Key Factors Affecting the Initial Regeneration Following Forest Fires

Jongsung Lee 1 and Yeonsook Choung 2,

1 National Institute of Biological Resources, Incheon 22689, Korea
2 Department of Biological Sciences, Kangwon National University, Chuncheon 24341, Korea
* Correspondence: yschoung@kangwon.ac.kr

Abstract: The independent and relative importance of ten variables related to fire, site, and prefire vegetation affecting the initial regeneration after fires was analyzed using the Random Forest statistical technique. The technique supplemented with the decision tree method was developed. This study was performed in prefire Pinus densiflora-dominated forests affected by large-scale fires in Korea. Among the ten variables, the basal area of prefire resprouter trees showed an overwhelmingly high contribution on the postfire regeneration (model improvement ratio (MIR) = 1.00). Consequently, stands with a high abundance of the resprouters showed rapid regeneration. Site factors including elevation, aspect, and slope had an MIR of 0.71, 0.63, and 0.57, respectively, while those for flame ratio and burn severity were 0.39 and 0.20. We revealed that the legacy of prefire vegetation had the most significant effect on the initial regeneration of stands, while site-variables played a lesser role, and fire-variables such as burn severity had a relatively minor effect. This technique was an important tool for explaining ecological phenomena involving the simultaneous action of multiple factors. Understanding the priorities of factors affecting the fast regeneration would be useful in establishing a restoration plan in forests where soil erosion is an issue following a fire.

Keywords: biological legacy; Pinus densiflora forest; Quercus; resprouting; restoration

1. Introduction

Regeneration generally occurs in forests affected by fire, however, disturbance patterns, vegetation before fire, or site have an effect on the rate of regeneration and the structure of the regenerated community [1–3]. Changes resulting from severe fires include increased net primary productivity and flowering promotion (e.g., increased available light, higher nutrient availability, and decreased competition and grazing pressure) [4–6]. The probability of seedling settlement is also increased [7–9]. Site factors also affect regeneration [10–12]. This is because there is variance in soil moisture, temperature, light quantity, and soil depth depending on elevation, slope, aspect, and micro-topography [13–15]. In particular, soil moisture is a limiting factor at the beginning of regeneration [16,17]. This is due to a decreased soil water holding capacity resulting from the increase in available light and water impermeability. Barton [1] reported that the burn severity and site factors were major determinants of the species composition that regenerated immediately after fire. However, Han et al. [11] argued that the influence of site factors (e.g., elevation, slope, and slope location) on regeneration was greater than that of burn severity.

Among the factors affecting the regeneration process, compared to fire and site factors, the importance of vegetation, which exists before a fire, has been ignored. The traditional succession theory was a dominant belief in the past [18,19]: it viewed the seed inflow and seed germination of pioneer species as the initial regeneration after a large-scale fire. However, according to the argument asserted by Dietze and Clark [20], the regeneration of vegetation after a disturbance was mainly controlled by the sprouting ability of the vegetation constituents before the disturbance. Resprouting, which is a species-specific
function, enables regeneration of plants with the activation of latent buds [21,22]. It has been reported in various vegetation types as well as after various disturbance types and intensities [19,23–27].

The East Coast fire (April 2000, burned area 23,794 ha) was the largest recorded fire in South Korea. The degree of initial regeneration of the entire affected area was investigated in the year the fire occurred [28], and rapid regeneration was reported [29–31]. Choung and Choong [32], as a result of individually examining the sources of all plants regenerated immediately after a fire, found that 95.5% of the initial vegetation coverage was the result of resprouting and only 4.5% was the result of seeding. This finding demonstrated that prefire species with sprouting ability make a major contribution to early stages of the regeneration process in South Korea [33,34]. In particular, tree species contributed the most to fast regeneration [32].

Fires that occur in South Korea are caused by humans, and the east coast region has been the location of most large fires [35]. The frequent occurrence of large-scale fires on the region is associated with the type and distribution of vegetation in the region. *Pinus densiflora*-dominated forests, which are particularly vulnerable to fires, show a continuous distribution over a wide area [36,37]. In South Korea, 69% of fires have started in pine forests [38].

Most of the forest soils in South Korea are Inceptisols and Entisols, which are erosive soils with a developing soil layer [39]. In particular, fires mainly occur in spring under a monsoon climate, and serious soil erosion is caused by heavy rainfalls in summer [40–42]. Because of this issue, rapid recovery of vegetation immediately after a fire is critical not only for restoration of vegetation but also for soil conservation. Therefore, understanding the priorities of factors affecting the fast regeneration after a fire would be useful in the effort to establish a management plan.

In the past, there was a limit to analyzing the relative importance between factors in addition to the independent influence of a factor. This is because the classification and regression tree (CART) used in the past causes large variations and has a data overfitting issue. However, Breiman [43] developed the Random Forest technique that generated multiple decision trees with random variables to overcome this limitation. This technique was applied to ecological studies and its excellence was recognized [44,45]. Moreover, it showed a lower variability and higher predictive accuracy than other regression models [46,47].

Therefore, the objectives of this study were to (1) measure the regeneration coverage of the initial stands in the fire year, (2) determine how it is independently affected by ten variables belonging to fire, site, and prefire vegetation factors, and (3) analyze the relative importance of the variables on the regeneration coverage using the Random Forest technique in three large-scale fire affected regions (i.e., 2000 Samcheok fire, 2004 Gangneung fire, and 2004 Sokcho fire) located in the east coast region of South Korea.

