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RESEARCH

Fire-induced shift from *Pinus* to *Quercus* forests: a twenty-year study following the 1996 Goseong forest fire

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Background: The 1996 Goseong forest fire, the largest recorded, prompted a debate on the potential for natural forest recovery, leading to the designation of a natural restoration research area. This study mainly aimed to demonstrate the forest's natural regenerative ability in a prefire *Pinus densiflora* forest that had been affected by a stand-replacing fire. To achieve this, the study tracked the key aspects of the succession process, specifically the formation of vertical structure and changes in species composition.
Results: The regenerating vegetation initially passed through stages dominated by herbaceous and shrub layers, then differentiated into the canopy layer, eventually forming the early-stage forest after 20 years. Site A had developed into a forest with an average canopy height of 13.3 m and 73% coverage, while Site B was restored with a canopy height of 10 m and 27% coverage. Tree species of the genus *Quercus* dominated the canopy layer, occupying 99% of the tree basal area (from 17% prefire). Consequently, the prefire pine forest shifted to a *Quercus*-dominated forest after secondary succession. *Pinus densiflora* (83% of the prefire basal area) occupied only 1% after 20 years. Oak species became dominant from the initial stages of regeneration, playing a key role in shaping the early-stage forest structure. The species composition of the regenerating stands was already determined in the initial stage and closely resembled that of 20 years later. Since most species regenerated through resprouting, the understory remained dominated by pine forest companion species. Oak-associated species tended to increase in later stages. No invasive species were observed, and annual plants had low abundance.
Conclusions: The study demonstrated the natural regenerative power of the forest following the fire, revealing that it takes around 20 years for a prefire pine forest to be restored an early-stage oak-dominated forest. *Quercus* trees, particularly *Quercus variabilis* and *Quercus mongolica*, regenerated rapidly immediately after fire, contributing to the development of the early-stage forest. Although this study was small in scale, it is a rare study conducted at permanent plots over 20 years, revealing the secondary succession process.

Keywords: disturbance, initial floristics, natural regeneration, secondary succession, sprouting

Introduction

Fire is one of the significant disturbances that impact the structure and function of natural ecosystems (e.g., Dietze and Clark 2008; Turner et al. 1997; Vesk and Westoby 2004). In boreal and Mediterranean climate regions, fires occur naturally with high frequency (e.g., Hart and Chen 2008; Johnstone et al. 2004; McKenzie and Tinker 2012). In Korea, however, hundreds of human-caused forest fires occur annually (Jeon and Chae 2016; Lee et al. 2005).

Since the 1970s, the primary disturbance factor that has affected forests on a large scale in Korea has been insect infestations and pest outbreaks (Park et al. 2009). Although they still occur over considerable areas, they are controlled to the extent that they do not cause severe damage. In contrast, fire is increasingly becoming an important disturbance factor affecting forests (Baek et al. 2022; Choung 2002). The frequent occurrences of large forest fires on the east coast during the spring are related not only to climatic phenomena such as strong winds but also to the widespread distribution of young pine forests (Seo and Choung 2014). In Korea, most fires initially occur in pine forests (Lee et al. 2005). Pine needles are easily ignited by sources like cigarette butts and burn at high temperatures for extended periods, making them particularly vulnerable to fire (Seo and Choung 2010). The vulnerability of pine forests is exacerbated by their continuous distribution and the accumulation of fuel due to forest development in recent decades (Choung et al. 2004; Lee et al. 2005; Seo and Choung 2014).

The 1996 Goseong fire received significant public attention due to its unprecedented scale, affecting 3,762 hectares—setting a record for forest fires at that time (Korea Forest Research Institute 1996). The subsequent forest restoration policy sparked concerns about the drawbacks of reforestation, while the potential for natural forest recovery through the ecosystem's inherent resilience became a significant social issue. This became the first significant social issue regarding postfire restoration (Choung et al. 2002; Dong-A Ilbo 2000; The Ecological Society of Korea 2000). Before this event, reforestation was the mandatory approach for restoring fire-affected forests (Ryu et al. 2017). Although this marked the first academic challenge to the prevailing forest restoration policy, research on postfire recovery was scarce, and existing studies were typically short-term, lasting only a few years, with no long-term investigations into natural forest regeneration (e.g., Cho and Kim 1992; Choung and Kim 1987; Kang and Lee 1982; Kim 1989). The issue gained further momentum when an even larger fire occurred on the East Coast in 2000, burning approximately 24,000 hectares (The Joint Association for the Investigation of the East Coast Fires 2000), further intensifying the debate over reforestation versus natural recovery.

Following a disturbance, secondary succession initiates due to the ecosystem's resilient characteristics (Barbour 1999; Burrows 1990). According to classical successional theory, a fire severely degrades forest structure, leading to its replacement by early successional species (McKenzie and Tinker 2012). However, this theory primarily applies to certain fire-prone forests that rely on seed sources or to areas that were heavily disturbed before the fire, resulting in low resprouting ability. In reality, many types of vegetation do not regress to earlier successional stages due to the resprouting capacity of preexisting plant species. Studies have shown that these species can regenerate through resprouting, generally restoring the vegetation to its prefire state (e.g., Bond and Midgley 2001; Choung and Choung 2019; Jung et al. 2023; Vesk and Westoby 2004).

