



Article The Large-Scale Investigation and Analysis of Lophodermium piceae in Subalpine Areas Based on Satellite Multi-Spectral Remote Sensing

Xin Luo ^{1,2,*}, Qian Feng ^{1,2}, Yuzhen Jia ³, Hongyan Chen ¹, Yiyun Song ¹ and Wenbo Xu ^{1,2}

- ¹ Yangtze Delta Region Institute (Huzhou), University of Electronic Science and Technology of China, Huzhou 313001, China
- ² School of Resources and Environment, University of Electronic Science and Technology of China, Chengdu 611731, China
- ³ Institute of Forest Pest Control, Sichuan Academy of Forestry, Chengdu 610081, China
- * Correspondence: luoxin@uestc.edu.cn; Tel.: +86-1355-023-2656

Abstract: Picea asperata, a common tree species in the subalpine areas of Li County, Sichuan Province, China, is susceptible to Lophodermium piceae. Remote sensing has the advantages of large-scale, fast information acquisition, and low cost, which can overcome the shortcomings of ground survey. Hence, we used Landsat 8 satellite multi-spectral images and forest resource distribution data to investigate and analyze this forest disease at a large scale. Firstly, we extracted the spatial distribution information of Picea asperata and chose a temporal sequence indicator to establish a regression model and obtained a significantly negative correlation between the damage degree of plants and the change rate of normalized difference vegetation index (NDVI). Accordingly, the investigation results of the disease have good consistency with the ground survey data in spatial distribution and damage degree. On this basis, a temporal regression analysis was performed by combining the remote sensing investigation results with climate variables, and canonical correspondence analysis (CCA) was utilized in the spatial comprehensive analysis of Lophodermium piceae with terrain, soil and forest stand factors. Conclusively, this study effectively coped with the difficulties in full investigation and analysis of Lophodermium piceae in ecologically fragile subalpine areas of Western Sichuan. It is of important reference value in the early warning and monitoring of this disease, and also provides objective and reliable information support for ecological restoration and management planning in the Wenchuan earthquake-stricken areas.

Keywords: *Lophodermium piceae*; subalpine area; satellite multi-spectral images; large-scale investigation; spatio-temporal analysis

1. Introduction

Forests are essential for biodiversity and human life. There are about 8000 forest pests in China, but over 200 of them have brought about serious losses [1]. It is urgent to investigate and control these forest pests. However, traditional survey methods greatly rely on human labor, which is costly and time-consuming. Their efficiency and accuracy largely depend on artificial factors. Particularly, it is difficult to investigate forest pests in high mountains and dangerous slope areas that humans cannot reach [2]. Moreover, because of complex topography and inconvenient transportation in forest areas, it is difficult for local forestry departments to accurately acquire large-scale and accurate information of pests in time [3]. All of the above make it difficult to control an epidemic situation once pests are found. With the development of remote sensing technology, its application in forest research has made remarkable achievements [4,5]. Benefitting from the advantages in plant growth monitoring, vegetation parameter inversion, and other fields, remote sensing technology has played a more significant role in the investigation and control of forest pests



Citation: Luo, X.; Feng, Q.; Jia, Y.; Chen, H.; Song, Y.; Xu, W. The Large-Scale Investigation and Analysis of *Lophodermium piceae* in Subalpine Areas Based on Satellite Multi-Spectral Remote Sensing. *Diversity* **2022**, *14*, 727. https:// doi.org/10.3390/d14090727

Academic Editors: Mateja Germ and Ivan Kreft

Received: 16 July 2022 Accepted: 29 August 2022 Published: 2 September 2022

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). than ever [6]. Meanwhile, it has been proven that various forms of vegetation indexes (VI) can manifest some important biophysical characteristics or functions of plants, and they have been widely used in monitoring plant pests. For instance, Ye et al. established a binary logistic regression (BLR) method to evaluate the spatial relationship between the normalized difference vegetation index (NDVI) and infected or uninfected banana plants by fusarium wilt based on UAV (unmanned aerial vehicles) multi-spectral images [7]. Their work indicates that remote sensing technology with a red-edge band is suitable for identifying this disease. Santos et al. studied the role of NDVI generated from Sentinel-2 data in mapping defoliation caused by leaf-cutting ants in Eucalyptus plantations. Greene et al. studied the spatial association between major *lepidopteran* pests and NDVI [8]. Oblinge et al. identified conifer mortality induced by Armillaria root disease using airborne LiDAR and ortho-imagery in south central Oregon [9]. On account of atrocious geography conditions, it is very difficult to perform large-scale field investigations of forest pests in Li County. Hence, the first purpose of this study was to evaluate the effectiveness of space-borne multi-spectral remote sensing technology in a large-scale investigation of Lophodermium *piceae* in subalpine areas.

On the other hand, emergence and evolution of forest pests are owing to many factors, which can generally be divided into two aspects. One is the own growth status of forest vegetation, and the other is the comprehensive influence of growth environment, such as natural geographical conditions and human factors. Meanwhile, these factors may also vary with time. For example, Li et al. proposed a multi-factor risk assessment method for *Dendrolimus tabulaeformis* based on climate, terrain and other factors [10]. Based on the existing species distribution model, Maxent, Melissa et al. mapped the potential probability distribution of invasive *Bretziella fagacearum* in eastern and southeastern Minnesota and correlated the occurrence of *Bretziella fagacearum* with environmental variables (including climate, terrain, land cover, soil and population density) [11]. They found that land cover and soil type were important variables to estimate the distribution. Therefore, our work also attempted to explore those variables that were more important in determining the severity of *Lophodermium piceae* in our study area, Li County.

In a word, this study was intended to establish an effective and reliable correlation model between disease degree and spectral parameters through a little amount of ground sampling data, so as to realize a large-scale investigation of *Lophodermium piceae* in subalpine areas. Moreover, the temporal and spatial distribution of this disease was analyzed, and its main impact factors were also explored in terms of terrain and climate. The remainder of this article is organized as follows. First of all, our data sources and adopted methods are introduced. Then, the investigation results of disease based on satellite-borne multi-spectral remote sensing technology are presented. In the end, spatio-temporal analyses of the whole study area are elaborated and the conclusion is drawn comprehensively.