2. Materials and Methods

2.1. Study Regions

The study areas were Samcheok, Gangneung, and Sokcho on the east coast where large fires were a frequent occurrence in South Korea (Figure 1). These three fires were caused by humans (Table 1). Samcheok included 72% of the area affected by the East Coast Fire (area 23,794 ha), which occurred simultaneously in several places from 7 April to 15 April 2000 [28]. During the Gangneung fire, which occurred on 17 March 2004, 430 ha of Gangneung City was burned, and 200 ha of Sokcho was burned during the Sokcho fire, which occurred on 10 March 2004 [48]. Gangneung City is 48 km north of the center of the Samcheok site, and Sokcho City is 75 km north of Gangneung City.

The mean annual temperature was 12.6 °C and the mean annual precipitation was 1119.0 mm over a period of 30 years in Samcheok (Uljin Meteorological Station, from 1981 to 2010). The mean annual temperature and annual precipitation were 13.1 °C and 1464.5 mm, respectively, in Gangneung and 12.2 °C and 1402.2 mm, respectively, in Sokcho [49]. Metamorphic rocks accounted for 80.0% of the parent rock found in Wondeok-eup, Samcheok...
City (Table 1). The main soil textures found in the area were sandy loam (57.0%) and loam (39.0%) (Table 1). Most of the parent rock found in Okgye-myeon, Gangneung City was sedimentary rock, and 65.0% of the soil was silty clay loam (73.8%). Acidic rocks accounted for 77.3% of the parent rock found in Joyang-dong, Sokcho City and 70.1% was sandy loam [39].

The mean annual temperature was 12.6 °C and the mean annual precipitation was 1119.0 mm over a period of 30 years in Samcheok (Uljin Meteorological Station, from 1981 to 2010). The mean annual temperature and annual precipitation were 13.1 °C and 1464.5 mm, respectively, in Gangneung and 12.2 °C and 1402.2 mm, respectively, in Sokcho [49].

Metamorphic rocks accounted for 80.0% of the parent rock found in Wondeok-eup, Samcheok City (Table 1). The main soil textures found in the area were sandy loam (57.0%) and loam (39.0%) (Table 1). Most of the parent rock found in Okgye-myeon, Gangneung City was sedimentary rock, and 65.0% of the soil was silty clay loam (73.8%). Acidic rocks accounted for 77.3% of the parent rock found in Joyang-dong, Sokcho City and 70.1% was sandy loam [39].

Figure 1. Study regions in the Republic of Korea. These regions, belonging to Gangwon-do Province, are located along the east coast where large-scale forest fires are a frequent occurrence.

2.2. Field Survey

Burned forests were investigated in the summer of the fire occurrence years: Samcheok in 2000, and Gangneung and Sokcho in the summer of 2004, respectively (Table 1). A total of 152 plots (10 m × 10 m) were installed (50 plots in Samcheok, 66 plots in Gangneung, and 36 plots in Sokcho). The plots were chosen to capture the full spectrum of variables. The four fire-related variables included flame height, flame ratio, burn severity, and the basal area of trees that survived. The height of the traces of soot remaining on burned trees was used for measurement of the flame height. The canopy height was used when the flame height could not be measured because the vegetation was completely burned down. Since the effect of flame height could vary depending on the structure of the vegetation, the calculation of a flame ratio (%) was also performed by dividing the flame height by the height of the prefire canopy layer. There were four classes of burn severity: “extremely severe burn”, all vegetation was lost and the bark could not be identified; “severe burn”, all vegetation was lost but the bark could be identified; “moderate burn”, the canopy layer was not burned but canopy trees were killed by heat; and “light burn”, canopy trees survived but understory vegetation was killed. Because the surviving dominant or co-dominant trees affect the regeneration of vegetation [50], we used the basal area of those trees, calculated the diameter at 10 cm above the ground, as one of four fire variables.
### Table 1. Characteristics of fire occurrence, climate, soil, and prefire forest in three study regions.

| Property                              | Samcheok          | Gangneung         | Sokcho          |
|---------------------------------------|-------------------|-------------------|-----------------|
| **Fire**                              |                   |                   |                 |
| Fire occurrence                      | April, 2000       | March, 2004       | March, 2004     |
| Burned area (ha)                      | 23,794            | 430               | 200             |
| **Climate**                           |                   |                   |                 |
| Annual mean temperature (°C)          | 12.6              | 13.1              | 12.2            |
| Annual precipitation (mm)             | 1119.0            | 1464.5            | 1402.2          |
| Fire-season precipitation (mm)        | 160.3             | 187.2             | 168.1           |
| 1 Monthly average from February to April. |
| Annual mean wind speed (m s⁻¹)        | 3.8               | 2.6               | 2.8             |
| Fire-season wind speed (m s⁻¹)        | 4.2               | 2.9               | 3.2             |
| **Soil**                              |                   |                   |                 |
| Parent rock                           | Metamorphic rock  | Sedimentary rock  | Acidic rock     |
| Soil texture                          | Sandy loam, Loam | Silt loam         | Sandy loam     |
| 3 Mean ± standard error. |
| Basal area (m² ha⁻¹)                  | 35.9 ± 2.93       | 41.2 ± 2.46       | 29.7 ± 3.28    |
| Pinus densiflora                      | 31.7 ± 2.97       | 39.0 ± 2.53       | 27.7 ± 3.32    |
| Other trees                           | 4.1 ± 0.39        | 2.2 ± 0.23        | 2.0 ± 0.25     |
| 4 Canopy height                       | 11.8 ± 0.60       | 7.8 ± 0.21        | 8.9 ± 0.18     |
| No. of stems ha⁻¹                     | 1128.0 ± 117.3    | 1093.9 ± 126.2    | 971.2 ± 91.5   |
| Pinus densiflora                      | 898.0 ± 110.5     | 957.4 ± 126.8     | 875.8 ± 91.6   |
| Other trees                           | 230.0 ± 15.3      | 136.5 ± 8.2       | 95.5 ± 6.0     |
| 5 Diameter (cm)                       | 12.2–16.0–21.3    | 12.5–15.7–20.7    | 17.2–21.3–26.0 |
| Pinus densiflora                      | 12.6–17.0–22.9    | 12.6–15.9–20.8    | 17.5–21.5–26.2 |
| Other trees                           | 11.8–13.0–17.8    | 11.0–13.5–17.9    | 11.1–12.0–14.3 |
| No. of plots                          | 50                | 66                | 36              |