Currently, 22% of South Korea's forested area consists of *Pinus densiflora* forests, most of which developed naturally (Korea Forest Service 2019). Pine forests cover the largest area of any single tree species. Their widespread presence indicates that site conditions were severely degraded in the past, particularly until the 1970s (Choung et al. 2020; Lee et al. 2010). In these degraded areas, the sites were extremely barren and dry, making the pine the most suitable species for establishment, and few tree species had the ability to resprout. However, if a disturbance occurs in these current pine forests, unlike in the past, the likelihood of natural restoration to pine forests is low. This is because the structure of these forests has changed significantly over time. Today's pine forests have a richer species composition, including not only deciduous trees as successor species but also shrubs and herbaceous plants capable of resprouting (Choung and Choung 2019). This formed the theoretical basis for suggesting the possibility of natural restoration after the Goseong fire. However, at that time, there was a lack of data to support this claim.

As the debate intensified, the Korea Forest Service designated a natural restoration research area in the forest affected by the Goseong fire. The most direct and clear way to document succession is through repeated monitoring of the same area over time (Barbour 1999). However, in practice, many researchers find it challenging to conduct direct successional studies this way due to the extended timeframes and resource limitations. As an alternative, they conduct chronosequence studies, which involve examining stands of different ages but under similar climate and site conditions simultaneously (Barbour 1999; Lee and Kim 1995). We also previously presented the chronosequence of the succession process following fires (Choung et al. 2002; Lee et al. 2004).

We established permanent plots within the natural restoration research area, specifically in prefire *P. densiflora* forests where the aboveground vegetation was completely lost due to a stand-replacing fire. Over 20 years, we conducted a classical direct study, tracking the successional process through repeated measures. We set the restoration goal as having the regenerating forest reach an early-stage forest. The burned landscape was a mosaic of forest patches with different stand ages (Korea Forest Research Institute 1996). Therefore, it was not possible to set the age or condition of the pre-fire stands as a single restoration target. The key questions were: First, how long does it take for the fire-affected stands to reach an early-stage forest through natural regeneration? Second, does the type of forest change as a result of the disturbance, and if so, at what stage of the regeneration process is this determined? Third, how do the composition and diversity of plant species change after the fire?

We defined an early-stage forest as one where secondary succession, after a stand-replacing disturbance, leads to the establishment of a tree canopy layer (with canopy trees exceeding 8 m in height) that achieves more than 10% coverage. The Food and Agriculture Organization (FAO) defines a forest as an area with a canopy cover exceeding 10% composed of trees that can reach a minimum height of 5 m (FAO 2010). We applied the 10% coverage criterion from this definition but modified the canopy tree height standard to 8 m. In Korea, trees that form the uppermost layer of the forest typically grow to a height of 8 m or more, so it is common practice to use this height as the standard for defining the canopy layer (Yeochon Association for Ecological Research 2005).

Materials and Methods

Study area

The Goseong Fire, which occurred in April 1996, affected 3,762 hectares of forested area in Goseong-gun, Gangwon-do (Korea Forest Research Institute 1996). At the time of the fire, maximum wind speeds ranged from 17 to 27 m s^{-1}, and relative humidity was low, between 26% and 53% (Korea Forest Research Institute 1996). Goseong has an average annual temperature of 12.6°C and an average annual precipitation of 1,127 mm. Due to the influence of the monsoon climate, more than half of the precipitation occurs during the summer months (July to August), while the rest of the year is mostly dry.

Before the fire, the vegetation consisted of 63% coniferous forest (primarily *P. densiflora* stands), 31% coniferous and broadleaved mixed forest, and 6% broadleaved forest. The forests were approximately 40 years old, characterized by shallow soil depth, a high content of gravel, and low site productivity (Korea Forest Research Institute 1996). About 46% of the area experienced stand-replacing fire, while 54% experienced surface fire (Lee and Hong 1998). The *P. densiflora* forests, in particular, were severely burned.

Establishment of permanent plots

We established permanent plots in two natural restoration research sites designated by the Korea Forest Service. These two sites are located approximately 4 km apart: Site A covers 70 hectares (The geographic coordinates of site A is 38°19'2.04"N, 128°29'3.41"E), and Site B covers 30 hectares (Site B is 38°19'22.46"N, 128°27'29.73"E). In March 1998, two years after the fire, we set up eight 10 m × 10 m permanent plots at each location.

Both sites were *P. densiflora*-dominated forests before the fire, and the above-ground vegetation was completely burned by stand-replacing fire. Site A is located on a southeastern slope at an average elevation of 130 m, with a slope of 30 degrees and a soil depth of 78 cm. In contrast, Site B is also on a southeastern slope but at a higher elevation of 225 m, with a slope of 25 degrees and a shallower soil depth of 34 cm, containing more gravel in the topsoil. Due to the plots being established two years after the fire, early regeneration had already begun. Site A already showed faster regeneration compared to Site B.

However, in 2000, the East Coast Fire occurred (The Joint Association for the Investigation of the East Coast Fires 2000). A significant portion of Site A was burned again, though some areas were preserved. The permanent plots we had established at Site A were also burned by the fire. Consequently, subsequent repeated monitoring was conducted only at Site B.

Prefire stand structure

There are no records of the vegetation in the study areas before the fire. To obtain this information, we measured the diameter at breath height (≥ 2.5 cm) of the canopy trees that remained standing but were burned in the permanent plots. We identified the tree species based on bark characteristics and tree morphology. Since we reconstructed the structure of the prefire forest using these burned trees, it is likely that our estimates were lower than the actual values. This is because severe burning of the bark by fire can result in a smaller measured diameter compared to when the tree was alive.

