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Article

The Effects of Climate on the Death and Growth Decline of *Pinus densiflora* Siebold & Zucc

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Abstract: The present study aimed to date the death of Korean red pine (*Pinus densiflora* Siebold & Zucc.) at Sogwang-ri, where is famous for the Korean red pine forests in Korea, using a dendrochronological method, and to investigate the effect of climatic factors on the death and growth decline of the pine trees. For the study, 51 Korean red pines were selected from three stands (Jungmi-gol A, Jungmi-gol B, and Neonam-gol) in the study area, and for the ring-width measurement the increment cores were extracted from the selected trees. The stand chronologies for the Jungmi-gol and Neonam-gol were established using the mean values of individual time series of the living trees from each site, and the chronologies were further used for cross-dating with individual time series of the dead trees to date their death. The abrupt growth reduction was also investigated based on the consecutive ring-width growth decline trend to know the vitality during the living. Results revealed that the red pines at Jungmi-gol A were dead in 2020, at Jungmi-gol B in 2012 or 2013, and at Neonam-gol in 2019. So, it was verified that the death of the red pines at the study sites occurred from high to low elevations. In the analysis of the role of climate in the annual ring growth, the trees at Jungmi-gol A and B located on the southwest slope showed more ring-width growth when precipitation in April, July, and August were increasing, at Neoman-gol located on the north slope when precipitation only in July was increasing. Although the correlations of the ring-width growths at the sites with temperature and precipitation were somehow different from each other, Drought Stress Index (DSI) from May to September at all sites were all negative. Therefore, water stress caused by increased temperature and decreased precipitation is the most significant climatic parameter for the death or growth decline of the pine trees in the study area.

Keywords: tree ring; Korean red pine; tree mortality; climatic factor

1. Introduction

Korean red pines (*Pinus densiflora* for. erecta Uyeki) have deep roots and can grow in dry soil through symbiotic relationship with mycorrhizal fungi [1]. However, over the last two decades, the Korean red pines are facing increased threats by unsuitable weather, mainly warm and/or hot winter or summer in Korea [2] and their numbers have decreased significantly. For example, Kim et al. [3] evaluated that about 9.5% of the Korean red pine forests in Sogwang-ri, where is famous for the Korean red pine in Korea, would die due to frequent unsuitable weather. Since 2014, it has been verified that dead red pines in the form of cluster were found. According to a report published by the National Institute of Forest Science in 2009, the number of dead Korean red pines reached 97

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million in the southeastern region (Gyeongsangman-do) of Korea. Most stands of dead Korean red pine are located at high elevations or on ridges with high solar radiation and some of them have been succeeded by a subtype of Mongolian oak (*Quercus mongolica*) [2].

In general, tree growth is highly correlated with topographic and soil conditions, as well as climate such as temperature and precipitation [4]. The annual climatic variation plays an important role in determining the annual tree growth [5]. Although, several researchers have studied the effect of climate on annual-ring growth of Korean red pine at some representative forests in Korea, such as at Mt. Songni-san [6], Worak-san [7], Seorak-san [8–10], and Baekdudaegan area [11,12], no systematic investigation for the Korean red pine in Sogwang-ri has been done to-date.

To monitor the mortality of Korean red pine in Korea, the National Geographic Information Institute of Korea conducted aerial photography bi-annually of the forest area of the country [2,3]. In these studies, the death of the trees was determined based on the visual features such as leaf browning, defoliation, and chlorosis of the branch and stem. However, such approach lacks precision as it is different from the death year determined accurately from the annual-ring growth by cambial activity [13].

The present study aimed to date the death year of Korean red pines (*P. densifora*) in Sogwang-ri, one of the largest habitats of pine in Korea, using dendrochronological methods, and investigate the effects of climatic factors on the death and/or growth decline of the pine trees. We believe that the results obtained from this study can serve as fundamental data which would act as a guide in the conservation of Korean red pines in the study area.

2. Materials and Methods

2.1. Study Sites

Three Korean red pine stands were selected in Sogwang-ri, Uljin-gun, Gyeongsangbuk-do, i.e., two of them in in Jungmi-gol (Jungmi-gol A and B) and the other one in Nanam-gol (Figure 1), where death occurred as colony. The elevations were between 650 and 800 meters above the sea level. The annual mean temperature for the last 39 years (19892–2020) was 9.6℃, and annual precipitation was 1,291mm (Figure 2). The warmest and coldest months were August (21.2℃) and January (-4.0℃), while the highest and lowest precipitation were in August (243 mm) and December (41 mm), respectively.