1 Sum from February to April. 2 Monthly average from February to April. 3 Canopy tree diameter > 10 cm. 4 Mean ± standard error. 5 First-second-third quartiles.

Measurement or evaluation of site-related variables, including elevation, slope, and aspect and micro-topography was performed. Aspect bearing was converted to cosine (between 1 and −1). The micro-topography was categorized according to four types: top and ridge, upper slope, middle slope, and lower slope.

As prefire forest-related variables, the height of the burned but remained top canopy was measured (Table 1). In addition, the diameter of all trees (including trees and subtrees with a diameter of 10 cm or larger at 10 cm above the ground) was measured and the density and basal areas were calculated. The dominance of relatively thick pine trees with large diameter was observed in Sokcho and Gangneung. There was also a dominance of pine trees in Samcheok, however the density and basal area of deciduous trees were higher than in the other two regions.

Twenty-eight taxa of trees were found in the three regions. Among them, regeneration by basal sprouting was observed for 26 taxa, except for Pinus densiflora and P. rigida (Supplementary S1). The basal area of 26 taxa with respouting ability was used as a prefire source variable for regeneration after the fire (referred to as “prefire tree BA”). In fact, regeneration by basal or clonal sprouting can occur in shrubs and herbaceous plants, as well as trees [32]. There was a limitation that the prefire understory structure could not be quantified because the understory of even the lightly burned plots was completely burned out. Thus, the structure of the prefire forest is underestimated.

### 2.3. Postfire Initial Regeneration

The degree of regeneration of vegetation in the year of the fire was defined as “initial regeneration”, which was measured according to vegetation coverage. There was significant variance in the degree of regeneration coverage between plots, and it could be divided into two layers: an herbaceous layer and a shrub layer (0.5–2.0 m high). Therefore, it was divided into two layers to reflect this, and the coverage was measured visually and added up. This included all plants with the growth traits of trees, subtrees, shrubs, or herbaceous...
plants. Only vegetation regenerated after the fire was measured in light burn stands where canopy trees survived.

2.4. Data Analysis

The Kolmogorov-Smirnov test was performed in order to confirm the normality of interval variables except for categorical variables; none of the variables met the normality assumptions. Therefore, an analysis of the regional differences of each variable was performed using the Kruskal-Wallis H test, a nonparametric test. Spearman’s rank correlation was also used [51].

When utilizing the Random Forest technique, initial vegetation coverage was used as a dependent variable, and ten variables related to prefire vegetation, fire, and site were used as independent variables (number of plots = 152): two prefire vegetation variables (prefire basal area of tree species and canopy height), four fire variables (flame height, flame ratio, burn severity, and the basal area of surviving trees), and four site variables (elevation, aspect, slope, and micro-topography). Prefire basal area and the basal area of surviving trees were converted to \( \log_{10} \) and used for analysis.

As a result of the analysis, variable importance was calculated. Since it is affected by the number of decision trees and variables, Model Improvement Ratio (MIR) was presented to compare the relative influences of variables. This is the value obtained by dividing the variable importance of each variable by the maximum variable importance. It ranged from 0 to 1, and the most important variable becomes 1 [52]. The result suggested the relative importance of the variable used [52]. The result of the Random Forest analysis can be evaluated as the mean squared error (MSE) calculated using the out-of-bag samples that were not selected during the bootstrap stage.

Ten thousand decision trees were used for analysis, and three variables were considered when generating one tree. A partial-dependence plot (PDP) was used in presenting the effect of each variable on the regeneration coverage. PDP is used for analysis of the functional relationship between independent variables and dependent variables. It performs a calculation of the expected values of all predicted dependent variable values when the independent variables to be analyzed are substituted with a specific fixed value. Therefore, PDP creates graphs showing the changes of the dependent variables according to a specific independent variable by lowering the effects of other independent variables. Random Forest and PDP were performed using the Random Forest package [53] in the R statistical program [54].

3. Results

3.1. Regeneration Coverage of Initial Stands

The regeneration coverages of the initial stands were between 10 and 110% (median 65%) (Figure 2); 50% of all plots (1st to 3rd quartiles) were between 45 and 80%. The median regeneration coverage was 70.0 and 69.0% in Samcheok and Sokcho, respectively. Although it was relatively low (65.0%) in Gangneung, there was no significant difference between regions \( (\chi^2 = 1.52, p = 0.468) \). In most stands, the dominance of deciduous trees such as \( Quercus \) spp. was observed among species, whereas herbaceous species were dominant in the areas where slow regeneration had occurred.