2. Methods

2.1. Study Areas

Li County is located in the upper Minjiang River, the east edge of Qinghai-Tibet Plateau, and the northwest of Sichuan Basin [12]. The geographical range of Li County is N30.91°~31.20°, E102.54°~103.51°. The tectonic structure of Li County belongs to the middle section of Longmenshan fault zone. The whole terrain of the county inclines from the northwest to southeast. The lowest point is the Wuli boundary marker of an ancient city in Taoping Village bordering Wenchuan County at an elevation of 1442 m, where Zagunao River flows out of Li County. The highest point is Zhegu Mountain, with an elevation of 5922 m. The altitude difference in this county reaches about 4500 m. The county has undulated terrain, deep canyons, high mountains, steep slope valleys and the average slope is 30 to 40° with a maximum of 60°. The terrain there is complex and is a typical mountain canyon landform. In terms of climate, this county is influenced by three circulations, namely, Siberian western flow, Indian Ocean warm current and Southeast Pacific monsoon. Due to large altitude differences and complex terrain, the climate there possesses

significant mountainous characteristics. It rains heavily in spring and summer and is mostly frosty in winter. The annual rainfall is between 650 to 1000 mm, and the annual average temperature in valleys is 6.9 to 11 °C. The high altitude and humid climate are very likely to cause the outbreaks of forest pests, which seriously affects the sustainable development of the local ecological environment. The location of Li County is illustrated as below, see Figure 1.



Figure 1. The location of Li County in Sichuan.

With regard to forestry resources, there are typical subalpine vegetation coverages in Li County, which are vertically stratified along altitudes and diverse in multi-level structures. According to the statistics of forest classification and division results in 2008, the area of Li County reached 432,000 hm², of which its forest area was 241,000 hm², accounting for 56% of the total, and the total stand volume is 17,630,000 m³. Picea asperata is planted in large quantities and one of the dominant tree species in this county. However, since Li County is very close to Wenchuan County, this county is one of the intensive damage areas of the "5.12" Wenchuan earthquake in 2008. Mountain collapses caused by the earthquake have seriously destroyed forest vegetation and surface soil. Since a large amount of fallen diseased (or dead) trees accumulated in forestlands after the earthquake, the forest ecosystem of this county was severely damaged and its ability to resist natural disasters and forest pests weakened. In addition, due to the special climate and geographical conditions, secondary disasters such as landslides, mountain torrents and debris flows frequently occur in the range of Li County, which does more harm to local fragile natural ecological environment and provides more benefits to the occurrence and spread of forest pests than before. On the other hand, due to its fragile ecology after the Wenchuan earthquake, Li County is a central area of ecological restoration, and many afforestation projects have been executed. However, because of the influence of traditional modes and technology limitation, densities of artificial spruce forests are rather high and result in low stress resistance of spruce populations. According to the records of the local forestry department, Lophodermium piceae occurred in 2007. After the Wenchuan earthquake in 2008, the disease was more serious. In addition, owing to inappropriate management, such as forbidding logging, thinning once every five years after plantation for reasonable density control cannot be implemented, which also promotes pest breeding and epidemic. In 2014, China launched a nationwide survey of forest pests [13]. In order to realize a detailed forest pest investigation of Li County in mountainous areas after the Wenchuan earthquake, we resorted to satellite multi-spectral remote sensing technology for the first time.

2.2. Characteristics of Lophodermium piceae

Picea asperata is an endemic shallow-rooted tree species of China, whose ideal growth environment includes a cool and humid climate, and fertile, deep, well-drained and slightly acidic sandy soil. It is resistant to shade and cold and grows slowly. Picea asperata is evergreen and widely distributed in Li County, and usually grows in the subalpine region with the altitude of 2400–3600 m [14]. There were, in total 36251.46 hm² of Picea asperata forests in Li County. Lophodermium piceae occurs frequently in some artificially renewed forest areas of Li County with an increasing trend of infectious area and damage degree year by year. The pathogeny of Lophodermium piceae is Lophodermium uncinatun Darker. It is also called spruce speckled shell fungus, belonging to the subclass ascomycetes. The Ascot disk is in the black Ascot and the Ascot is solitary. Its top is combined with a host epidermis to form a shield cover. After the Ascot disk is mature, the shield cover is broken, and the seed layer is exposed. Ovary is clavate, shortly stipitate. The lateral filaments are linear, and the tip is slightly thick and curved, slightly longer than the ovary. Ascospores are colorless and linear. The asexual stage is Leptostroma sp. In the conidia produced by the pathogen, there is colorless single-celled cylindrical conidia. Generally, Lophodermium piceae pathogens first infect young needles of Picea asperata, invading through stomata. Then, they cause infected areas of yellow-brown spots. As they spread, needles turn yellow completely. In severe cases, the needles will fall off and eventually the entire plant will die [15]. In addition, ascospores of pathogens can also be transmitted by wind, rain, insects and birds, or directly invade from wounds of needles. Infections of this forest disease usually occur once a year, mostly in summer from June to August [16], since high temperature, heavy rain and strong wind may contribute to life activities of pathogenic spores. The period for pathogen spores to release their ascospores can last from mid-tolate May to early August. The peak of pathogen infections is from June to late August, and diseased needles begin to fall off in September. Typical symptoms of Lophodermium *piceae* are displayed in Figure 2b,c.



Figure 2. The distribution of *Picea asperata* in Li County and the typical symptom of *Lophodermium piceae*: (a) the distribution of *Picea asperata*; (b) a healthy *Picea asperata* forest; (c) an infected *Picea asperata* forest. The dots represent locations of the county, village or town governments.

Since needles infected with *Lophodermium piceae* will wither and fall off, these symptoms will be reflected in canopy spectra, mainly as spectral reflectance decreases the needles, especially in the near-infrared band. This kind of spectral phenomenon is primarily manifested as changes in pixel values and anomalies of image textures in remote sensing images. Accordingly, combinations of various vegetation indices and different image channels can be utilized to enhance information of damaged forests, thereby achieving remote sensing investigation of the forest disease.