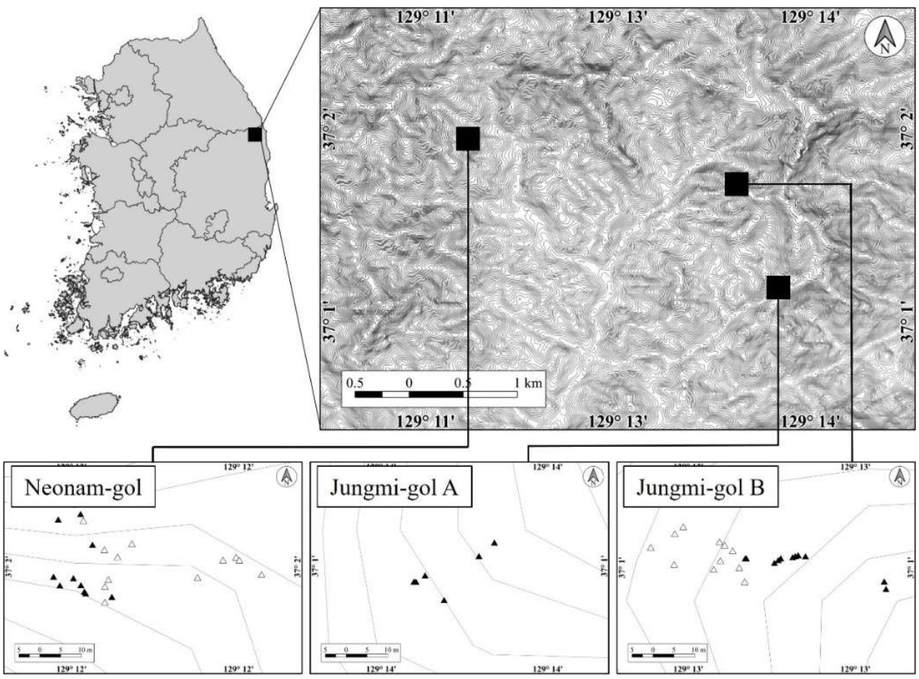

Figure 1. Study sites (■) and sampling points of living (△) and dead (▲) Korean red pine (Pinus densiflora) in Sogwang-ri, Uljin-gun, the Republic of Korea.

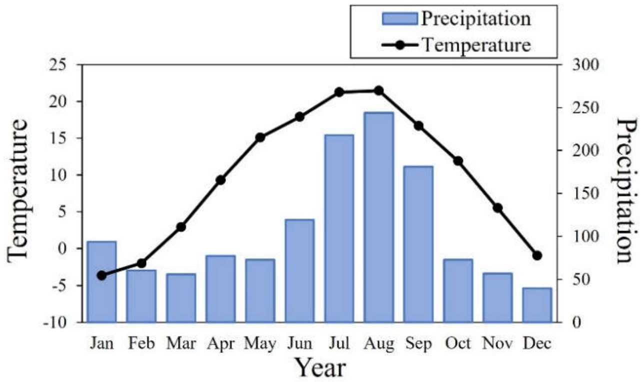

Figure 2. Monthly mean temperature and total precipitation for the last 39 years (19892–2020).

2.2. Experimental Trees and Tree-Ring Samples

Tree-ring samples were extracted from 24 living and 27 dead red pines from the study sites (Table 1). Out of the 24 living trees, 11 were selected from Jungmi-gol and 13 from Neonam-gol to develop master chronology of the respective sites to date the death years of the dead trees at Jungmi-gol A and B, and Neonam-gol, respectively. The increment cores were extracted from the stems at breast height using an increment borer with Ø 5.15 mm for living trees and Ø 10.00 mm for dead trees. Since the stems of the dead trees were partially decayed, their increment cores were extracted using increment borer with Ø 10.00 mm for ring-width measurement.

Table 1. Description of the sampled Korean red pine (Pinus densiflora).

Sites	ID	DBH* (cm)	Number of rings	Pith	Bark	Condition
Jungmi-gol A (37°01′17″N / 129°14′06″E)	SJMPDD21	41.0	65	P	-	D***
	SJMPDD22	23.0	55	nP**	-	D
	SJMPDD23	31.0	187	-	-	D
	SJMPDD24	42.0	173	P	-	D
	SJMPDD25	37.0	191	P	B	D
	SJMPDD26	34.0	197	P	-	D
Jungmi-gol B (37°01′17″N / 129°14′06″E)	SJMPDD01	36.0	57	P	-	D
	SJMPDD02	45.0	66	-	-	D
	SJMPDD03	38.0	66	-	-	D
	SJMPDD04	25.0	64	-	-	D
	SJMPDD05	25.0	58	nP	-	D
	SJMPDD06	25.0	63	P	-	D
	SJMPDD07	25.0	51	P	-	D
	SJMPDD08	38.0	63	P	-	D
	SJMPDD09	33.0	65	P	-	D
	SJMPDD10	32.0	64	-	-	D
	SJMPDD11	30.0	60	-	-	L
	SJMPDL01	44.0	78	nP	B	L****
	SJMPDL02	42.0	70	nP	B	L
	SJMPDL03	37.0	84	-	B	L
	SJMPDL04	37.0	84	-	B	L
	SJMPDL05	44.0	90	nP	B	L
	SJMPDL06	44.0	72	-	B	L
	SJMPDL07	42.0	75	nP	B	L
	SJMPDL08	39.0	80	nP	B	L
	SJMPDL09	44.0	71	-	B	L
	SJMPDL10	43.0	82	nP	B	L
	SJMPDL11	49.0	75	P	B	L
Neonam-gol (37°01′17″N /	SNNPDD01	46.0	185	-	-	D
	SNNPDD02	44.0	187	nP	B	D

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129°14′06″E)	SNNPDD03	39.0	170	-	-	D
	SNNPDD04	33.0	183	nP	-	D
	SNNPDD05	39.0	189	nP	B	D
	SNNPDD06	49.0	157	-	B	D
	SNNPDD07	35.0	184	-	-	D
	SNNPDD08	60.0	185	-	B	D
	SNNPDD09	24.0	177	-	-	D
	SNNPDD10	55.0	194	P	B	D
	SNNPDL01	56.0	189	-	B	L
	SNNPDL02	43.0	178	-	B	L
	SNNPDL03	55.0	182	-	B	L
	SNNPDL04	52.0	73	P	B	L
	SNNPDL05	34.0	58	-	B	L
	SNNPDL06	61.0	185	-	B	L
	SNNPDL07	49.0	52	-	B	L
	SNNPDL08	38.0	58	-	B	L
	SNNPDL09	36.0	58	-	B	L
	SNNPDL10	38.0	64	P	B	L
	SNNPDL11	56.0	51	-	B	L
	SNNPDL12	54.0	98	-	B	L
	SNNPDL13	57.0	71	-	B	L

*: diameter at breast height / **: near pith / ***: dead tree / ****: living tree

2.3. Ring-Width Measurement and Cross-Dating

The collected increment cores were mounted on wooden stick with their cells vertically aligned, and their cross-planes were sanded using a belt sander. The sanding was done with sandpaper in the sequence #80, #120, #360, and up to #600, so that the tree-ring boundaries become clearly visible. The tree-ring widths were measured using the WinDENDRO (REGENT, Canada) to the nearest 0.01mm.