3.2. Fire-, Site- and Prefire Forest Factors

The flame height ranged from 0.5 to 14.0 m (median 5.3 m) (Figure 3a). The median flame height for Samcheok, Gangneung, and Sokcho regions was 6.0, 5.0, and 5.0 m, respectively, however the differences were not significant \( (\chi^2 = 4.81, p = 0.09) \). The flame ratio showed no significant difference between regions \( (\chi^2 = 4.81, p = 0.09) \), and the values in the first to third quartiles were 44.4% and 91.3%, respectively (Figure 3b).
Postfire coverage of initial stands. The first (25%), second (median), and third (75%) quartiles are indicated above each box. Fifty, 66, and 36 plots were investigated in Samcheok, Gangneung, and Sokcho, respectively, resulting in a total of 152.

Figure 2. Postfire coverage of initial stands. The first (25%), second (median), and third (75%) quartiles are indicated above each box. Fifty, 66, and 36 plots were investigated in Samcheok, Gangneung, and Sokcho, respectively, resulting in a total of 152.

Figure 3. Four variables of the fire factor: (a) flame height, (b) flame ratio, (c) burn severity, (d) basal area of the survived trees. Data was not included in the case of plots with no surviving trees. Fifty, 66, and 36 plots were investigated in Samcheok, Gangneung, and Sokcho, respectively, resulting in a total of 152.
Moderate to extremely severe burn was observed for 89% of plots, resulting in loss of aboveground vegetation (Figure 3c). Moderate burn plots showed the most common (39.0%). In Gangneung, “extremely severe burn plots” accounted for 33.3% of the plots, which was more than in other regions. In Sokcho, they accounted for 5.6% of the plots. This could have occurred because a massive amount of water was sprayed to extinguish the forest fire as it was close to the urban area of Sokcho. The basal area of surviving trees in the light burn plots (11% of all plots), where some or all of the canopy survived, was between 0.057 and 103.423 m² ha⁻¹ (Figure 3d). In Gangneung, although the median basal area of living trees was small, there was a substantial difference between the plots.

All plots were located between 50 and 670 m in elevation (Figure 4a). The median height of the plots in Samcheok was 228 m, which was significantly higher than that in Gangneung (150 m) and that in Sokcho (92.5 m) (χ² = 25.8, p < 0.001). In Sokcho, the fire spread mainly along the northern slopes, so that there was a high proportion of plots with cosine (Aspect) values greater than 0 (67.0%) (Figure 4b). The slope range of all plots was 0 to 43°, and there was no significant difference between regions (χ² = 0.91, p = 0.634, Figure 4c). The median slope of all plots was 25.0°, and that for 50% of the plots (1–3 quartiles) was 19–32°. Among all plots, the upper slope showed the greatest abundance (45.4%) and the lower slope (9.2%) was the least abundant (Figure 4d).

The median of prefire tree BA was 2.76 m² ha⁻¹, and the range was 0.002 to 26.768 m² ha⁻¹, showing a large variance between plots, like other variables (Figure 5a). Among the three regions, the highest median was observed for Sokcho (4.97 m² ha⁻¹). The lowest median was observed for Gangneung (1.62 m² ha⁻¹) (χ² = 29.58, p < 0.001). Among the prefire resprouter trees, Quercus spp. accounted for 79.5% of the basal area. In particular, Q. mongolica and Q. variablis accounted for 43.2% and 20.6%, respectively (Table S1).
median canopy height before the fire was 9.0 m. The highest median canopy height (12.0 m) was observed in Samcheok, followed by Sokcho (9.0 m) and Gangneung (7.5 m) ($\chi^2 = 32.75, p < 0.001$) (Figure 5b).

**Figure 5.** Two variables of prefire forest factor: (a) basal area of the trees with resprouting ability, (b) canopy height. Fifty, 66, and 36 plots were investigated in Samcheok, Gangneung, and Sokcho, respectively, resulting in a total of 152.

### 3.3. Effects of Fire, Site, and Prefire Forest Factors on the Regeneration Coverage of Initial Stands: Random Forest Analysis

An analysis of the relative importance of ten variables (belonging to three factors) affecting the regeneration coverage was performed using the Random Forest technique (MSE = 0.31). Among all variables, importance of prefire tree BA was the highest distinctly (Figure 6; variable importance 17,351, MIR 1.00). In comparison, the MIR of the prefire canopy height was low (0.33). The MIR of the site variable was 0.71, 0.63, and 0.57 for elevation, aspect, and slope, respectively, which were important variables following prefire tree BA (Figure 6). Micro-topography showed relatively low importance (MIR 0.36). Among the four variables of the fire factor, the MIR for flame ratio and flame height was 0.39 and 0.35, respectively. Burn severity and the basal area of surviving trees were the ninth and tenth, showing the lowest importance.

**Figure 6.** Relative importance of ten fire, site, and prefire vegetation-related variables analyzed using...
the Random Forest statistical technique. The values shown above each bar indicate the model improvement ratio (MIR). The mean squared error of the Random Forest is 0.31. Prefire tree BA: $\log_{10}$-transformed basal area of the prefire trees with resprouting ability, Surviving tree BA: $\log_{10}$-transformed basal area of the surviving trees.

3.4. Partial-Dependence of Ten Variables on the Regeneration Coverage of Initial Stands

Regeneration coverage showed an abrupt increase in the plots where there was more than a certain level of prefire tree BA (ca. 0.5 m$^2$ ha$^{-1}$) (Figure 7a). Although the coverage tended to be high when the canopy height was between 9.0 and 13.0 m, the difference was not substantial according to the canopy height (Figure 7b).