Development of vertical stand structure

We investigated the developmental process of the vertical stand structure at Site B at 5, 7, 9, 16, and 20 years after the fire. The vegetation was divided into five layers based on plant height: canopy layer (≥ 8 m), subcanopy (5–8 m), first shrub (2–5 m), second shrub (0.5–2 m), and herbaceous (< 0.5 m for woody species). The abundance of each layer was visually estimated by assessing the projected coverage, which is the proportion of ground covered by the vertical projection of the canopy. The height of each layer was determined by measuring the tallest plant within each layer using a hypsometer or a steel tape measure.

The vertical structure of Site A was also examined 20 years after the fire (in 2016) across eight plots (10 m × 10 m). Since the permanent plots we established were burned again in the 2000 fire, we randomly selected areas that had not burned in 2000 and had been recovering since the 1996 fire.

Change in species composition

The coverage of all species appearing in each layer was visually assessed. For clump-structured plants, such as woody plants with multiple sprouts, the coverage was measured by the widest part of the crown of each clump. The classification of species' growth forms followed Choung et al. (2021). Species diversity was calculated using the Shannon–Weiner diversity index ($H' = -\sum P_i \ln P_i$, where P_i is the relative coverage). Species richness (R) was determined by the number of species, and species evenness was calculated using the formula $H' / \ln R$.

Canopy tree abundance and basal area accumulation

The changes in canopy tree density and basal area accumulation were repeatedly tracked within the permanent plots. At the time of plot establishment, all regenerated stems (with a height of 10 cm or more) were labeled with paint at a height of 10 cm above the ground. The diameter at the labeled point was measured over a 20-year period following the fire (at 2, 3, 4, 5, 7, 9, 11, 16, and 20 years). During each measurement period, only the living stems were measured. Additionally, any stems that had grown to the target size (≥ 10 cm in height) were newly labeled and included in subsequent monitoring.

Results

Prefire stand structure

The study area (B site) was a typical pine stand dominated by *P. densiflora* in the canopy layer before the fire (Table 1). In addition to pine, there were six canopy tree species including *Quercus variabilis*, *Quercus mongolica*, *Quercus serrata*, *Quercus dentata*, and *Robinia pseudoacacia*. There were 1,713 trees per hectare with a diameter of 10 cm or more, of which 1,400 were pine trees, accounting for 81.7% of the total. The remaining broadleaved trees made up 18.3%. The total basal area was 51.1 m^2 per hectare, with pine contributing 46.1 m^2 (90.2%), while broadleaved trees contributed 5.1 m^2 (9.8%). In contrast, for trees with a diameter of less than 10 cm, the density of broadleaved trees was 1.8 times that of pine, and the basal area was 2.9 times greater, indicating that broadleaved species dominated the understory. Among the broadleaved trees, *Q. variabilis* was the most dominant. Although the tree number was only 0.9 times that of *Q. mongolica*, its basal area was 1.4 times greater.

Development of the stand structure over time

We tracked the regeneration process of a forest affected by a stand-replacing fire, assessing its development by monitoring the formation, height, and coverage of each layer (Fig. 1). Although regeneration began the year of the fire, we first measured the forest structure five years later. By that time, the herbaceous layer, second shrub layer, and first shrub layer had already formed (Fig. 1A). Nine years after the fire, a subcanopy layer had developed above these

Table 1 The prefire structure of the *Pinus densiflora* forest was reconstructed based on the burned canopy trees in the permanent plots (Site B)

Diameter[a] class (cm)	Coniferous	Broadleaved			Total
	Pinus densiflora	*Quercus variabilis*	*Quercus mongolica*	Others	
No. of stems ha^{-1}					
2.5–4.9	188	25	238	-	450
5.0–9.9	375	288	213	50	925
10.0–19.9	825	188	100	-	1,113
20.0–49.9	575	-	13	13	600
Total	1,963	500	563	63	3,088
Basal area (m^2 ha^{-1})					
2.5–4.9	0.2	0.0	0.3	-	0.5
5.0–9.9	1.6	1.4	1.0	0.2	4.2
10.0–19.9	13.7	2.7	1.1	-	17.6
20.0–49.9	32.4	-	0.6	0.5	33.5
Total	48.0	4.1	3.0	0.7	55.8

-: not applilcable.
[a]Stem diameter over 2.5 cm at breast height.

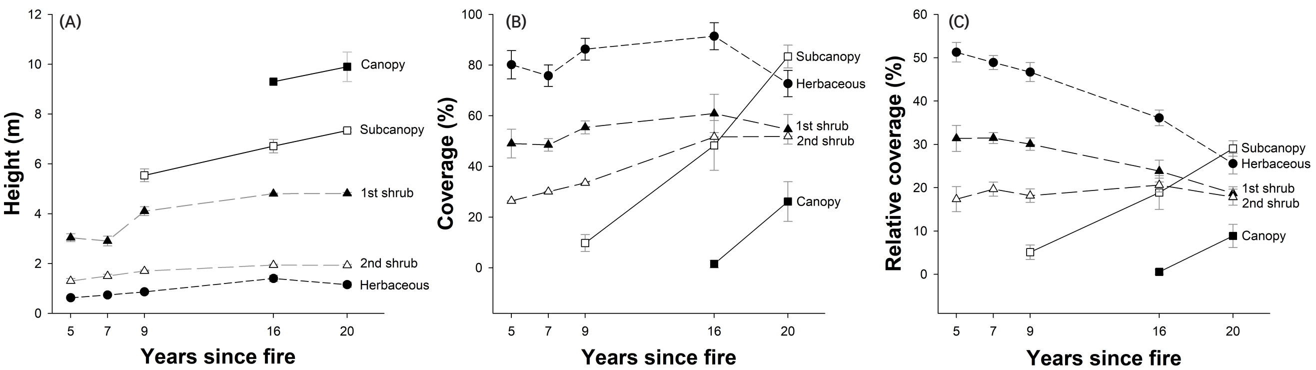

Fig. 1 The formation of an early-stage forest through the development of vertical structure. (A) Height by layer, (B) coverage by layer, and (C) relative coverage by layer. Data was collected from permanent plots (Site B). The average ± standard error (n = 8) is provided.

layers, and by 16 years, the canopy layer had emerged. Although initially with low coverage, by 20 years, canopy coverage increased to 26%, exceeding the 10% threshold for an early-stage forest.