Cross-dating was done to date the exact year of each tree ring to build the site chronologies and date the year of death of the dead trees based on synchronization between the individual ring-width time series from the dead ones and the corresponding site chronologies. To verify the success of cross-dating, the *t*-value from Equation 1 and G value (%) from Equation 2 were run in the TSAP-Win program (RINNTECH, Germany). The *t*-value was calculated based on the correlation coefficients between the individual time series and the number of overlapped years, while the G value was calculated as percentage of the synchronized pattern between the time series compared in the overlapping years [14–16]. In general, if *t*- and G values are ≥ 3.5 and 65%, respectively, when tree-ring time series are overlapped 100 years or more, the cross-dating is considered successful [17].

$$\boldsymbol{r} = \frac{\sum(\boldsymbol{S_i}-\boldsymbol{S})\times(\boldsymbol{R_i}-\boldsymbol{R})}{\sqrt{\sum(\boldsymbol{S_i}-\boldsymbol{S})^2\times(\boldsymbol{R_i}-\boldsymbol{R})^2}} \rightarrow \boldsymbol{t} = \frac{\boldsymbol{r}\times\sqrt{\boldsymbol{n}-\boldsymbol{2}}}{\sqrt{(\boldsymbol{1}-\boldsymbol{r})^2}} \quad (1)$$

Where $\boldsymbol{S_i}$ is the *i*-th annual-ring width of a sample tree, $\boldsymbol{S}$ is the mean annual-ring width of a sample tree, $\boldsymbol{R_i}$ is the *i*-th annual-ring width of the reference tree, $\boldsymbol{R}$ is the mean annual-ring width of a reference tree and *n* is the number of overlapped years.

$$\boldsymbol{G}_{(\boldsymbol{x},\boldsymbol{y})} = \frac{\boldsymbol{1}}{\boldsymbol{n}-\boldsymbol{1}}\sum_{\boldsymbol{i}=\boldsymbol{1}}^{\boldsymbol{n}-\boldsymbol{1}}\left|\boldsymbol{G_{ix}}+\boldsymbol{G_{iy}}\right| \quad (2)$$

If, $(x_{i+1}-x_i) > 0$, $G_{ix} = +1/2$, $(y_{i+1}-y_i) > 0$, $G_{iy} = +1/2$,

$(x_{i+1}-x) = 0$, $G_{ix} = 0$, $(y_{i+1}-y_i) = 0$, $G_{iy} = 0$,

$(x_{i+1}-x) < 0$, $G_{ix} = -1/2$, $(y_{i+1}-y_i) < 0$, $G_{iy} = -1/2$,

Where $G_{(x,y)}$ is the G value and x_i and y_i are the measured ring-width values for the *i*-th year.

2.4. Death Year and Season

The death year was determined from the youngest tree ring dated through cross-dating between the individual ring-width time series of dead trees and the corresponding site chronology, whereas the season was determined by the development condition of the last formed wood cell in the outmost

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tree ring. The earlywood formation in Korean red pine occurs from spring to early summer and the latewood from late summer to autumn [18,19]. Therefore, if the outmost tree ring has only earlywood, the death season was inferred as between spring and summer, if it has incomplete latewood, between summer and autumn, and if the latewood formation is complete, the death season was between the autumn of the current year and spring of the following year (Figure 3).

Figure 3. (A) the outermost annual rings with earlywood, (B) not completed latewood formation, and (C) completed latewood formation.

2.5. Monitoring of Abrupt Growth Reduction

The effects of strong natural events, such as mechanical injury, destruction of the foliage, land movement, thinning, or typhoons on the tree growth can be evaluated from abrupt growth reduction [4]. The abrupt growth reduction is actually a marked decreased in the tree-ring width for three consecutive years or more and categorized into three classes depending upon the extent of such decrease. Ring width reduced by 40–55% is class I, 56–70% is class II, and more than 70% is class III.

2.6. Standardization

Standardization is the process to remove biological trends such as aging and/or stand dynamics from the measured ring-width time series according to the equation 3.

$$\boldsymbol{I_t} = \frac{\boldsymbol{W_t}}{\boldsymbol{Y_t}} \tag{3}$$

I_t : relative ring-width index at t year
W_t : measured ring width at t year
Y_t : predicted ring width at t year

In the present study, double detrending method was applied using the ARSTAN program [20]. In this method, a negative exponential curve was applied in the first step to remove the growth trend determined by ageing; in the second step, a smoothing spline (50% response period: 60 years) was applied to remove the trend by stand dynamics [21,22]. After standardization, autocorrelation was removed to create a residual index chronology.