![Figure 7. Partial-dependence plots of ten variables of fire, site, and prefire forest factors on the postfire regeneration coverage. Prefire forest-related variables are shown in the first row (a,b), site-related variables in the second row (c–f), and fire-related variables in the third row (g–j).](image)

Among the site variables, elevation had an obvious effect. Regeneration coverage was the highest when the elevation was 100 m or lower, and it showed a sharp decrease in plots higher than 100 m (Figure 7c). The increase in regeneration coverage tended to be greater in plots that faced north than in those facing south (Figure 7d). In addition, relatively high coverage was observed on gentle slopes, and it decreased in plots above 25$^\circ$ (Figure 7e). In addition, the coverage at low and middle slope tended to be higher than that of other micro-topography, although the difference was minor (Figure 7f).
When compared with the effects of prefire forest or site-related variables, the response of regeneration coverage according to the type or size of fire variables was not clear. In particular, a certain trend in the coverage according to the flame height was not observed (Figure 7g). Considerable fluctuation was observed in the range of 4.0 to 8.0 m, which included the largest number of plots (Figure 7h). Higher coverage was observed when the flame ratio was approximately 60% or less, but the trend was not consistent. Slightly higher coverage was observed in the light burn plots, but the difference was minor (Figure 7i). In plots where the basal area of the surviving trees is large, the regeneration coverage was slow. However, the difference was minor (Figure 7j).

4. Discussion

This study was performed to identify key factors affecting the initial regeneration following forest fires. The median of all initial regeneration coverages was 65% (45–80% in quartiles one to three) (Figure 2). As it was a result of the regeneration for only three to four months after the fire, it was quite rapid. Previous studies also showed that restoration of vegetation was usually rapid [55–59]. Although there was no significant difference between three regions, the difference between the plots was more than ten times. The prefire abundance of plant species that were able to resprout after was the most important factor for the initial regeneration of vegetation (Figures 6 and 7a). In other words, the degree of initial regeneration was proportional to the abundance of the belowground system such as roots and clonal stems that survived even though aboveground was burned. Choung and Choung [32] conducted an examination of individual regenerating plants in stands 1–2 years after the East Coast fire. According to their findings, 95.5% of the regeneration coverage was the result of resprouting (from tree base or clonal organ such as rhizome, bulbs), whereas only 4.5% was the result of seeding. They also found that 81% of all taxa in the regenerating stands were regenerated by resprouting, and, in particular, resprouting occurred in all deciduous trees except conifers.

The regeneration coverage of all species, including shrubs, herbaceous plants, and trees was measured in this study. However, as a prefire source, only the basal area of the burned trees was able to be measured. This is because other than trees, most whole plants were burned down, therefore, no measurable plant parts remained. Although trees made the greatest contribution to actual regeneration coverage [32], the impact of the actual prefire plants could be underestimated because measurement of the abundance of prefire shrubs or herbaceous plants could not be performed. The initial regeneration coverage is sometimes high in areas where there were few or fewer trees before the fire, which were instead dominated by shrubs such as Lespedeza cyrtobotrya, and herbs such as Pteridium aquilinum var. latiusculum, and Lysimachia clethroides [29,60]. Therefore, this study has a limitation in that direct tracking of changes occurring before and after forest fires in the same location was not be performed [61].

Seeding is a major strategy for regeneration where there is dominance of serotiny species (e.g., Pinus contorta and P. banksiana) [62–66]. In addition, it is a major strategy for use in areas with a low abundance of species with sprouting ability, such as in rocky areas or areas that are subject to repeated disturbances [3,50,67]. However, according to findings from recent studies, the sprouting regeneration strategy contributes to restoration of vegetation in various vegetation and disturbance types [23–26]. Such cases have also been reported in recent years in South Korea as well [29,32,68,69]. According to the argument presented by Bond and Midgley [25], the dominance of the sprouting regeneration strategy was evolved from where there was high disturbance intensity and frequency. It appears that this also applies to forests in South Korea, which were used intensively throughout the long history of human settlement and high population density.

On the other hand, among ten variables, prefire canopy height, which was considered to affect positive regeneration, ranked 8th in contribution (Figure 6). A significant correlation was observed between the canopy height and the prefire tree BA ($r = 0.233, p < 0.05$). Nevertheless, this result (Figure 7b) could reflect the site effects. This is because forests
with high canopy heights were located at relatively high elevations \( r = 0.373, p < 0.001 \), and on steep slopes \( r = 0.194, p < 0.05 \). In addition, although it was not significant, tall forests were mainly distributed on the upper slopes, probably because most high canopy forests were distributed in sites that showed slow regeneration.

Site factors including elevation, slope, and slope on regeneration coverage were important following the prefire tree basal area (Figures 6 and 7c–e). That is, good regeneration was observed for stands located at a low elevation gentle slope facing north. Takaoka and Sasa [13] also presented the argument that regeneration was favorable at the bottom of the slope and north aspect due to good moisture conditions, suggesting the influence of moisture factors [70]. Changes in the environment after a fire (e.g., increase in light quantity and evaporation and decrease in permeability) resulting from the removal of vegetation can lead to drying of the soil and slow the regeneration of stands [71,72]. Micro-topography was not an important variable in the study (Figures 6 and 7f). Nevertheless, relatively high regeneration coverage was observed in the lower and middle parts of the slope, which were relatively mesic. Conversely, low regeneration coverage was observed on the upper slope, and the ridge or mountain top, where soil moisture is low due to shallow soil depth, and the slope was steep.