2.3. Data Sources

2.3.1. Satellite-Borne Multi-Spectral Remote Sensing Images

In this study, multi-spectral remote sensing images are applied to investigate Lophodermium piceae of Picea asperata forests. However, the quality of optical remote sensing data depends on photographing conditions to large extent. For example, if there is a large area of cloud occlusion, the acquired image is useless. Actually, our study area, Li County, is mountainous and often covered by clouds for most of the year. In virtue of coverage range, spatial resolution and actual quality of satellite remote sensing images collected from the study area, we found some historical Landsat 8 satellite multi-spectral data acquired in 2014, after the Wenchuan Earthquake, as the main data sources for remote sensing investigation of Lophodermium piceae. Moreover, in order to research the forest disease in detail, it is necessary to compare the remote sensing images of the same sensor from the study area at two time points in the same year. Therefore, the chosen Landsat 8 data should also satisfy the following requirements: the image acquisition time should be before and after the occurrence of the disease, during *Picea asperata* flourishment, and there is slight cloud cover and snow coverage. According to the local experience, *Picea asperata* forests grow vigorously from May to June. The climax period of disease lasts from June to August, and the disease begins to stabilize in September. Hence, the images obtained from May to June can serve as a reference benchmark, and September to October is the most effective time for the remote sensing investigation of Lophodermium piceae. Through sifting, there are two scenes of Landsat 8 in 2014 that can meet the above requirements. They were obtained from the study area on 1st June and 23 October, respectively. Finally, the near-infrared band and red band of Landsat 8 multi-spectral data are adopted, whose resolution are all 30 m.

2.3.2. Forest Resources Data

The forest resource data of Li County is constructed and updated according to the historical records and an artificial ground survey by the local forestry department every five years. A later survey after the Wenchuan earthquake is in 2009. Its results are employed in this study. The data include tree species, forest stand status, age group, origin, soil type and thickness. As indicated in Figure 2a, *Picea asperata* forests in Li County are scattered in thirteen villages or towns, and mostly gathered in the western region of this county, such as Miyaluo Town, Putou Village and Guergou Town. In the forest resource data, environmental and stand factors, such as age group, soil type, soil-layer thickness, slope, and aspect, are denoted as different attributes corresponding to the vector data of *Picea asperata* forest patch maps, whose different values are numerically coded.

2.3.3. Ground Survey Data of Lophodermium piceae

The ground disease survey is performed by the local forestry department. Due to the limitation of geographical and environmental conditions in subalpine forest areas, the ground survey of *Lophodermium piceae* in Li County is mainly implemented through the combination of route inspection by walking and fixed-point observation. There are 43 routes and 15 fixed points covering all the stands, with *Picea asperata* as the dominant tree species in the forest areas of Li County. The survey time is from March to October every year, with an interval of 30 days, and the survey frequency is 5 times per route or point. Considering different site conditions and forest types, the size of standard plots is 20 m \times 20 m in the same sort of stand. The site intervals, standard plot specifications,

sampling inspection methods, and relevant technical standards refer to Chinese national forest pest survey technical scheme [17]. In the final step, the ground survey data of the disease in the whole county were summarized and counted, including distribution scope, damage degree and damage area. The Chinese grading protocol of forest harmful biological disasters was referred to in this study [18]. According to this protocol, there are four grades: normal (damaged trees $\leq 10\%$), light (10–29%), moderate (30–59%), and severe (>60%). To keep consistent with the acquired satellite images, we employed the ground survey data in 2014 to establish our remote sensing investigation model. The 123 ground survey sites distribution is illustrated in Figure 3. Some survey results of sites in 2014 are given in Table A1 of the Appendix A.



Figure 3. The ground survey site distribution in Li County. The dots (points) represent the locations of county, village or town governments.

2.3.4. Other Relevant Data

After the Wenchuan earthquake, the surface coverages in Li County have been changed greatly. Therefore, the geographic information data of Li County came from a recent national survey of geographic conditions, including the detail classification information of land cover and terrain data in Li County. Meanwhile, the meteorological data used in this study were downloaded from the National Meteorological Information Center of China Meteorological Administration, including annual average values of relative humidity, sunshine hours, temperature and wind speed, and annual total rainfall. Due to the remote geographical location of Aba prefecture, the number of public meteorological stations is limited. There is no meteorological station in Li County. In order to cope with this problem, the data of Xiaojin and Maerkang meteorological station closest to Li County were utilized in this study. The average values of the data from the two stations at same time served as the weather data of Li County.

2.4. Remote Sensing Investigation Indicator of Lophodermium piceae

NDVI is a widely used vegetation parameter and can indicate both vegetation coverage ratio and vegetation growth status. It can eliminate some radiation errors and is sensitive to changes of soil background. Thus, it can be regarded as the chief indicator to reflect forest vegetation ecological environments [19]. According to the characteristics of *Lophodermium piceae*, we chose an NDVI-based time-sequence indicator for *Lophodermium piceae* investigation. In order to yield NDVI maps, the acquired multi-spectral images need to be preprocessed. Due to the influences of sensor platform and terrain, geometric distortion is usually inevitable in the acquired remote sensing images. Consequently, it is essential to make geometric correction in advance [20]. Then, the raw Landsat data must be radiometrically calibrated. That is, the digital quantization value (DN) of original remote sensing images must be converted into actual physical quantities, such as radiance values. In addition, due to atmosphere effects, the MODTRAN+ radiative transfer model was applied to fulfil atmospheric correction. Finally, owing to their inconsistent coverages, these remote sensing images were projected into CGCS2000 (China Geodetic Coordinate System 2000) coordinate system and cropped according to the scope of our study area. NDVI is calculated by Equation (1):

$$NDVI = \frac{\rho_{NIR} - \rho_{RED}}{\rho_{NIR} + \rho_{RED}},$$
(1)

where ρ_{NIR} and ρ_{RED} represent the reflectance of near-infrared and that of red band, respectively. The range of NDVI value is -1 to 1. The generated NDVI map for Li County is given in Figure 4. Then, the change rate of NDVI can be defined in the Equation (2):

$$VI_{rate} = \frac{VI_{T_2} - VI_{T_1}}{VI_{T_1}} \times 100\%,$$
(2)

where VI_{T_1} and VI_{T_2} represent the NDVI maps at T_1 and T_2 , respectively, namely before and after infection, and VI_{rate} represents the change rate of NDVI. Since the dynamic ranges of NDVI change rate for non-vegetation-covered areas are uncertain, only an NDVI difference map of two phases of remote sensing images in Li County is exhibited below.



Figure 4. A NDVI difference map for Li County, where T_1 is 1st June and T_2 is 23 October.

A remote sensing image-processing software is utilized to align the resources data with NDVI change maps generated from remote sensing images, and then extract map patches of the concerned tree species, so that two kinds of information are merged together. Then, the extracted damage patches are imported into a GIS (Geographic Information System) software and their damage degree is graded according to our remote sensing investigation model, established by a model described in the next section, and corresponding damage areas are calculated.