2.7. Correlation Analysis

To investigate the influence of climatic parameters, viz. monthly mean temperature, total precipitation, and drought stress index (DSI), on the experimental trees, correlation analyses were done using the DendroClim 2002 for the last 39 years between 1981–2020 [23]. In this analysis, the adjusted monthly mean temperature and total precipitation were used which were calculated using the model of inverse distance weighted interpolation [24]. The model calculates the values considering the distance between the site and meteorological stations, and the site elevation and slope. DSI was calculated using the equation 4 [25]. The weighted values (α and β) were set to 1, and the HI and SPI were the average values calculated using the growing degree days and monthly precipitation, respectively, over the previous 3 months (n).

$$DSI = \alpha \times HI_n - \beta \times SPI_n \tag{4}$$

HI (heat index): deviations among growing degree days per month
SPI (standardized precipitation index): deviations among monthly precipitation
α, β : weighted values contributing the deviations of temperature and precipitation
n: the number of previous months used to calculate *HI* and *SPI*

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3. Results

3.1. Establishing the Stand Chronologies

All the ring-width time series from the living trees at Jungmi-gol were successfully cross-dated. However, 2 out of 13 time series at Neonam-gol could not be cross-dated well with the others. Therefore, the stand chronology of Jungmi-gol was established using all the ring-width time series (SJMPDL-M), whereas the stand chronology of Neonam-gol was set using 11 ring-width time series (SNNPDL-M) (Figure 4). To verify the confidence of the cross-dating, synchronization test with *t*-value and G value were applied. According to the *t*-value and G value between the individual time series and corresponding site chronologies at Jungmi-gol, the mean (range from the lowest to the highest values) *t*-value and G value were 19.3 (10.5–31.3) and 78.2 (72.0–88.0) and at Neoman-gol 6.4 (1.0–9.6) and 78.0% (70.0–85.0), respectively (Table 2).

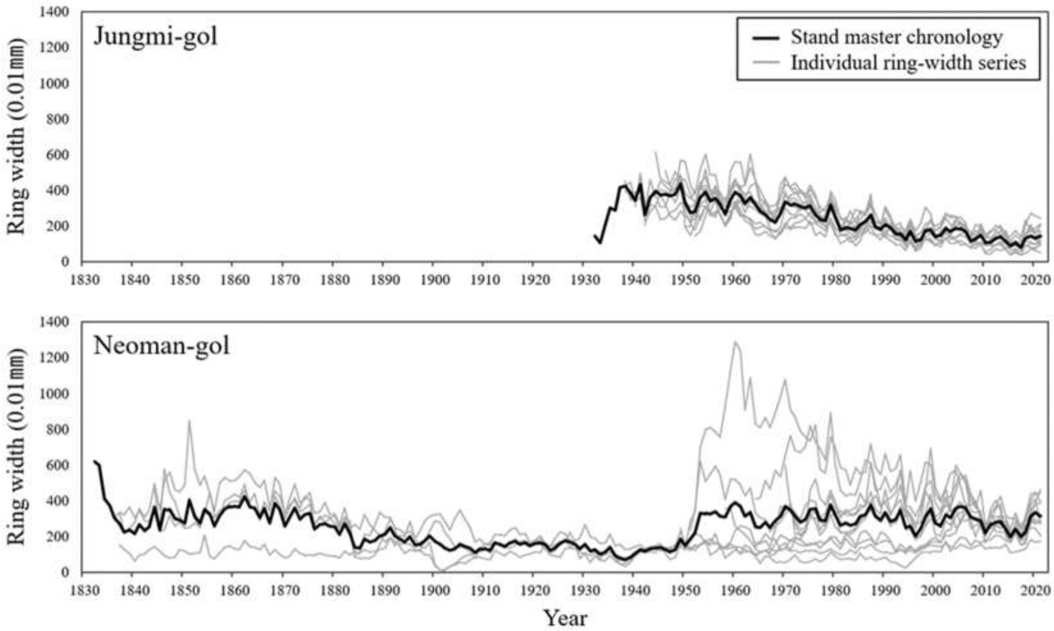

Figure 4. Ring-width time series from individual living Korean red pines (grey time series) with the stand master chronology (bold time series) of Jungmi-gol and Neonam-gol.

Table 2. t-values and G values between individual ring-width time series from living Korean red pines and the corresponding stand master chronologies.

Site	**Jungmi-gol**											
(ID)	**01**	**02**	**03**	**04**	**05**	**06**	**07**	**08**	**09**	**10**	**11**	**Mean**
t-value	14.0	10.5	11.5	21.5	22.9	14.6	24.7	18.2	14.3	28.8	31.3	19.3
G value	79	77	76	76	81	82	72	85	86	87	88	81
Site	Neonam-gol											
(ID)	01	02	03	04	05	06	07	09	10	11	13	Mean
t-value	7.6	4.2	7.3	7.3	8.6	1.0	9.6	7.6	4.4	7.2	5.8	6.4
G value	80	76	71	85	77	70	84	75	79	85	76	78

3.2. Dating the Death Years and Seasons

Except 3 dead trees which intensively decayed, the death years were successfully dated (Table 3). The dead trees sampled at Jungmi-gol A and Neoman-gol were dead in 2020 and 2019, respectively, and those at Jungmi-gol B between 2012 and 2013. The first death of the Korean red pine occurred at Jungmi-gol B located at the highest elevation among the study sites, followed by the pines at Neonam-gol located at the second highest altitude. The death at Jungmi-gol A located at the lowest height among the sites occurred in the most recent year. Considering the death season, most of the

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deaths occurred between spring and early summer as 41.6% (10 trees), then between late summer and autumn or late autumn and spring in the next year as 29.2% (7 trees) each.

Table 3. Death years of individual dead Korean red pines (Pinus densiflora) and the statistical results (t-values and G values between ring-width time series of individual dead Korean red pines and the corresponding stand master chronologies).