The four variables of the fire factor had less impact on regeneration than the prefire forest and site factors (Figure 6). Among the four variables, the MIR for the flame ratio was the highest (Figure 7h). In other words, the regeneration coverage was relatively high in locations where the flame passed low to nearly ground compared to the canopy height. On the other hand, the height of the flame was not an acceptable variable for use in explaining the degree of regeneration (Figure 7g). This is because even if the flame height is low, significant damage can occur in a forest with small size trees. The burn severity and the effects of the surviving canopy were the lowest among the ten variables. This could be because the influence of the resprouting source before a fire was far greater than the severity. Surviving trees can provide seeds or shading; thus, they could have a positive impact on early regeneration in burned areas where drying is a limiting factor [73,74]. Jung [50] and Lee [75], which conducted the regeneration of lightly burned stands and severely burned stands for 20 years, demonstrated that lightly burned stands with surviving trees showed slow regeneration and the number of species that regenerated was significantly lower. This difference persisted even after 20 years.

An analysis of the independent and relative effects of the prefire forest, fire, and site-related variables on the regeneration coverage of the initial stands after fire was performed using the Random Forest technique. The results agreed with the predictions based on intuition in the field and the results reported in previous studies. It was confirmed that this technique was a useful tool for explaining ecological phenomena that involves the simultaneous action of multiple factors [44,45].

Soil erosion is the most serious secondary damage after fires [40–42]. Soil erosion resulting from reforestation has been a major issue in many debates regarding restoration since the record-breaking East Coast Fire in 2000. In South Korea, fires occur mainly in spring, and then burnt forests are exposed to frequent heavy rainfall in summer due to the influence of the monsoon climate; therefore, the potential for erosion is high [49]. Furthermore, as a result of repeated disturbances in the past, the soil is erosive with a shallow depth and poorly developed soil structures [39]. To make this matter worse, removing burned trees and regenerating sprouts in the reforestation process involves the introduction of heavy equipment, which causes disturbance to the site, further weakening the physical stability of the soil. Kim et al. [42] conducted an evaluation of soil erosion according to the initial degree of regeneration in burned forests on the east coast for 11 years. The stands showing low and intermediate regeneration classes lost seven and four times more soil, respectively, than the site showing high regeneration class. In addition, soil stabilization took three years in stands showing high regeneration coverage, while seven years in stands showing low and intermediate coverages.
Therefore, assurance that development of vegetation occurs as soon as possible with a focus on preventing soil erosion is required when establishing a forest restoration policy after a fire. According to the findings of this study, the source of regeneration before a fire had the greatest impact on the initial regeneration after a fire. As studied by Jung [50] and Lee [75], the regeneration process, such as the structure and species composition of the stands, was influenced by the degree of the initial regeneration for at least several decades. Therefore, identification of stands showing slow regeneration after a fire and introduction of appropriate practices, such as woodchip mulching as revealed by Kim et al. [76], promote regeneration of vegetation, and consequently prevent serious soil erosion [76,77].

5. Conclusions

An analysis of the independent and relative importance of ten variables related to fire, site, and prefire vegetation, affecting the regeneration coverage of early vegetation after the fire was performed using the Random Forest statistical technique. Among the ten variables, the abundance of species with sprouting strategy before the fire made the most significant contribution to the initial regeneration coverage after fires. Only the abundance of prefire resprouter trees were able to be measured, as small trees, shrubs, and perennial herbs were completely burned. If there were information on the abundance of all resprouter species before the fire, the contribution of the resprouter species would have been higher in the analysis results. Among site variables, it was followed by the effects of elevation, aspect, and slope. On the other hand, fire variables such as burn severity showed relatively minor effects. Therefore, we finally revealed that the legacy of prefire vegetation had the most significant effect on the initial regeneration of stands, while site-variables played a lesser role, and fire-variables such as burn severity had a relatively minor effect. Seeding was only a major strategy for regeneration in areas with a low abundance of species with sprouting ability, such as in rocky areas.

Using a Random Forest model, the relationship between nonparametric independent variables and dependent variables, including category and class variables, was analyzed in this study, which was consistent with the empirical intuition and predictions obtained from field studies. The technique was useful as an important tool for explaining ecological phenomena involving the simultaneous action of multiple factors.

In South Korea, forest fires occur mainly in spring, and soil erosion is an important issue in summer due to the heavy rainfall under the monsoon climate. Therefore, understanding the priorities of factors affecting the fast regeneration would be useful in establishing a restoration plan in forests.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/f13111859/s1, Table S1: Composition of prefire tree species with resprouting ability after fire.

Author Contributions: Conceptualization, Y.C. and J.L.; formal analysis, J.L; investigation, Y.C. and J.L.; writing—original draft preparation, Y.C. and J.L.; writing—review and editing, Y.C. and J.L.; visualization, J.L.; supervision, Y.C.; project administration, Y.C.; funding acquisition, Y.C. All authors have read and agreed to the published version of the manuscript.

Funding: This Funding was provided by the Eco-technopia 21 Project (Grant number 051-041-012), and Long-term Ecological Research Program of the Ministry of Environment.

Data Availability Statement: The data are available on request to the corresponding author.

Acknowledgments: We thank Youngseob Shin, Yuntaek Lee, and Byoungchul Seo for their assistance in the field.