2.5. Establishment of Remote Sensing Investigation Model

Generally, as a result of different species of forest vegetation, the types of forest pests are different, and damaged symptoms of plants are also different. Therefore, the remote sensing investigation methods for different tree species pests are also different [21], which can be summarized as follows: (1) difference or ratio method (i.e., direct subtraction or division of two temporal images); (2) combining difference and principal component analysis; (3) regression analysis; and (4) cross correlation analysis. Regression analysis is similar to relative radiometric correction of remote sensing images. Thus, it can be said that this method can, to some degree, reduce the influences of atmosphere, terrain and illumination on remote sensing images at different times. Figure 5 is a scatter plot that reveals the relationship between the NDVI change rate and damage degree over all the ground survey sites. The horizontal axis represents the change rate of NDVI and the vertical axis represents the damage level, where "0" represents normal, and "1" represents light, "2" represents moderate and "3" represents severe. It can be seen that there are clear correlations between the NDVI change rate and damage degree.



Figure 5. The relationship between the NDVI change rate and damage degree.

In order to study quantitatively, a correlation analysis was performed between the damage degree of *Picea asperata* forests and the NDVI change rate from the ground survey sites to verify whether there is a significant correlation. The correlation analysis results showed that there was a significant negative correlation between the NDVI change rate and damage degree when R = -0.860 and significance level α is 0.01. According to Pearson statistical theory, the two corresponding variables, *x* and *y*, are significantly correlative, and mathematical models based on them are reliable. Thus, we randomly selected 100 ground survey sites for regression analysis in order to obtain a disease estimation model, and the remaining 23 sites were taken as real values in accuracy verification. The semi-empirical estimation model between the change rate of NDVI and damage degree is built as follows:

$$Y = -0.103 \times V I_{\text{rate}} - 0.520. \tag{3}$$

When *Y* is less than 0.5, the damage is normal; when *Y* is 0.5 to 1.2, the damage is light; when *Y* is 1.2 to 2.1, the damage is moderate; and when *Y* is greater than 2.1, the damage is severe. Then, consider a linear regression equation expressed in the form of y = ax + b, where the independent variable *x* is the damage level estimated by the remote sensing investigation model and *y* is the actual damage level obtained from the ground survey data.

F-test method was adopted to verify the reliability and adaptability of this model. In the light of *F*-test theory, if $F > F(m, n-m-1, \alpha)$, there is a significant linear regression relationship between *x* and *y*, where *m* is the number of independent variables, *n* is the number of samples, *n*-*m*-1 is the degree of freedom, and α is the significance level. The *F*-test results of the established model are given in Table 1.

Table 1. The estimated model test results.

Р	R	R^2	а	a b		RMSE	F
0.010	-0.860	0.740	-0.103	-0.520	32.657	5.715	344.715

Here, MAE represents mean absolute error, i.e., the mean absolute deviation of all the estimated values and actual values for a parameter. RMSE is root mean-square error. The results revealed that there is a significantly negative correlation between the NDVI change rate and the damage degree, at a significant level of 0.010. Therefore, it is effective to investigate diseases through the NVDI change rate. In Table 1, F = 344.715 > F(1, 98, 0.01), and it is manifested that the model possesses high adaptability and reliability.

Consider that the remaining ground survey data served as the true values to verification the estimation model. The verification formula is:

$$E_i = (1 - |\frac{x_i - y_i}{y_i}|) \times 100\%$$
(4)

where E_i represents the estimation accuracy for the i-th ground survey site, x_i represents the estimated damage grade of the i-th ground survey site, y_i represents the actual damage grade of this site, and *i* is the order number of the current ground survey site used for verification. Through analysis, it was found that among the 23 ground survey sites, the estimated damage degree for 19 survey sites is consistent with the real values. The average estimation accuracy of the model reaches 82.61% and can meet the accuracy requirements of large-scale investigation in our study area.

2.6. Spatio-Temporal Analysis Methods for Lophodermium piceae

The emergence and evolution of forest pests depend on the growth environment and natural geographical conditions. The planting areas of *Picea asperata* in Li County are large, and the topography and climate there are also representative of typical subalpine areas. Therefore, it is of great significance to study the influence factors of the disease in Li County by the remote sensing investigation results and explore general emergence patterns of diseases, which is of considerable reference value in guiding effective prevention and control of pests. The occurrence and evolution of forest diseases are owing to a variety of factors, and these factors generally can be divided into two aspects: one is the growth status of forest plants itself, and the other is external factors, such as growth environment, natural geographical conditions, and human influences [22–25]. Therefore, we focused on meteorology, terrains, and forest stands in the spatio-temporal analysis of the disease.

2.6.1. Temporal Analysis Methods

In this study, a stepwise regression method was exploited to analyze the disease damage in Li County by meteorological factors. The analysis purpose was to obtain an optimal set of explanatory factors, which contributed most to the interpretation of response factors and can be useful for explaining response variables. Its basic procedure is to add each explanatory factor to the model and assess their significance by *F*-test; then, if the factor is significant, evaluate all explanatory factors in the model by normal distribution testing (*t*-test); and if all formerly added explanatory factors become insignificant because of the later explanatory factors, delete them. When no significant explanatory factor is deleted from or added to the regression equation, the process ends and the optimal set of explanatory factors can be obtained. According to the growth characteristics of pathogens and *Picea*

10 of 20

asperata, five variables were chosen, including annual average temperature (°C), annual total rainfall (0.1 mm), annual average relative humidity (%), annual average sunshine hours (0.1 h), and annual average wind speed (0.1 m/s).

2.6.2. Spatial Analysis Methods

Based on the remote sensing investigation results of Lophodermium piceae, canonical correspondence analysis (CCA), also called multivariate direct gradient analysis, was employed to analyze the disease damage by different environmental impact factors. Its essence is to perform multiple linear regression analysis during the iterative process of correspondence analysis. That is, regression analysis is carried out between the ranking coordinate value of each sample and environmental impact factors. In CCA analysis, there are two data matrices, corresponding to samples and environment factors [26,27]. The primary steps of CCA are as follows: first, the ranking values of a group of samples from different species are calculated, and the ranking values of samples are combined with environmental factors mainly by using regression analysis, which can not only reflect the species composition of samples, but also reflect the impacts of environmental factors on different species composition; then, the ranking values of species composition are obtained from the weighted average of the ranking value of samples, which makes the species ranking value relate to the environmental factors. The credibility of the results mainly lies in the analysis of the correlation between environment factors and research objects in the first two ranking axes, as well as the cumulative contribution rate of the ranking axes.