Sites	ID	Statistical result		The outmost annual ring			Elevation (m a.s.l.)	Aspect
		***t*-value**	G value (%)	Wood cell*	Season**	Year		
Jungmi-gol A	SJMPDD21	8.2	59	LW	Sum-Aut	2020	677	South-West
	SJMPDD22	0.8	67	EW	Spr-Sum	2020	678	
	SJMPDD24	5.4	71	EW	Spr-Sum	2020	679	
	SJMPDD25	10.0	56	cLW	Aut-SPR	2020	665	
	SJMPDD26	4.2	67	LW	Sum-Fal	2020	686	
Jungmi-gol B	SJMPDD01	14.3	73	EW	Spr-Sum	2013	800	West
	SJMPDD02	10.2	74	EW	Spr-Sum	2013	798	
	SJMPDD03	13.3	66	EW	Spr-Sum	2012	798	
	SJMPDD04	11.8	81	cLW	Aut-SPR	2012	800	
	SJMPDD05	17.4	77	LW	Sum-Aut	2012	802	
	SJMPDD06	10.0	71	LW	Sum-Aut	2012	800	
	SJMPDD08	15.0	72	EW	Spr-Sum	2013	802	
	SJMPDD09	15.0	73	LW	Sum-Aut	2013	801	
	SJMPDD10	16.1	81	EW	Spr-Sum	2013	804	
Neonam-gol	SNNPDD01	8.3	67	cLW	Aut-SPR	2019	774	North
	SNNPDD02	5.3	72	cLW	Aut-SPR	2019	782	
	SNNPDD03	2.1	74	LW	Sum-Aut	2019	788	
	SNNPDD04	4.3	68	cLW	Aut-SPR	2019	790	
	SNNPDD05	3.1	71	EW	Spr-Sum	2019	785	
	SNNPDD06	5.9	70	EW	Spr-Sum	2019	778	
	SNNPDD07	0.7	64	cLW	Aut-SPR	2019	782	
	SNNPDD08	3.9	64	LW	Sum-Aut	2019	777	
	SNNPDD09	3.7	71	EW	Spr-Sum	2019	786	
	SNNPDD10	6.5	66	cLW	Aut-SPR	2019	787	

*: EW, LW, and cLW are earlywood, uncompleted latewood, and completed latewood, respectively / **: Spr, Sum, and Aut are spring, summer and, autumn of the current year, respectively, and SPR is the spring of the next year

3.3. Abrupt Growth Reduction

The abrupt growth reduction was observed in 14 out of 24 dead tree samples (59.4%) and 5 out of 22 living tree samples (22.8%) (Figure 5). Moreover, the length of the reduction years and intensity was longer and stronger for the dead trees than those for the living ones. Therefore, it can be presumed that the dead trees were under more stress than the living ones during the same growing years. Although there was relatively high intensity of abrupt growth reduction in the 1880s and 1930s at Neoman-gol, only 3 out of 9 trees (33.3%) showed such pattern.