Conflicts of Interest: The authors declare no conflict of interest.
32. Choung, Y.; Choung, M.S. Biodiversity of burned forests is controlled by the sprouting ability of prefire species in Pinus densiflora forests. *Ecol. Eng.* 2019, 127, 356–362. [CrossRef]
33. Johnstone, J.F.; Chapin, F.S.; Foote, J.; Kemmitt, S.; Price, K.; Viereck, L. Decadal observations of tree regeneration following fire in boreal forests. *Can. J. For. Res.* 2004, 34, 267–273. [CrossRef]
34. Donato, D.C.; Cambell, J.L.; Franklin, J.F. Multiple successional pathways and precocity in forest development: Can some forests be born complex? *J. Veg. Sci.* 2012, 23, 376–384. [CrossRef]
35. Ireland, G.; Petropoulos, G.P. Exploring the relationships between post-fire vegetation regeneration dynamics, topography and forest fire occurrence danger index using fuel and topographical characteristics on coastal plain in south-eastern Brazil. *J. Ecol.* Field Biol. 2010, 33, 343–349. [CrossRef]
36. Lee, S.Y.; Won, M.S.; Han, S.Y. Developing of forest fire occurrence danger index using fuel and topographical characteristics on a monsoon climate: A decade of monitoring. *J. Plant Biol.* 2021, 64, 123–133. [CrossRef]
37. Lee, J.M.; Lee, S.W.; Lim, J.H.; Won, M.S.; Lee, H.S. Effects of heterogeneity of pre-fire forests and vegetation burn severity on forest fire based on ignition characteristics. *J. Ecol.* Field Biol. 2010, 33, 343–349. [CrossRef]
38. Lee, S.Y.; Won, M.S.; Han, S.Y. Developing of forest fire occurrence danger index using fuel and topographical characteristics on a monsoon climate: A decade of monitoring. *J. Plant Biol.* 2021, 64, 123–133. [CrossRef]
39. Liaw, A.; Wiener, M. Classification and regression by random forest. *R News* 2002, 2, 18–22. [CrossRef]
40. Prasad, A.M.; Iverson, L.R.; Liaw, A. Newer classification and regression tree techniques: Bagging and random forests for ecological prediction. *Ecosystems* 2006, 9, 181–199. [CrossRef]
41. Shin, S.S.; Park, S.D.; Lee, K.S. Sediment and hydrological response to vegetation recovery following wildfire on hillslopes and the hollow of a small watershed. *J. Hydrol.* 2013, 499, 154–166. [CrossRef]
42. Kim, Y.; Kim, C.G.; Lee, K.S.; Choung, Y. Effects of post-fire vegetation recovery on soil erosion in vulnerable montane regions in Korea—Rusle approach. *J. Hydrol. Eng.* 2012, 17, 292–304. [CrossRef]
43. Abrahamson, W.G. Species responses to fire on the Florida lake wales ridge. *Am. J. Bot.* 1984, 71, 35–43. [CrossRef]
44. Goetz, S.J.; Fiske, G.J.; Bunn, A.G. Using satellite time-series data sets to analyze fire disturbance and forest recovery across Canada. *Remote Sens. Environ.* 2006, 101, 352–365. [CrossRef]
45. Murphy, M.A.; Evans, J.S.; Storfer, A. Quantifying *bufo boreas* connectivity in Yellowstone National Park with landscape genetics. *Ecol. Eng.* 2010, 41, 252–261. [CrossRef]
46. Choung, Y. Forest fires and vegetation responses in Korea. In *Ecology of Korea*; Lee, D., Jin, V., Choe, J.C., Son, Y., Yoo, S., Lee, H.Y., Hong, S.K., Ihm, B.S., Eds.; Bumwoo Publishing Co.: Paju, Korea, 2002; pp. 119–137.
47. R Core Team. R: A Language and Environment for Statistical Computing; R Foundation for Statistical Computing: Vienna, Austria, 2020.
48. Li, M.; Qi, Z.; Zuo, F.; Zhang, Y. Effects of fire regime on the serotiny level of Jack pine. *J. Ecol.* 1996, 84, 539–548. [CrossRef]
49. Seo, H.; Choung, Y. Vulnerability of *Pinus densiflora* to forest fire based on ignition characteristics. *J. Ecol.* Field Biol. 2010, 33, 343–349. [CrossRef]
50. Jung, S. Dynamics of 20-Year Natural Regeneration of Canopy Tree Species in the Damaged Forests with Different Severity and Initial Regeneration. Master’s Thesis, Kangwon National University, Chuncheon, Korea, 2022. (In Korean).
51. SPSS. *IBM SPSS Statistics for Windows*, Version 24.0; IBM Corp.: Armonk, NY, USA, 2016.
52. Murphy, M.A.; Evans, J.S.; Storfer, A. Quantifying *bufo boreas* connectivity in Yellowstone National Park with landscape genetics. *Ecol. Eng.* 2010, 41, 252–261. [CrossRef]
53. Lee, S.Y.; Won, M.S.; Han, S.Y. Developing of forest fire occurrence danger index using fuel and topographical characteristics on a monsoon climate: A decade of monitoring. *J. Plant Biol.* 2021, 64, 123–133. [CrossRef]
54. Oliveira, S.; Oehler, F.; San-Miguel-Ayanz, J.; Camia, A.; Pereira, J.M.C. Modeling spatial patterns of fire occurrence in Mediterranean Europe using multiple regression and random forest. *For. Ecol. Manag.* 2012, 275, 117–129. [CrossRef]