The herbaceous layer maintained over 70% coverage from the beginning, while the second shrub layer showed a gradual increase over time (Fig. 1B). The first shrub layer had higher coverage than the second shrub layer, increasing gradually before declining after 20 years. The subcanopy layer expanded rapidly, reaching 48% coverage by year 16 and 83% by year 20. Some of the rapidly growing subcanopy trees had joined the canopy by year 16, with the canopy reaching 26% coverage by year 20. When comparing the relative coverage across layers, two distinct trends emerged (Fig. 1C): the lower layers (herbaceous and shrub layers) had high relative coverage early on but declined over time, while the subcanopy and canopy layers, which appeared later, rapidly increased in coverage.

To compare with Site B, the vertical structure of Site A was measured once, 20 years later. Site A had developed into a forest with a canopy height of 13.3 m and a coverage of 73% (Fig. 2). In contrast, Site B had a canopy layer height of 9.9 m and coverage of 27%, indicating a marked difference in forest structure. Site A had a higher coverage in the canopy layer but lower coverage in the understory layers compared to Site B.

Density regulation and biomass accumulation of canopy tree species over time

In Site B, 10 canopy taxa were observed over the study period. Of the 6 taxa identified from the burned trees (*P. densiflora*, *Q. variabilis*, *Q. mongolica*, *Q. serrata*, *Prunus sargentii*, and *R. pseudoacacia*), only 5 species (excluding *R. pseudoacacia*) were found to regenerate. Additional taxa observed included *Q. dentata*, *P. sargentii*, *Fraxinus rhynchophylla*, *Sorbus alnifolia*, and *Styrax obassia*. These new taxa were not regenerated from seeds but rather resprouted from surviving trees that were present before the fire. These species were present in the prefire vegetation but were not included in the initial measurements because their diameters were smaller than the 2.5 cm threshold used for inclusion.

Thanks to vigorous resprouting immediately after the fire, the total number of stems peaked at 38,000 stems ha^{-1} three years after the fire (Fig. 3A). This number gradually decreased to 14,238 stems ha^{-1} after 20 years. Basal area steadily increased from 2.6 m^2 ha^{-1} two years after the fire to 30.1 m^2 ha^{-1} after 20 years (Fig. 3B). When examined by species, *Q. mongolica* initially had a large number of stems, but this declined rapidly over time. A small number of *P. densiflora* seedlings that germinated from seeds were observed growing within gaps in the regenerating forest. Excluding *P. densiflora*, the basal area of broadleaved species increased linearly (Fig. 3D). Although the basal area of *Q. mongolica*, which had the highest stem density, was the largest until 16 years after the fire, by year 20, the basal area of *Q. variabilis* surpassed that of *Q. mongolica*.

Over the 20-year period, the diameter distribution and the basal area of the regenerated trees were analyzed (Table 2). The distribution exhibited the typical characteristics of a regenerating stand, with a majority of stems having a diameter of 2.5 cm or less. However, 7.5% of all stems had diameters of 10 cm or more, and there were even a few *Q. variabilis* with diameters exceeding 20 cm.

Q. mongolica accounted for 52.1% of the total stem count, followed by other broadleaf species at 29.5%, and *Q. variabilis* at 18.0%. While *P. densiflora* did regenerate, it constituted only 0.4% of the total stems and was confined to gaps in the forest. The stem count of *Q. mongolica* was 4.1 times that of *Q. variabilis* and 1.6 times that of other broadleaf species.

The distribution of basal area differed from that of stem count (Table 2). The largest basal area was found in the 10.0–19.9 cm diameter class. *Q. variabilis* accounted for 41.5% of the total basal area, followed by *Q. mongolica* at 39.8%, with other broadleaf species making up 17.3%. *P.*

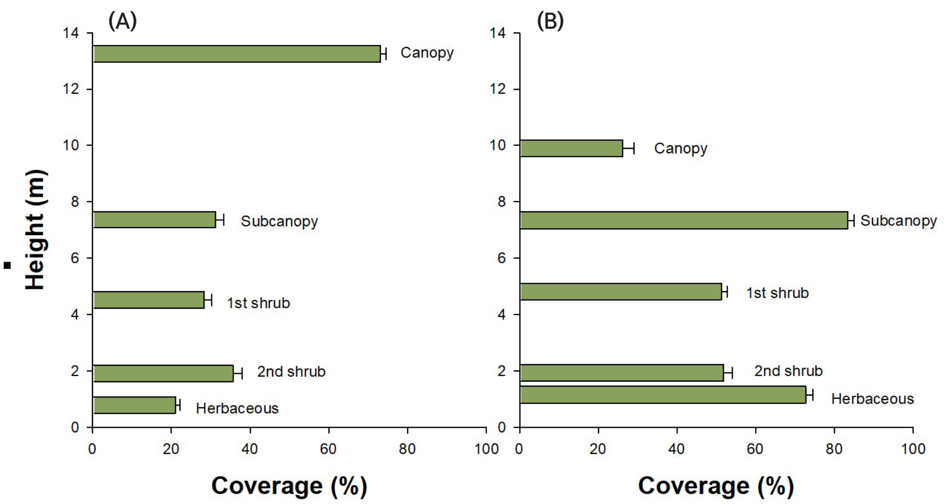

Fig. 2 The vertical structure of early-stage forests regenerating over 20 years at two sites, (A) and (B) following the fire. Average ± standard error is provided (n = 8).