3. Results

3.1. Remote Sensing Investigation Results of Lophodermium piceae

As mentioned before, an NDVI change-rate map was calculated by the two scenes of Landsat 8 in 2014, which are obtained from the study area on 1st June and 23 October, respectively. Then, the distribution map of *Lophodermium piceae* in our study area, Li County, was generated by using the remote sensing estimation model, as presented in Figure 6. It realizes geospatial visualization of damage position and degree.



Figure 6. The remote sensing investigation results of *Lophodermium piceae* for Li County: (**a**) the global investigation results of *Lophodermium piceae* for Li County; (**b**) the investigation results for Miyaluo Town; (**c**) the investigation results for Putou Village.

According to the results of the remote sensing investigation in Li County, the areas infected with Lophodermium piceae were counted. The damage situation of Picea asperata forests in Li County generated by remote sensing investigation is as follows: the area of light damage is 346.14 hm^2 , the area of moderate damage is 268.92 hm^2 , the area of severe damage is 258.66 hm², and the total area of damaged *Picea asperata* forests is 873.72 hm², which is about 2.410% of the total area of this tree species in this county. From the ground survey data of Li County, it can be seen that the damage situation of *Picea asperata* forests in 2014 is: the area of light damage is 344.64 hm², the area of moderate damage is 242.14 hm², the area of severe damage is 220.29 hm², and the total area of damaged Picea asperata forests is 807.07 hm², which is about 2.226% of the total area of this tree species in this county. The remote sensing investigation result is 66.65 hm^2 more than the ground survey results. In terms of distribution, the ground survey data *Lophodermium piceae* mostly occurred in Miyaluo town and Putou village in Li County, and remote sensing investigation results also indicated that *Picea asperata* infected by this disease mostly distributed there, which is consistent with the ground survey data, as depicted in Figure 6b,c. Hence, it can be drawn that the remote sensing investigation results coincide with the survey results in damage degree and areas of *Picea asperata* forests. The feedback from the local forestry department of Li County also confirmed that the spatial distribution of Lophodermium piceae in the remote sensing investigation results also agree with their practice experience.

3.2. Temporal Analysis Results about Climate Variables

Figure 7 respectively exhibits fitting trends charts between the ground survey data of the nine years after the Wenchuan earthquake and climate variables, such as annual average temperature, annual total rainfall, annual average relative humidity, annual average sunshine hours, and annual average wind speed and damage areas of Lophodermium piceae. Since Lophodermium piceae occurs repeatedly every year if there are infections, it is difficult to cure this disease thoroughly. In order to help the local forestry department to take preventive measures in advance, the annual climate variables are analyzed in this work. Firstly, as can be seen in Figure 7a,b, pathogens of *Lophodermium piceae* often begin their life activities when environment temperature is greater than 11 °C. As environment temperature increases, their life activities become more and more strong, and they start to emit a large number of spores, and only decay at high temperature or low temperature. Thus, it can be deemed that the temperature has a direct influence on spore emissions of pathogens, and indirect influence on the ascospore transmission of pathogens. Secondly, the amount of rainfall has a direct effect on the humidity in soil and air, and also on water absorption by *Picea asperata* and the life activities of pathogens. Consequently, the incidence of *Lophodermium piceae* is also related to rainfall, which can be seen in Figure 7c,d. Moreover, pathogens can be spread through rainfall. The greater the rainfall amount and the longer the rainfall duration, the more booming the spread of pathogenic spores. Furthermore, relative humidity has direct relationships with rainfall. From June to August, the average relative humidity in Li County is about 75%, which is also favorable to the life activities of pathogenic spores, such as reproduction and epidemic, as revealed in Figure 7e,f. Thirdly, since sunshine time is very important to the growth status of plants, it also has a great impact on the damage degree. Sunlight directly participates in the photosynthesis of *Picea* asperata and has a strong influence on their growth. As implied in Figure 7g,h the better *Picea asperata* forests grow, the less their susceptible is. The spread of pathogens generally relies on winds, rains, birds and insects, thereby the wind speed is the important decisive factor for the spread of pathogens. Finally, as depicted in Figure 7i,j because Picea asperata is a kind of conifer, frictions between dense needles will result in abrasions [28]. The greater the wind speed is, the more likely that needles are destroyed, which consequently provides beneficial conditions for pathogen infection.



Figure 7. The relationship between annual climate factors and the annual total damage area by *Lophodermium piceae*: (**a**) the relationship between annual total damage area and annual average temperature; (**b**) the trend obtained by fitting annual total damage area to annual average temperature; (**c**) the relationship between annual total damage area and annual total rainfall; (**d**) the trend obtained by fitting annual total rainfall; (**e**) the relationship between annual total damage area and annual total damage area to annual total damage area to annual total damage area and annual average relative humidity; (**f**) the trend obtained by fitting annual total damage

area to annual average relative humidity; (g) the relationship between annual total damage area and annual average sunshine hours; (h) the trend obtained by fitting annual total damage area to annual average sunshine hours; (i) the relationship between annual total damage area and annual average wind speed; (j) the trend obtained by fitting annual total damage area to annual average wind speed. The ground survey data of the nine years after the Wenchuan earthquake are listed in Table A2 of Appendix A.

Meanwhile, through the trend-fitting analysis of the total damage area of Li County by Lophodermium piceae recorded in the ground survey data of the nine years after the Wenchuan earthquake, with annual average temperature, annual total rainfall, annual average relative humidity, annual average sunshine hours, and annual average wind speed, the fitting results are not acceptable and the determination coefficients are all below 0.5. Especially, the determination coefficient for annual total rainfall R^2 is only 0.0923. This means that the influences of all the five climate factors on this forest disease are not obvious. The reason is that the five climate variables collaborate together, rather than work alone. As a result, we exploited a stepwise regression analysis method to analyze the forest disease by the five climate variables, where the annual average sunshine hours (X_1) , annual average temperature (X_2), annual average relative humidity (X_3), annual total rainfall (X_4), annual average wind speed (X_5) , and damage area (Y) by Lophodermium piceae were examined simultaneously. By this means, the factors that have significant effects on *Lophodermium piceae* can be screened out. Then, it is found that only annual average temperature and annual average wind speed are closely associated with the infection area of *Lophodermium piceae*, where the correlation coefficient R is 0.879 and the determination coefficient R^2 is 0.773.