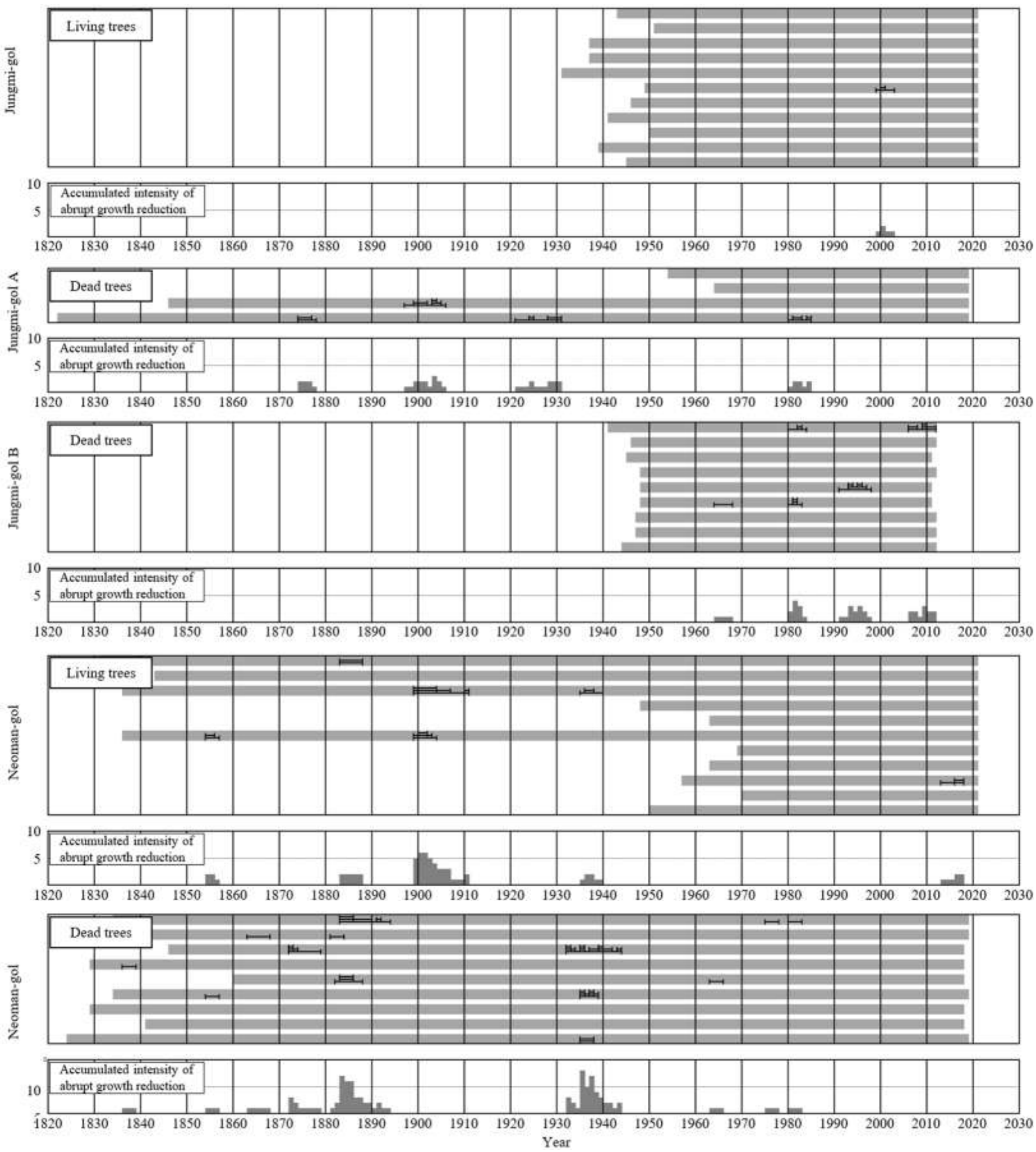

Figure 5. The periods of abrupt growth reduction and intensity of living and dead Korean red pines (Pinus densiflora) at Jungmi-gol and Neonam-gol.

3.4. Effects of Climate on the Annual Ring Growth

Three index chronologies for each stand were constructed using the successful cross-dated ring-width time series. The lengths of the index chronologies of Jungmi-gol A and B and Neoman-gol were 197 (1823–2019), 74 (1942–2016), and 195 (1825–2019) years (Figure 6). The climatic factors that influenced the ring-width growth are precipitation in April (positive; hereafter +) and August (+) and DSI in March (+) and September (negative; hereafter –) at Jungmi-gol A, and temperature in December of the previous year (+), February (+), April (+), and August (–), precipitation in April (+), July (+), and August (+), and DSI in February (+) and July – August (–) at Jungmi-gol B (Table 4). At Neoman-gol, only precipitation in July (+) played important role. Furthermore, the DSI in spring played a positive role, whereas that in summer and autumn played negative role in the ring-width growth. For the last 39 years, the DSI from May to September had been increasing (Figure 7).

Table 4. The results of response function analysis of the index chronologies of each site and climatic factors (monthly mean temperature, total precipitation, and DSI (Drought Stress Index)).

Sites	**Year**	Months	Climate factors		
			Temperature	Precipitation	DSI

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Jungmi-gol A	Previous year	OCT	-0.208	0.217	0.077
		NOV	-0.006	0.130	-0.296
		DEC	0.085	-0.233	-0.111
	Current year	Jan	-0.189	-0.268	0.259
		Feb	0.079	-0.192	0.301
		Mar	0.254	-0.007	0.355*
		Apr	0.146	0.418*	0.135
		May	-0.114	0.166	-0.134
		Jun	0.038	0.138	-0.168
		Jul	-0.168	0.286	-0.284
		Aug	-0.150	0.265*	-0.323
		Sep	-0.087	0.088	-0.339*
		Oct	-0.034	-0.046	-0.221
Jungmi-gol B	Previous year	OCT	-0.118	0.156	0.072
		NOV	0.021	0.096	-0.220
		DEC	0.351*	0.112	-0.045
	Current year	Jan	-0.060	0.158	0.198
		Feb	0.306*	0.228	0.407*
		Mar	0.143	-0.029	0.179
		Apr	0.374*	0.456*	-0.018
		May	-0.079	0.250	-0.119
		Jun	0.070	0.199	-0.188
		Jul	-0.211	0.359*	-0.402*
		Aug	-0.481*	0.507*	-0.580*
		Sep	-0.132	0.138	-0.591*
		Oct	-0.139	0.032	-0.556*
Neonam-gol	Previous year	OCT	-0.048	-0.231	0.151
		NOV	-0.080	-0.018	-0.102
		DEC	-0.031	-0.115	0.172
	Current year	Jan	-0.148	-0.155	0.007
		Feb	0.185	-0.091	0.032
		Mar	0.225	0.151	0.234
		Apr	0.099	0.199	0.041
		May	-0.058	0.203	-0.191
		Jun	0.211	-0.001	-0.088
		Jul	0.088	0.339*	-0.223
		Aug	0.018	0.039	-0.108
		Sep	-0.006	0.012	-0.150
		Oct	0.129	-0.158	0.037

