeon, S.W.; Lee, W.K. Impact of deforestation on agro-environmental variables in cropland, North Korea. *Sustainability* **2017**, *9*, 1354. [CrossRef]
22. Lim, C.-H.; Choi, Y.; Kim, M.; Lee, S.J.; Folberth, C.; Lee, W.-K. Spatially explicit assessment of agricultural water equilibrium in the Korean Peninsula. *Sustainability* **2018**, *10*, 201. [CrossRef]
23. Lim, C.-H.; Yoo, S.; Choi, Y.; Jeon, S.W.; Son, Y.; Lee, W.-K. Assessing climate change impact on forest habitat suitability and diversity in the Korean Peninsula. *Forests* **2018**, *9*, 259. [CrossRef]
24. Kwon, M.; Sung, J.H.; Ahn, J. Change in Extreme Precipitation over North Korea Using Multiple Climate Change Scenarios. *Water* **2019**, *11*, 270. [CrossRef]
25. Kim, J.; Lim, C.-H.; Jo, H.-W.; Lee, W.-K. Phenological Classification Using Deep Learning and the Sentinel-2 Satellite to Identify Priority Afforestation Sites in North Korea. *Remote Sens.* **2021**, *13*, 2946. [CrossRef]
26. Sharp, R.; Tallis, H.T.; Ricketts, T.; Guerry, A.D.; Ennaanay, D.; Wolny, S.; Olwero, N.; Vigerstol, K.; Pennington, D.; Mendoza, G.; et al. *InVEST 3.0 User's Guide: The Natural Capital Project*; Stanford University: Stanford, CA, USA, 2016.
27. Lee, S.J.; Yoo, S.; Ham, B.; Lim, C.H.; Song, C.; Kim, M.; Kim, S.J.; Lee, W.K. Ecosystem service assessment of urban forest for water supply and climate mitigation of Seoul Metropolitan Area. Korean. *J. Remote Sens.* **2017**, *33*, 1119–1137.
28. Scordo, F.; Lavender, T.M.; Seitz, C.; Perillo, V.L.; Rusak, J.A.; Piccolo, M.C.; Perillo, G.M.E. Modeling Water Yield: Assessing the Role of Site and Region-Specific Attributes in Determining Model Performance of the InVEST Seasonal Water Yield Model. *Water* **2018**, *10*, 1496. [CrossRef]
29. Hamel, P.; Valencia, J.; Schmitt, R.; Shrestha, M.; Piman, T.; Sharp, R.P.; Francesconi, W.; Guswa, A.J. Modeling seasonal water yield for landscape management: Applications in Peru and Myanmar. *J. Environ. Manag.* **2020**, *270*, 110792. [CrossRef]
30. Halder, S.; Das, S.; Basu, S. Estimation of seasonal water yield using InVEST model: A case study from West Bengal, India. *Arab. J. Geosci.* **2022**, *15*, 1293. [CrossRef]
31. Benra, F.; De Frutos, A.; Gaglio, M.; Álvarez-Garretón, C.; Felipe-Lucia, M.; Bonn, A. Mapping water ecosystem services: Evaluating InVEST model predictions in data scarce regions. *Environ. Model. Softw.* **2021**, *138*, 104982. [CrossRef]
32. Redhead, J.W.; Stratford, C.; Sharps, K.; Jones, L.; Ziv, G.; Clarke, D.; Oliver, T.H.; Bullock, J.M. Empirical validation of the InVEST water yield ecosystem service model at a national scale. *Sci. Total Environ.* **2016**, *569*, 1418–1426. [CrossRef]
33. National Institute of Forest Science (NIFoS). *Development of Management Technology and Long-Term Monitoring of Forest Water Resources*; NIFoS: Seoul, Korea, 2016.
34. NRCS-USDA. Chapter 10. Estimation of Direct Runoff from Storm Rainfall. Part 630 Hydrology. National Engineering Handbook. In *United States Department of Agriculture*; United States Department of Agriculture: Washington, DC, USA, 2004. Available online: http://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/national/water/?cid\protect$\relax\protect{\begingroup1\endgroup\@@over4}$stelprdb1043063 (accessed on 11 July 2021).
35. Karger, D.N.; Conrad, O.; Böhner, J.; Kawohl, T.; Kreft, H.; Soria-Auza, R.W.; Kessler, M. Climatologies at high resolution for the earth's land surface areas. *Sci. Data* **2017**, *4*, 170122. [CrossRef]
36. Hargreaves, G.H.; Samani, Z.A. Reference crop evapotranspiration from temperature. *Appl. Eng. Agric.* **1985**, *1*, 96–99. [CrossRef]
37. Chiew, F.H.S.; Zhou, S.L.; McMahon, T.A. Use of seasonal streamflow forecasts in water resources management. *J. Hydrol.* **2003**, *270*, 135–144. [CrossRef]
38. Konapala, G.; Mishra, A.K.; Wada, Y.; Mann, M.E. Climate change will affect global water availability through compounding changes in seasonal precipitation and evaporation. *Nat. Commun.* **2020**, *11*, 3044. [CrossRef]
39. Lee, J.; Lim, C.H.; Kim, G.S.; Markandya, A.; Chowdhury, S.; Kim, S.J.; Son, Y. Economic viability of the national-scale forestation program: The case of success in the Republic of Korea. *Ecosyst. Serv.* **2018**, *29*, 40–46. [CrossRef]
40. Choi, H.A. Prospect and Implementation Strategy of the Inter-Korean Forest Cooperation: A case study of international organization support project in DPRK. *Unification Policy Stud.* **2018**, *27*, 1–20.
41. Lim, C.-H.; Choi, H.-A. Environmental cooperation strategies of Korean Peninsula considering International Environmental Regimes. *Korean J. Environ. Biol.* **2022**, *40*, 224–238. [CrossRef]
42. Kim, D.; Lim, C.H.; Song, C.; Lee, W.K.; Piao, D.; Heo, S.; Jeon, S. Estimation of future carbon budget with climate change and reforestation scenario in North Korea. *Adv. Space Res.* **2016**, *58*, 1002–1016. [CrossRef]
43. Eum, H.I.; Simonovic, S.P. Integrated reservoir management system for adaptation to climate change: The Nakdong River Basin in Korea. *Water Resour. Manag.* **2010**, *24*, 3397–3417. [CrossRef]
44. Nam, W.H.; Choi, J.Y.; Hong, E.M. Irrigation vulnerability assessment on agricultural water supply risk for adaptive management of climate change in South Korea. *Agric. Water Manag.* **2015**, *152*, 173–187. [CrossRef]