55. Abrahamson, W.G. Species responses to fire on the Florida lake wales ridge. *Am. J. Bot.* 1984, 71, 35–43. [CrossRef]
56. Seo, H.; Choung, Y. Vulnerability of *Pinus densiflora* to forest fire based on ignition characteristics. *J. Ecol.* Field Biol. 2010, 33, 343–349. [CrossRef]
57. Goetz, S.J.; Fiske, G.J.; Bunn, A.G. Using satellite time-series data sets to analyze fire disturbance and forest recovery across Canada. *Remote Sens. Environ.* 2006, 101, 352–365. [CrossRef]
58. Jones, M.O.; Kimball, J.S.; Jones, L.A. Satellite microwave detection of boreal forest recovery from the extreme 2004 wildfires in Alaska and Canada. *Glob. Change Biol.* 2013, 19, 3111–3122. [CrossRef]
59. Ireland, G.; Petropoulos, G.P. Exploring the relationships between post-fire vegetation regeneration dynamics, topography and burn severity: A case study from the Montane cordillera ecozones of western Canada. *Appl. Geogr.* 2015, 56, 232–248. [CrossRef]
60. Lee, J.M.; Lee, S.W.; Lim, J.H.; Won, M.S.; Lee, H.S. Effects of heterogeneity of pre-fire forests and vegetation burn severity on short-term post-fire vegetation density and regeneration in Samcheok, Korea. *Landscape Ecol. Eng.* 2014, 10, 215–228. [CrossRef]
61. Fornwalt, P.J.; Kaufmann, M.R. Understorey plant community dynamics following a large, mixed severity wildfire in a *Pinus ponderosa*-Pseudotsuga menziesii forest, Colorado, USA. *J. Veg. Sci.* 2014, 25, 805–818. [CrossRef]
62. Turner, M.G.; Romme, W.H.; Gardner, R.H.; Hargrove, W.W. Effects of fire size and pattern on early succession in Yellowstone National Park. *Ecol. Monogr.* 1997, 67, 411–433. [CrossRef]
63. Schoennagel, T.; Turner, M.G.; Romme, W.H. The influence of fire interval and serotiny on postfire lodgepole pine density in Yellowstone National Park. *Ecol. Monogr.* 1997, 67, 411–433. [CrossRef]
65. Radeloff, V.C.; Mladenoff, D.J.; Guries, R.P.; Boyce, M.S. Spatial patterns of cone serotiny in Pinus banksiana in relation to fire disturbance. *For. Ecol. Manag.* 2004, 189, 133–141. [CrossRef]  
66. Hernández-Serrano, A.; Verdú, M.; González-Martínez, S.C.; Pausas, J.G. Fire structures pine serotiny at different scales. *Am. J. Bot.* 2013, 100, 2349–2356. [CrossRef] [PubMed]  
67. Hong, E. Establishment and Growth of Pinus Densiflora in Early Vegetative Regeneration Stage after Fire. Master’s Thesis, Kangwon National University, Chuncheon, Korea, 2004. (In Korean).  
68. Lee, K.S.; Choung, Y.; Kim, S.C.; Shin, S.S.; Ro, C.H.; Park, S.D. Development of vegetation structure after forest fire in the east coastal region, Korea. *Korean J. Ecol.* 2004, 27, 99–106. (In Korean) [CrossRef]  
69. Kim, J.; Lim, J.H.; Shin, M.; Han, S.H.; Kang, W. Oak resprouting survival and competition for 19 years after wildfire in the Republic of Korea. *Forests* 2020, 11, 515. [CrossRef]  
70. Mansuy, N.; Gauthier, S.; Robitaille, A.; Bergeron, Y. Regional patterns of postfire canopy recovery in the northern boreal forest of Quebec: Interactions between surficial deposit, climate, and fire cycle. *Can. J. For. Res.* 2012, 42, 1328–1343. [CrossRef]  
71. Luo, Y.; Chen, H.Y.H. Observations from old forests underestimate climate change effects on tree mortality. *Nat. Commun.* 2013, 4, 1965. [CrossRef]  
72. Petrone, R.M.; Chasmer, L.; Hopkinson, C.; Silins, U.; Landhäusser, S.M.; Kljun, N.; Devito, K.J. Effects of harvesting and drought on CO2 and H2O fluxes in an aspen-dominated western boreal plain forest: Early chronosequence recovery. *Can. J. For. Res.* 2015, 45, 87–100. [CrossRef]  
73. Chazdon, R.L. Tropical forest recovery: Legacies of human impact and natural disturbances. *Perspect Plant Ecol. Evol. Syst.* 2003, 6, 51–71. [CrossRef]  
74. Bartels, S.F.; Chen, H.Y.H.; Wulder, M.A.; White, J.C. Trends in post-disturbance recovery rates of Canada’s forests following wildfire and harvest. *For. Ecol. Manag.* 2016, 361, 194–207. [CrossRef]  
75. Lee, J. Twenty-Year Natural Regeneration Process of Forest Structure and Plant Species Assembly in Burned Pinus Densiflora Forests. Master’s Thesis, Kangwon National University, Chuncheon, Korea, 2022. (In Korean).  
76. Kim, C.G.; Shin, K.; Joo, K.Y.; Lee, K.S.; Shin, S.S.; Choung, Y. Effects of soil conservation measures in a partially vegetated area after forest fires. *Sci. Total Environ.* 2008, 399, 158–164. [CrossRef] [PubMed]  
77. Kim, C.G.; Choung, Y.; Joo, K.Y.; Lee, K.S. Effects of hillslope treatments for vegetation development and soil conservation in burned forests. *J. Ecol. Field Biol.* 2006, 29, 295–303. (In Korean) [CrossRef]