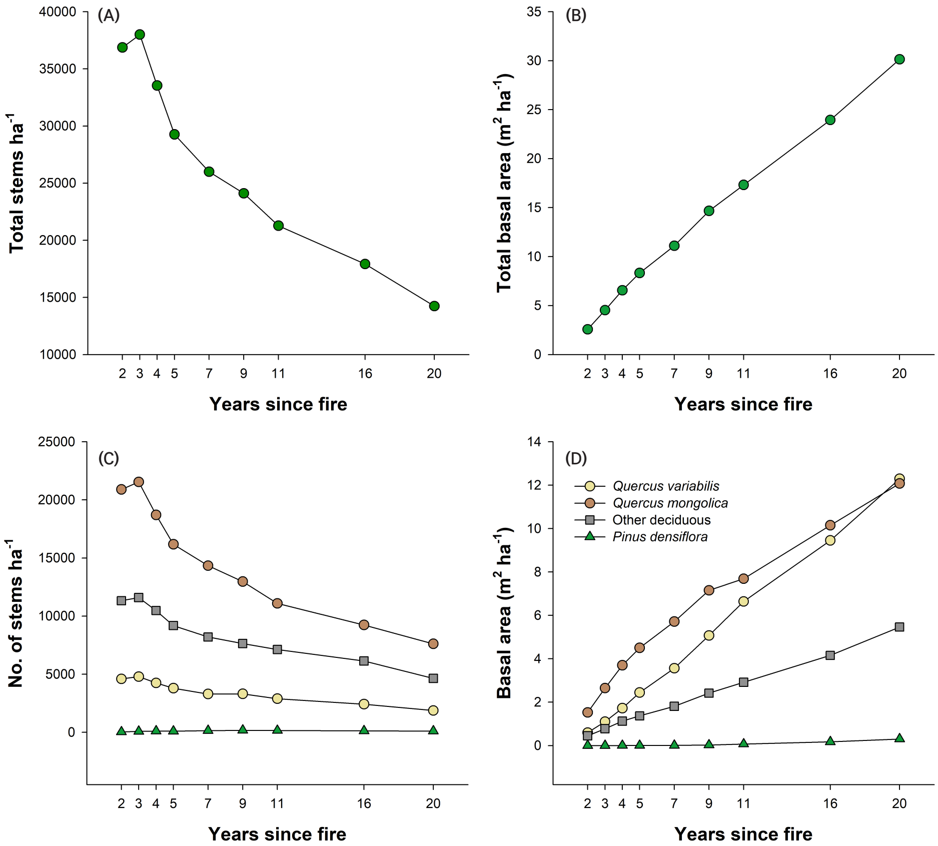

Fig. 3 Temporal changes in (A) total number of stems, (B) total basal area accumulation, (C) the number of stems by canopy tree species, and (D) basal area by canopy tree species. Data was collected from permanent plots over 20 years (Site B).

Table 2 The postfire stand structure of the forest regenerated for 20 years in the permanent plots (Site B)

Diameter class (cm)	Coniferous	Broadleaved			Total
	Pinus densiflora	*Quercus variabilis*	*Quercus mongolica*	Others	
No. of stems ha^{-1}					
0.1–2.4	88	613	3,963	2,575	7,238
2.5–4.9	-	200	1,775	1,213	3,188
5.0–9.9	13	425	1,563	750	2,750
10.0–19.9	13	613	313	100	1,038
20.0–30.0	-	25	-	-	25
Total	113	1,875	7,613	4,638	14,238
Basal area (m^2 ha^{-1})					
0.1–2.4	0.0	0.0	0.4	0.3	0.8
2.5–4.9	-	0.2	1.9	1.2	3.3
5.0–9.9	0.0	1.9	6.4	2.7	11.1
10.0–19.9	0.3	9.2	3.4	1.2	14.1
20.0–30.0	-	0.9	-	-	0.9
Total	0.3	12.3	12.1	5.5	30.1

-: not applilcable.

densiflora contributed only 1.0% to the basal area. The basal area of *Q. variabilis* was equivalent to that of *Q. mongolica* and 2.2 times larger than that of other broadleaf species.

The total basal area of the species that regenerated over 20 years was 29.4 m^2 ha^{-1} (for diameters greater than 2.5 cm). This represents a recovery of 52.7% compared to the prefire basal area of 55.1 m^2 ha^{-1}. The stem count ratio of *Q. variabilis* to *Q. mongolica* decreased from 0.9 before the fire to 0.3 after 20 years, while their basal area ratio increased from 1.4 to 2.1.