Thus, a prediction model can be built based on the two significantly relevant climate variables for the damage area by *Lophodermium piceae* (Y). It can be expressed as below:

$$Y = -3037.888 + 49.902 \times X_5 + 299.739 \times X_2 \tag{5}$$

From this prediction model, it can be clearly seen that the higher temperature is and the faster wind speed is, the larger the damage area of *Picea asperata* forests. The *F*-test results of this prediction model are presented in Table 2, where MSE represents mean square error, i.e., the expectation value of square deviation of the estimated value and actual value for a parameter, and *P* is significance level. It is indicated that the two climate variables are remarkably relevant to the damage area.

Table 2. The *F* -test results for the prediction model of damage area.

Р	R	R^2	MSE	RMSE	F
0.020	0.879	0.773	38.497	6.204	10.207

3.3. Spatial Analysis Results about Other Environmental Impact Factors

Some growth environmental factors of *Picea asperata*, such as age group, soil type, slope and aspect, can be extracted from our collected forest resource and geographic information data for the spatial analysis of *Lophodermium piceae* based on CCA. The CCA two-dimensional ranking chart for ground survey sites and environmental impact factors is given in Figure 8. Every coordinate axis is a complex function combination of environmental factors. The quadrant that each red arrow belongs to reflects positive or negative correlations between an environmental factors. As described in Figure 8, it is revealed that the impacts of altitude, soil-layer thickness and slope, are mainly reflected on the horizontal axis, which is positively correlated with slope and negatively correlated with soil type and negatively correlated with age group and aspect. Its correlation with soil type and age group are more obvious. In addition, the CCA quantitative values indicate that

the contribution rates of the first two ranking axes are 72.90% and 13.63% with F = 12.6, P = 0.002, and the cumulative contribution rate reaches 86.53%. It means that the first two ranking axes are extremely significant and can explicate the 86.53% of the damage degree data of *Picea asperata* forests and the ranking results are ideal to some extent.



Figure 8. The CCA ranking chart for the ground survey sites and impact factors. The horizontal axis corresponds to the first ranking axis, the vertical axis corresponds to the second ranking axis, black circles are damage degree data of survey sites and red arrows represent environmental impact factors.

Similarly, the CCA two-dimensional ranking chart for the damage degree of *Picea asperata* forests and environmental impact factors are shown in Figure 9, where black arrows represent different levels of damage degree and red arrows represent environmental impact factors. The angles between arrow lines of different colors illustrate the correlation between environmental impact factors and different levels of damage degree. An acute angle means that there is a positive correlation between two environmental factors, and an obtuse angle means a negative correlation.



Figure 9. The CCA ranking chart for the damage degree of *Picea asperata* forests and impact factors.

As shown in Figure 9, the thicker the soil layer is and the higher the altitude is, the less infected spruces are. The primary reason is that thick soil layers can preserve much water

and nutrients, which is favorable for the growth of *Picea asperata* forests and enhances their disease resistance. Meanwhile, higher altitudes mean lower temperatures, which can restrain the life activities of pathogens. On the other hand, the distribution of light, moderate and severe damage to *Picea asperata* forests is primarily associated with slope, aspect, age group, and soil type. In terms of correlativity, the damage degree of *Picea asperata* forests presents a comprehensive gradient distribution along soil-layer thickness, slope and altitude, while the influences of soil type, age group and aspect are not remarkable. Thinner soil layer, lower altitude, and steeper slope are more likely to lead to a more severe damage degree. The distribution of light and moderate damage degree are mainly affected by the aspect and age group, with few differences.

In terms of visualization, based on the remote sensing disease-investigation results and geographic information data, it is found that the occurrence regions of *Lophodermium piceae* is mainly distributed between 3000 to 3300 m above sea level; an example is displayed in Figure 10. It can be summarized that to some extent, the lower the altitude is, the more damaged the *Picea asperata* forest is, which coincides with the ranking chart for the damage degree of *Picea asperata* forests and impact factors.



Figure 10. The relationship between altitude and *Lophodermium piceae*: (**a**) the altitude distribution of Putou Village; (**b**) the disease-investigation results of Putou Village.

As for slope, it is remarkable in Figure 11 that *Lophodermium piceae* more commonly occurs in steep terrains, mostly in steep slopes (26 to 35°), urgent slopes (36 to 45°) and dangerous slopes ($\leq 46^{\circ}$). The steeper the slope is, the greater the damage degree is, which can also be drawn from the CCA ranking chart for ground survey sites and impact factors that damage degree is strongly negatively correlated with slope. The reason is that the larger the slope, the more difficulties there are in the development of spruce root systems. At steeper slopes, water and nutrients in the soil are more likely to be lost, which has disadvantages for the growth of *Picea aswperata*.

In general, thick soil is more suitable for *Picea asperata*. As illustrated in Figure 12, it can be noticed that *Lophodermium piceae* mainly occurs at the areas where the thickness of the soil layer is 70 or 80 cm. This kind of soil layer is relatively thin and lacks water and nutrients, which is also unfavorable to the growth of *Picea asperata*. From the CCA ranking chart of damage degree and impact factors, we can also find that damage degree is strongly negatively relevant to soil-layer thickness, and the thicker the soil layer is, the less susceptible spruces are. The primary reason is that the thicker the soil layer is, the more water and nutrients are in the soil, so the better the spruces grow and the less susceptible they are.



Figure 11. The relationship between slope and *Lophodermium piceae*: (**a**) the slope distribution of Miyaluo Town; (**b**) the disease-investigation results of Miyaluo Town.



Figure 12. The relationship between soil-layer thickness and *Lophodermium piceae*: (**a**) the soil-layer thickness distribution of Putou Village; (**b**) the disease-investigation results of Putou Village.

Last but not the least, it can be observed from Figure 13 that Lophodermium piceae mostly occurs in young or over-mature forests. Some reasons can be employed to interpret this phenomenon. One is that the plants of young forests are newly reforested and of young age. Owing to weak root systems and tender needles, their capability to resist forest diseases is low. The other is that physiological functions of over-mature forests are degrading, and their needles start to get sparse, promoting the spread of pathogens by strong winds. Moreover, continuous accumulations of pathogens and repetitive infections make over-mature spruces more susceptible. Of course, the possibility that some foliage of over-mature stands have no Lophodermium piceae, but are simply declining due to age, cannot entirely be excluded. For mid-aged forests, near-mature forests and mature forests, they are very robust. If no special natural disasters happen, they normally grow well with strong root systems and sound physiological functions. Hence, these spruces are not easy to get infected. Also, it can be seen from the CCA ranking charts that the positive correlation between age group and damage degree is not significant. The reason is that *Lophodermium* piceae often infects young forests and over-mature forests and the distribution of ground survey sites is uneven, so that ranking charts are not applicable in this case.