*: $p<0.05$

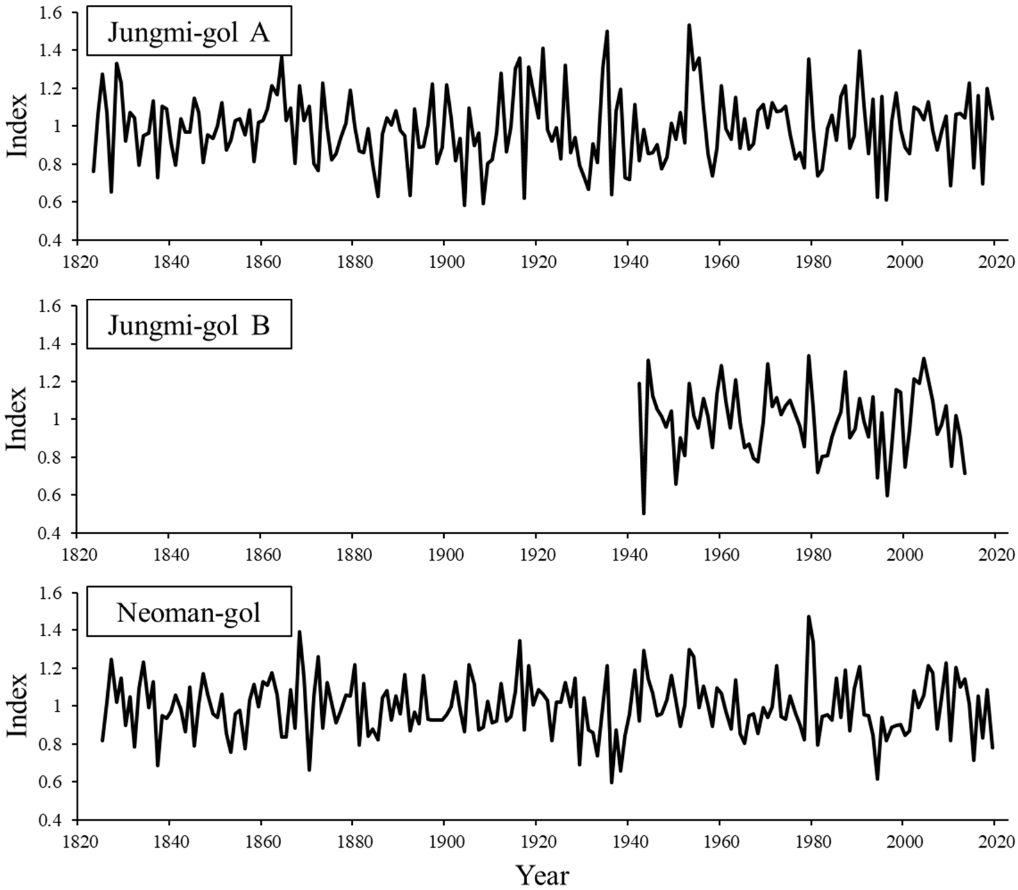

Figure 6. Index chronologies of the study sites.

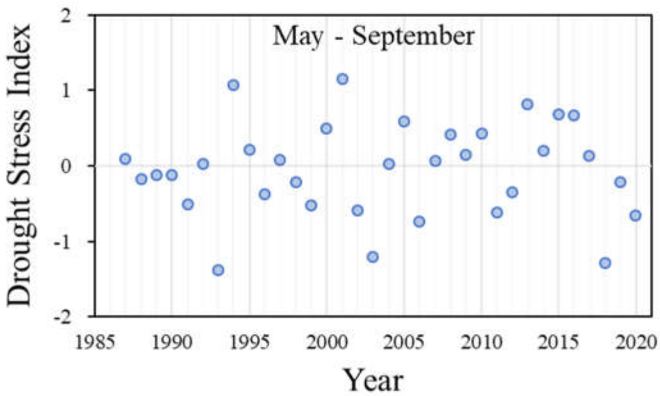

Figure 7. The mean Drought Stress Index (DSI) from 1987 to 2020.

To investigate the effect of extreme weather condition on the death of the pine trees, the monthly mean temperature, total precipitation, and DSI, which were investigated as a significant parameter (p<0.05) by response function analysis (see Table 4), were compared with the mean values for the last 39 years (1982–2020). At Jungmi-gol A, where the pine trees died between spring 2020 and early spring 2021, the precipitation and DSI did not show any meaningful differences with the average. At Jungmi-gol B, where deaths occurred between spring 2012 and autumn 2013, the temperatures of February, 2012 and April, 2013 were lower than the average, and August, 2013 was higher than the average (Figure 8). Furthermore, the August–October DSI in 2013 were prominently higher than the

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average. At Neonam-gol, where the pines died between spring 2019 and early spring 2020, the July precipitation did not show any meaningful difference from the average.

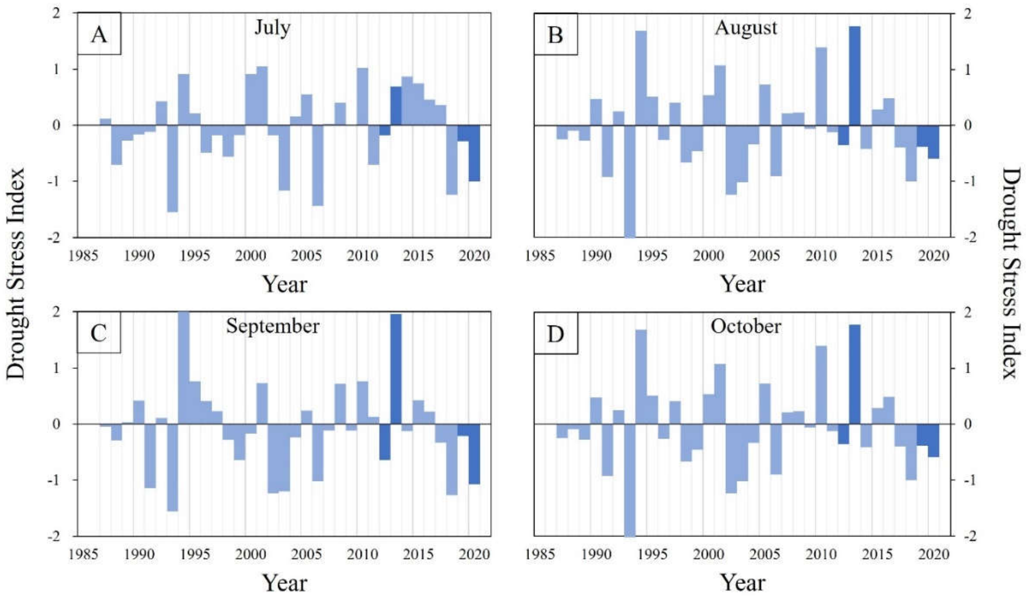

Figure 8. Variations of monthly Drought Stress Index (DSI) from 1982 to 2020 (dark blue: the death years).