Species composition and diversity

The temporal changes in the number of species and coverage for each layer and growth form in the forest structure were presented (Table 3). Five years after the fire, a total of 60 species (800 m^2) were recorded. While there were some fluctuations among perennial and annual herbaceous spe-

Table 3 Changes in species composition by layer and growth form in the permanent plots (Site B) over 20 years following the fire

Layer	Growth form	5 years		7 years		9 years		16 years		20 years	
		No. sp[a]	C (%)[b]	No. sp	C (%)	No. sp	C (%)	No. sp	C (%)	No. sp[a]	C (%)
Canopy	Tree[c]							1	1.5	3	26.1
Subcanopy	Tree			2	4.8	2	12.9	3	51.4	4	100.0
1st shrub	Tree	7	47.8	6	50.0	5	63.1	8	59.5	8	54.5
	Shrub[c]	5	5.5	4	2.3	4	3.3	5	4.0	5	3.8
2nd shrub	Tree	9	15.5	10	16.2	9	16.4	8	15.5	7	15.4
	Shrub	7	14.8	8	14.3	9	22.8	10	36.7	11	37.5
Herbaceous	Tree	7	2.8	7	3.8	8	3.6	10	1.0	9	1.5
	Shrub	13	11.6	13	12.4	13	10.5	14	5.9	13	10.2
	Herb[d]	37	106.8	32	80.6	34	97.7	40	94.3	40	65.0
	Perennial	34	106.5	29	79.9	32	96.5	38	94.0	38	64.8
	Annual	3	0.3	3	0.7	2	1.3	2	0.2	2	0.1
Total		60	204.8	55	184.4	57	230.4	68	269.7	65	314.0

[a]Number of species, [b]cover, [c]tree refers to canopy tree species only, while shrub includes all woody species except for canopy tree species. Shrub species were dominant over other woody species. [d]Herb is the sum of perennial and annual species, and data for perennial and annual species are additionally presented.

Table 4 Temporal changes in species diversity indices at permanent plots (Site B) over 20 years following the fire

Attribute	Years since fire				
	5 years	7 years	9 years	16 years	20 years
Species diversity index (H′)	2.39	2.46	2.57	2.50	2.34
Species evenness	0.58	0.61	0.63	0.59	0.56
Species richness	60	55	57	68	65

Plot size 10 × 10 m^2 (n = 8).

cies, the species composition of the early stand closely resembled that of the 20-year-old stand. In the first shrub layer, 7 tree species emerged, with *Q. mongolica* and *Q. variabilis* being dominant. Among shrubs, *Lespedeza cyrtobotrya* and *Zanthoxylum schinifolium* showed high coverage.

In the herbaceous layer, 57 species were recorded, of which 37 were herbaceous. Dominant species included typical pine forest plants such as *Carex humilis* var. *nana*, *Spodipogon sibiricus*, and *Pteridium aquilinum* var. *latiusculum*. While three annual species, including *Commelina communis*, appeared, the relative coverage of annual species was only 0.3%. No alien species were observed during the entire survey period.

Over 20 years, the total coverage of tree species (sum of all five layers) was 66% five years after the fire and surged to 75%, 96%, 129%, and 198% after 7, 9, 16, and 20 years, respectively. By the 20th year, *Q. variabilis*, *Q. mongolica*, and *P. sargentii* formed the canopy layer, with *Q. variabilis* being the most dominant. However, in the subcanopy layer, *Q. mongolica* slightly outcompeted *Q. variabilis*. Coverage of herbaceous species peaked at 107% five years after the fire but dropped to 65% by the 20th year.

The total number of species was 60 after five years, and though it initially declined due to a reduction in herbaceous species, it peaked at 68 species by 16 years (Table 4). New seedlings such as *Betula schmidtii*, *Acer pseudosieboldianum*, *F. rhynchophylla*, and *Actinidia arguta* appeared, along with herbaceous plants like *Viola collina*, *Viola keiskei*, *Chimaphila japonica*, *Polygala japonica*, and *Lilium amabile*. The number of annual species decreased from 3 to 2, and their populations weakened to just a few individuals. The evenness index remained fairly stable, peaking by 9 years and then slightly decreasing. The diversity index (H′) followed a similar trend, dropping from 2.39 five years after the fire to 2.34 by 20 years.

Discussion

The mechanisms of ecological succession have long been debated, but it is well established that most ecosystems undergo directional succession, eventually developing into stable systems following disturbances (e.g., Barbour 1999; Bormann and Likens 1994; Burrows 1990; Finegan 1984). However, in Korea, research on succession, especially in the context of postfire natural regeneration, is limited. Historically, burned forests have been subject to mandatory reforestation. As a result, the prevailing belief among both the public and scholars has been that natural restoration of burned forests through succession would take an extended period and might not lead to the development of a healthy forest (Choung et al. 2002; Dong-A Ilbo 2000; The Ecological Society of Korea 2000).

We hypothesized that, unlike the heavily degraded forests of the past, Korea's forests have regained their natural resilience, enabling them to recover quickly into sound forests. Since the 1970s, forest utilization has significantly decreased due to a change in fuel sources and economic growth (Lee et al. 2010). As a result, the dominance of species with resprouting abilities has increased.

To test this hypothesis, we conducted a comprehensive study, including direct succession research through the establishment of permanent plots in forests affected by the East Coast fires, with findings already reported (Jung et al. 2023). We also examined vegetation recovery in various East Coast areas with varying times elapsed since past fires (Choung et al. 2002; Lee et al. 2004).