Figure 13. The relationship between age group and *Lophodermium piceae*: (**a**) the age group distribution of Putou Village; (**b**) the investigation results of Putou Village.

4. Discussion

This study verifies that space-borne multi-spectral remote sensing is suitable for Lophodermium piceae large-scale investigation in subalpine areas. Our study area covers 16 forest farms, villages or towns in the whole county of Li County, instead of a single forest farm, several sampling yards or plots in general vegetation disease monitoring research [29,30]. By downloading the historical remote sensing images of the research areas in a specific period of time, a regression model of Lophodermium piceae damage degree and the change rate of NDVI was established. The correlation coefficient of the model *R* is -0.860 and the determination coefficient of the model R^2 is 0.740. The investigation results largely agree with the ground survey data in quantity and spatial distribution. The accuracy of the model can reach 82.61%, which is acceptable in the large-scale investigation of forest diseases in mountainous and dangerous slope areas, where humans cannot reach. Generally, Lophodermium piceae will occur repeatedly every year if there are infections and it is difficult to cure this disease thoroughly. Artificial ground surveys are to determine the approximate range and degree of this disease occurrence through sampling. However, the spatial distribution and damage degree can be exactly explored by the means of multi-spectral remote sensing. On the basis of remote sensing investigation results, through spatiotemporally analyzing, more influential environmental factors are summarized. According to the characteristics of the study area and life activities of *Lophodermium piceae* pathogens, five climate variables, including annual average temperature, annual total rainfall, annual average relative humidity, annual average sunshine hours, and average wind speed, were utilized in temporal analysis of this forest disease. Based on the stepwise regression analysis method, it can be concluded that annual average temperature and annual average wind speed are significantly correlated with Lophodermium piceae in the study area. Moreover, the spatial comprehensive analysis of this forest disease by soil, forest, and topographical factors based on the CCA method revealed that the distribution of Lophodermium piceae is primarily determined by altitude, slope, and soil-layer thickness, and is slightly affected by aspect, soil type, and age group. We found that the damage will be more severe in the places with lower altitude, thinner soil layers and steeper slope.

In effect, this study not only solved the problem of large-scale accurate investigation and visualization representation of *Lophodermium piceae* in Western Sichuan subalpine areas, but also provided an important scientific reference for the prevention and control of this forest disease, and effectively promoted the ecological restoration of the areas seriously destroyed by the "5.12" Wenchuan earthquake in 2008. However, we aimed at the large-scale investigation of *Lophodermium piceae* in subalpine areas by using satellite multi-spectral remote sensing technology. Although regression analysis can describe the linear differences between two images by defining linear relationships between the same pixels at different times, the growth and the change of forest vegetation are nonlinear because of the nonuniform distribution of forest stand factors and site conditions. Consequently, the accuracy of linear methods is usually lower than that of non-linear models. In subsequent research, we can take improved measures to establish more-accurate remote sensing investigation models in unevenly distributed forest stands. Furthermore, the 30-m resolution of the applied Landsat 8 images also has an effect on the investigation results. Other remote sensing images with higher spectral, spatial, and temporal resolution can be used in future research to improve investigation accuracy and accomplish dynamic monitoring. At the same time, since only the dominant tree species in each region is presented in our forest resources data, mixed pixels are not taken into consideration of tree species classification. The pixel unmixing methods are also helpful in enhancing investigation accuracy.

Author Contributions: Conceptualization, X.L.; methodology, X.L. and Y.J.; validation, X.L. and H.C.; investigation, X.L., Y.J. and H.C.; resources, W.X.; data curation and writing—original draft preparation, Q.F. and Y.S.; writing—review and editing, X.L., Q.F. and Y.S.; visualization, Q.F.; project administration, W.X.; funding acquisition, X.L. and W.X. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Science and Technology Program of Sichuan, grant number 2017GZ0327 and 18YYJC0746, "Study on Remote Sensing Monitoring Methods of Forest Diseases in Mountainous Areas" and "Study on rapid and accurate diagnosis and targeted recovery technology of wasteland in Northwest Sichuan by destroyed by rodent pests", and the Science and Technology Program of Hebei, grant number 20355901D, "Research on Generalized Stereo Modeling Technology Based on High Resolution Satellite Images".

Institutional Review Board Statement: Not applicable.

Data Availability Statement: The Landsat 8 data used in this work is available on http://www.gscloud.cn/ (accessed on 28 August 2022) at any time and the download website of the climate data images used in this work is http://cmdp.ncc-cma.net/cn/index.htm (accessed on 28 August 2022). The contact phone number of ground survey personnel of Li County Forestry Department is +86-13990444756.

Acknowledgments: We would like to thank the Forestry and Grassland Bureau of Li County, Aba Prefecture, for their data support of forest resources and disease survey, and thank Sichuan Bureau of Surveying, Mapping and Geoinformation for providing the geographic information data of the study area. Moreover, we would like to thank the anonymous reviewers for their valuable and helpful comments, which substantially improved this paper. At last, we also would also like to thank all of the editors for their professional advice and help.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Site Number	Longitude	Latitude	Damage Degree
1	102.71	31.86	Light
2	102.68	31.78	Light
3	102.88	31.53	Normal
4	102.79	31.29	Light
5	102.96	31.33	Serious
6	102.90	31.40	Serious
7	103.22	31.54	Moderate
8	103.03	31.73	Normal
9	103.18	31.62	Normal

Table A1. The data of some ground survey sites in 2014 (survey time: 1 May to 31 October 2014).

Table A2. The total damage area (hm^2) by *Lophodermium piceae* of the nine years after the Wenchuan earthquake.