4. Discussion

4.1. Stand Chronologies

Stand chronology was established using the individual time series of trees at the same stand, which were cross-dated well. Usually, *t*-value with 3.5 and G value with 65% between the time series are used as the threshold to determine the success of cross-dating statistically, when the length of time series is longer than ~100 years [17]. According to the statistical results, except one time series at Neoman-gol which showed low *t*-value of 1.0, all the other showed values higher than the threshold (Table 2). Although the ring-width time series showed such low *t*-value, the G value was enough high as 70% and displayed well synchronization with the chronology of Neoman-gol. Therefore, it was verified that only well synchronized ring-width time series with each other were used to establish the stand chronology.

4.2. Tree Death

The death among the study sites occurred sequentially at Jungmi-gol B (798–804 m a.s.l.), Neoman-gol (774–788 m a.s.l.), and Jungmi-gol A (677–686 m a.s.l.) (Table 3) following in the order from the highest to the lowest elevation. This result is akin to that of the previous studies done in Sokwang-ri area which reported that the vitality of the Korean red pine there is going weaker from low to high elevations [2,3]. The pine trees at high elevations are more sensitive to temperature than the ones at low elevations [26,27], because the role of temperature in the cambial activity to produce wood cells increases with elevation [28]. So, the temperature warming observed in recent decades affects the growth of the pine trees more negatively. Furthermore, Jungmi-gol B has more moisture stress due to its westward location and rocky soil condition. These play as principal triggers causing the death of more pine trees at higher elevations.

Regarding the death season of the trees, the main season was from spring to the early summer with 41.6% death and the death for the growing season reached up to 70.8%. The correlation analysis of the effect of climatic factors on the tree growth revealed that the climate between March and October played the main role (Table 3). According to a past study of the pine trees of Sokwang-ri [19], the pine trees started radial growth in April and ceased in October. So, it can be concluded that the

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role of climate in the growing season is more important for tree growth than in the dormant season. Even the December temperature of the previous year and February temperature and DSI at Jungmi-gol B have also been verified as important factor statistically.

4.3. Abrupt Growth Reduction

The abrupt growth reduction for longer than 3 years can be due to natural stress, such as mechanical injury, destruction of the foliage, land sliding, or any kinds of abnormal stress [4,29]. When such stress is strong enough to stunt the tree growth in a forest, the growth decreases dramatically and does not recover for several years. In our present study, only a few trees showed abrupt growth reduction in irregular intervals and different periods within the study sites (Figure 5). It is possibly because the stress factor did not play a strong role as much as the trees could not withstand the stress. The tree growth not only depends on climate, but in a small area due to different microsite conditions [30], it also relies on environmental factors, such as soil or topographical condition [12]. To evaluate the influencing factor more precisely, stress related to moisture, insects, wildfires, or competition with neighbor trees should be considered as stress factors, referring to the past research on their role in the decline of tree growth [31–35].

4.4. Climate Effects on the Death and/or Growth Reduction of the Korean Red Pines

Jungmi-gol B has higher correlation coefficients for temperature and precipitation and is about 130 meters higher in elevation with more rocky terrain than Jungmi-gol A (Tables 3 and 4). In the tree-ring analysis of Korean red pines at high elevations in Baekdudaegan [12], temperature was found to be an important influencing factor [12]. Although a study in the Mt. Worak [30] showed similar result for several Korean red pine stands there, the growth in rocky soil and south-facing slopes was mostly limited by precipitation. Therefore, the higher correlations with temperature and precipitation at Jungmi-gol B than Jungmi-gol A would be related to not only altitude but also soil conditions. On the other hand, Neonam-gol showed meaningful positive correlation only with July precipitation and low correlations with climatic parameters. These results depend upon the water retention capacity of the soil, considering the fact that the forests on the north-facing slopes support moisture-loving plants [36].

Different from the correlations with temperature and precipitation, the Korean red pines in this study exhibited negative correlations with DSI from May to September (Table 4), signifying that tree growth increased with decrease in drought stress from May to September. However, the DSI from May to September for 4 (2007–2010) and 5 (2013–2017) consecutive years were higher than zero (Figure 7). So, most pine trees, regardless of site conditions, face drought stress during the periods. Thus, drought stress would become one of influence factors causing the death of trees. Moreover, DSI from August to October in 2013 were extremely higher than the other years as the level 1.50–1.99 (very stressed) (Figure 8). This drought stress is possibly the main driver for the death of pine trees at Jungmi-gol B in 2013, but the indirect one together with the DSI in July caused death at Jungmi-gol A and Neonam-gol. Since the DSI of July in 2013 was not as strong as the DSI from August to October, however DSI of July gave negative effect on the ring-width growth until 2017. This continuous water stress in July from 2013 to 2017 would be a meaningful climatic parameter that induces the death of the trees in 2019 and 2020.

5. Conclusions

The death of Korean red pines at 3 study sites were not the same as 2012–2013 at Jungmi-gol B, 2019 at Neoman-gol, and 2020 at Jungmi-gol A. The death pattern depended upon elevation, temperature and precipitation of the different sites. The DSI played negative role on the tree growth during the growth season. So, the elevation and DSI seems to be common parameter in the death and/or growth decline of the pine trees at the study sites. To improve our understanding about the influences of other factors on the death and/or growth decline, the role of soil characteristics, forest fire or insects need to be further considered.

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