Restoration to early-stage forest in twenty years

Once spring fires are extinguished, vegetation begins to regenerate almost immediately (Choung and Choung 2019; Hwang et al. 2011; Lee and Choung 2022). Tree species grow rapidly and occupy the upper layer of the regenerating vegetation. Although there are site-specific variations, in some locations, a two-layer shrub structure can develop within the fire year (Choung et al. 2004). Over time, the species that initially formed the shrub layer evolve into a sub-canopy layer and eventually differentiate into a full canopy layer. In this study, the canopy layer developed by the 16th year. After the 1986 fire in Songgang-ri, Goseong, the canopy layer developed by the 13th year, reaching a height of 10 m and 60% coverage by the 17th year (Choung et al. 2002; Lee et al. 2004). Similarly, in a permanent plot in Samcheok affected by the 2000 East Coast fire, the canopy layer began to develop by the 13th year and by the 20th year, had formed a forest with a height of 10 m and 25% coverage (Lee 2022). A similar development of the canopy layer was observed in pine forests in Japan 18 years after a fire (Angara et al. 2000).

In most areas, the canopy layer appears a few years before the 20-year mark. As these layers continue to develop, they evolve into 'early-stage forests' as we modified from FAO (2010), with a height of over 8 m and more than 10% coverage. The notable differences in forest development between Sites A and B in this study highlight the significant impact of site conditions such as soil depth, fertility, and moisture conditions. In areas such as pine forests established on rocky or shallow soils, early-stage forests did not form within 20 years (Jung et al. 2023). This slower regeneration is likely due to a lack of resprouting sources and significant soil moisture stress (Boiffin and Munson 2013; Harvey et al. 2016). However, these poorly regenerating sites represent a minimal portion of the overall affected area. Therefore, we suggest that in 'most' areas, restoration to early-stage forests can occur within approximately 20 years.

Complete canopy shift from pine forests to oak forests

The prefire pine forests shifted entirely to oak forests 20 years after the fire (Fig. 4), with the basal area recovering to approximately 52.7% of prefire levels within this time. In the Hubbard Brook area in the United States, the basal area was 18.7 m^2 ha^{-1} (> 5 cm) 20 years after logging (Reiners 1992). Applying the same diameter and 20-year criteria, this study recorded 26.0 m^2 ha^{-1}, while the permanent survey site in Samcheok recorded 23.0 m^2 ha^{-1} (Jung et al. 2023), indicating higher biomass accumulation compared to the logged areas in Hubbard Brook.

The resulting forests were co-dominated by *Q. variabilis* and *Q. mongolica* 20 years after the fire. However, considering the growth rate of the former species, its dominance is expected to further increase. The dominance of *Q. variabilis* was also observed in other fire-affected regions, such as Imwon-ri in Samcheok (20 years post-2000 fire), Songgang-ri in Goseong (34 years post-1986 fire), Gwanmobong in Yangyang (38 years post-1980 fire), and Eoseongjeon in Gangneung (48 years post-1972 fire) (Jung et al. 2023). In the early stages of regeneration, *Q. mongolica* produced more sprouts, while *Q. variabilis* produced fewer but taller

Fig. 4 Photos from the forest regenerated over 20 years following the stand-replacing fire. Left: overview of the natural restoration area (Site A), where nearly the entire landscape has shifted from a prefire *Pinus densiflora* forest to a postfire *Quercus*-dominated forested landscape. Top right: a *Quercus variabilis* stand, where the regeneration of this species was particularly prominent. Middle right: measuring the height of *Q. variabilis* trees. Bottom right: the largest *Q. variabilis* that has regenerated over 20 years in the survey plot, with a diameter at breath height of 22.5 cm.

stems, allowing it to reach the canopy layer first and accumulate more basal area than *Q. mongolica* by the 20th year (Jung et al. 2022; Shin 2015). Before the fire, the higher basal area of *Q. variabilis* likely provided a foundation for its dominance over *Q. mongolica*. Additionally, this species is known for its drought tolerance, to the extent that it can form pure stands in limestone areas, which may have favored its growth under the dry conditions following the fire (Choung and Lee 2019).

Meanwhile, the fate of *P. densiflora* that regenerated from seed germination in the regenerating stand occupied the gaps within the stand. However, these gaps are likely to be filled by taller resprouting species, which will shade out the light-demanding pines, ultimately leading to their disappearance. The pine stands, which were once dominant across a wide area in the pre-fire landscape, have now been reduced to small patches found in open areas or rocky ridges across several regions (Jung et al. 2023; Shin et al. 2014).

Species composition and regeneration strategy

Choung and Choung (2019) studied the regeneration strategies of plants in fire-affected areas of the East Coast, finding that approximately 81% of species regenerated through resprouting from stem bases or clonal organs, contributing to 95% of the total coverage. Resprouting species, with their deep roots, withstand moisture stress well, leading to rapid early growth that suppresses the establishment and growth of seed-regenerating species, giving them a competitive advantage (González-De Vega et al. 2018). The mortality rate of resprouting species was also low (Kim 2015). Consequently, fires burn the aboveground parts of the forest but do not significantly alter the species composition of vegetation (i.e., the species list) (Abrahamson 1984a, b; Han et al. 2015). We investigated the species composition of unburned pine forests as a reference in previous studies (Choung and Choung 2019). By comparing it with the species composition of early post-fire regenerating vegetation, we found that there was almost no difference in terms of species absence and presence.

All deciduous tree species in the study area exhibited resprouting regeneration (Choung and Choung 2019). These tree species quickly occupied space and grew rapidly, contributing to the rapid restoration of the forest's vertical structure. No invasive species were observed, and annual species had low dominance. Initially, *P. aquilinum* var. *latiusculum* and *L. cyrtobotrya* dominated, but their coverage decreased over time, while *Lespedeza maximowiczii* and *Rhododendron schlippenbachii* species, common in oak forests, increased, and *A. pseudosieboldianum* also became established.

Although the canopy shifted to an oak-dominated, the species composition of the understory changed gradually, maintaining the typical species composition of a pine forest (e.g., Choung and Hong 2006; Chun et al. 2007; Lee and Lee 1989). Most species present before the fire, except for pine, resprouted (Choung and Choung 2019; Rodrigo et al. 2004). The herbaceous layer, which maintained high coverage for 20 years, likely limited the available space for oak forest companion species to recruit and establish. This suggests that during postfire succession, canopy species expand their dominance first, followed by the introduction of typical understory species under the oak canopy. We observed that in the *Q. variabilis* forests of two regions, 35 (Songgang-ri, Goseong) and 48 (Eoseongjeon, Gangneung) years after the fire, pine-associated species were replaced by oak-associated species. There were also differences in species composition between the two regions. This study area is geographically close to both locations and has similar climatic and soil conditions. Therefore, it is expected that this community will develop over time into a community with a species composition similar to that of the two regions along the successional pathway.

Forest management and implications

This study was conducted in a "natural restoration research area" (100 ha) designated by the Korea Forest Service. The area was selected to study natural restoration following debates about restoration policies after the Goseong fire. Although the prefire pine forest was nearly burned by the stand-replacing fire, the forest naturally restored itself remarkably well, completely shifting from a pine forest to an oak forest (Fig. 4).

Even without disturbances like fires, pine forests naturally transition to oak forests since they are pioneer forests (Choung et al. 2020). Abrahamson (1984a, b) argued that fires accelerate this slow successional process, with Abrams (1992) suggesting that fires contributed to the proliferation of oak forests in eastern North America. Since the 1970s, oak forests have occupied large areas in South Korea, likely due to the resprouting regeneration of oaks following logging or fires (Choung et al. 2020).

Aside from the 100 ha natural restoration research area, most of the 3,762 ha of fire-affected forest in Goseong was subjected to artificial reforestation (Korea Forest Research Institute 1996). This reforestation process repeated many of the issues previously criticized in plantation efforts, including planting fire-prone *P. densiflora* trees over large areas. Inappropriate reforestation with species like *Pinus koraiensis* and *Pinus thunbergii* led to large-scale mortality. However, the most severe issue was soil erosion (Hwang et al. 2007). Burned trees and early regenerating ground vegetation were removed, roads were constructed for planting, and heavy machinery was used, exposing mineral soils and causing significant soil erosion, which washed away organic nutrients, including ash. Soil erosion immediately after a fire is more influenced by vegetation cover than by weather conditions (Kim et al. 2021). The issues caused by the salvage logging and postfire reforestation have also been raised by Donato et al. (2006) in western U.S. forests, leading to considerable debate.

In contrast, naturally restored forests significantly reduce secondary damage. Rapid early vegetation regeneration effectively prevents erosion (Kim et al. 2021), and naturally restored forests quickly develop a healthy structure compared to plantations (Choung et al. 2002). Additionally, oak forests support high biodiversity. Hwang et al. (2011) argued that oaks regenerated through resprouting tend to decay internally within a few years. In areas where forestry management is not the primary goal, allowing natural forests to establish is desirable from both ecological perspectives. Furthermore, oak forests, especially *Q. variabilis* forests, act as firebreaks. It has thick bark, a characteristic of fire-resistant species (Agee 1993; Seo and Choung 2010, 2014).

The East Coast region accounts for two-thirds of all large fires (Choung 2002). Currently, pine forests cover extensive areas, with young forests distributed continuously. A viable strategy to prevent large fires is to promote the development of oak forests through natural restoration when the opportunity arises. This would create a mosaic of firebreak forests, interspersing oak forests with pine forests.

This study represents a small-scale, long-term ecological research project. While it does not account for various factors such as different fire regimes or burn severities, it remains significant as one of the few classical long-term succession studies in South Korea. It explores natural restoration through postfire succession and provides valuable research findings on the issues that emerged following the Goseong fire.

Conclusions

This study was conducted in a designated natural restoration research area following the 1996 Goseong fire. Permanent plots were established in a prefire pine forest that had experienced stand-replacing fire, and the research was carried out over a 20-year period using long-term repeated measures in a classical direct succession study. The findings revealed that the regenerating community developed a canopy layer within 20 years, forming an early-stage forest. The extent of quantitative development varied depending on site conditions. The pine forest, which was entirely burned by the fire, shifted completely to a *Quercus* forest dominated by mainly *Q. variabilis* and *Q. mongolica*. This trend was apparent from the early stages of regeneration, with oak species quickly becoming dominant and contributing to the early forest structure. However, the understory layer remained dominated by species associated with the original pine forest. The initial species composition was largely maintained until the 20th year. However, in the later stages of the study, oak-associated species began to appear. No invasive species were observed, and the presence of annual plants was minimal.

As a small-scale, long-term ecological study, this research has demonstrated the natural restoration capacity of forests following the Goseong fire and has provided valuable insights into changes in forest structure and species composition during the secondary succession process.

Abbreviation

FAO: The Food and Agriculture Organization

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Authors' contributions

YC conceptualization, methodology, investigation, supervision, project administration, data curation, funding acquisition, writing – original draft, and writing – review & editing. KSL conceptualization, methodology, investigation, supervision, and writing – review & editing. HKO investigation, validation, formal analysis, and data curation. SC investigation, validation, formal analysis, data curation, and visualization. YK investigation, validation, formal analysis, data curation, and writing – original draft. KL investigation, formal analysis, and data curation. JL investigation, formal analysis, data curation, and visualization. SJ investigation, formal analysis, and data curation.

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Availability of data and materials

The datasets are available from the corresponding author on reasonable request.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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