Years	2009	2010	2011	2012	2013	2014	2015	2016	2017
Total Damage Areas	520.26	1000.5	867.1	867.1	867.1	807.07	940.47	1113.89	973.82

References

- 1. Pan, H. Problems and Countermeasures in Forest Pest Prevention in China. J. For. Pest Dis. 2002, 21, 42–47.
- Bai, X.; Zhang, X.; Zhang, N.; Zhang, L.; Ma, Y. Monitoring Model of *Dendrolimus tabulaeformis* Disaster Using Hyperspectral Remote Sensing Technology. J. Beijing For. Univ. 2016, 13, 16–22. [CrossRef]
- Wang, L.; Luo, Y.; Huang, H.; Shi, J.; Keliovaara, K.; Teng, W. Reflectance Features of Water Stressed Larix gmelinii Needles. For. Stud. China 2009, 11, 28–33. [CrossRef]
- 4. Xu, Z.; Li, C.; Liu, J.; Yu, K.; Gong, C.; Tang, M. Fisher Discriminant Analysis of *Dendrolimus Punctatus* Walker Pest Levels. *Nongye Jixie Xuebao Trans. Chin. Soc. Agric. Mach.* **2014**, *45*, 275–283. [CrossRef]
- Ghavidel, M.; Bayat, P.; Farashiani, M.E. Satellite Image Processing of the Buxus hyrcana Pojark Dieback in the Northern Forests of Iran. J. For. Sci. 2021, 67, 71–79. [CrossRef]
- Bhattarai, R.; Rahimzadeh-Bajgiran, P.; Weiskittel, A.; Meneghini, A.; MacLean, D.A. Spruce Budworm Tree Host Species Distribution and Abundance Mapping Using Multi-Temporal Sentinel-1 and Sentinel-2 Satellite Imagery. *ISPRS J. Photogramm. Remote Sens.* 2020, 172, 28–40. [CrossRef]
- Ye, H.; Huang, W.; Huang, S.; Cui, B.; Dong, Y.; Guo, A.; Ren, Y.; Jin, Y. Recognition of Banana Fusarium Wilt Based on UAV Remote Sensing. *Remote Sens.* 2020, 12, 938. [CrossRef]
- 8. Greene, A.D.; Reay-Jones, F.P.; Kirk, K.R.; Peoples, B.K.; Greene, J.K. Spatial Associations of Key Lepidopteran Pests with Defoliation, NDVI, and Plant Height in Soybean. *Environ. Entomol.* **2021**, *50*, 1378–1392. [CrossRef]
- Oblinger, B.W.; Bright, B.C.; Hanavan, R.P.; Simpson, M.; Hudak, A.T.; Cook, B.D.; Corp, L.A. Identifying Conifer Mortality Induced by Armillaria Root Disease Using Airborne Lidar and Orthoimagery in South Central Oregon. *For. Ecol. Manag.* 2022, 511, 120126. [CrossRef]
- 10. Li, N.; Zhang, X.; Zhang, N.; Zhu, C.; Sun, Z. Hazards Evaluation of *Dendrolimus tabulaeformis* (*Lepidoptera: Lasiocampidae*) Based on Weighted Information Value Model. *Sci. Silvae Sin.* **2019**, 55, 106–117.
- 11. Gearman, M.; Blinnikov, M.S. Mapping the Potential Distribution of Oak Wilt (*Bretziella fagacearum*) in East Central and Southeast Minnesota Using Maxent. J. For. 2019, 117, 579–591. [CrossRef]
- 12. Li County, Sichuan. Available online: http://en.wikipedia.org/wiki/Li_County,_Sichuan/ (accessed on 13 June 2021).
- 13. Forest and Grassland Pest Control Station General of State Forestry and Grassland Administration. *Forest Pests in China* (2014–2017 *National Forest Pest Survey Results*), 1st ed.; China Forestry Press: Beijing, China, 2020.
- 14. Tang, B.; Yin, C.; Yang, H.; Sun, Y.; Liu, Q. The Coupling Effects of Water Deficit and Nitrogen Supply on Photosynthesis, WUE, and Stable Isotope Composition in *Picea Asperata. Acta Physiol. Plant.* **2017**, *39*, 1–11. [CrossRef]
- 15. Jasinski, J.P.; Payette, S. Holocene Occurrence of *Lophodermium piceae*, a Black Spruce Needle Endophyte and Possible Paleoindicator of Boreal Forest Health. *Quat. Res.* **2006**, *67*, 50–56. [CrossRef]
- 16. Müller, M.M.; Hamberg, L.; Morozova, T.; Sizykh, A.; Sieber, T. Adaptation of Subpopulations of the Norway Spruce Needle Endophyte *Lophodermium piceae* to the Temperature Regime. *Fungal Biol.* **2019**, *123*, 887–894. [CrossRef] [PubMed]
- 17. GB/T 23617-2009. National standard of the People's Republic of China: General Principles of Survey on Forestry Quarantine Pest. State Forestry Administration of China: Beijing, China, 2006.
- 18. LY/T 1955-2011. Forestry industry standard of the People's Republic of China: Technical Regulations for Defining Forest Land Border in Forest Land Planning on Protection and Utilization. State Forestry Administration of China: Beijing, China, 2011.
- 19. Zhong, S.; Sun, Z.; Di, L. Characteristics of Vegetation Response to Drought in the CONUS Based on Long-Term Remote Sensing and Meteorological Data. *Ecol. Indic.* 2021, 127, 107767. [CrossRef]
- Kartal, H.; Sertel, E.; Alganci, U. Comperative Analysis of Different Geometric Correction Methods for Very High Resolution Pleiades Images. In Proceedings of the 8th International Conference on Recent Advances in Space Technologies (RAST), Istanbul, Turkey, 22 June 2017. [CrossRef]
- Fang, L. Research on Plant Diseases and Insect Pests Monitoring Technology under the Background of Internet of Things Technology. In Proceedings of the International Wireless Communications and Mobile Computing (IWCMC), Xi'an, China, 20 October 2020. [CrossRef]
- Skendžić, S.; Zovko, M.; Živković, I.P.; Lešić, V.; Lemić, D. The Impact of Climate Change on Agricultural Insects Pests. *Insects* 2021, 12, 440. [CrossRef] [PubMed]
- Baeten, L.; Bruelheide, H.; Van Der Plas, F.; Kambach, S.; Ratcliffe, S.; Jucker, T.; Allan, E.; Ampoorter, E.; Barbaro, L.; Bastias, C.C.; et al. Identifying the Tree Species Compositions That Maximize Ecosystem Functioning in European Forests. *J. Appl. Ecol.* 2018, 56, 733–744. [CrossRef]
- Felipe-Lucia, M.R.; Soliveres, S.; Penone, C.; Manning, P.; Van Der Plas, F.; Boch, S.; Prati, D.; Ammer, C.; Schall, P.; Gossner, M.M.; et al. Multiple Forest Attributes Underpin the Supply of Multiple Ecosystem Services. *Nat. Commun.* 2018, *9*, 4839. [CrossRef]
- 25. Cai, W.; Yang, C.; Wang, X.; Wu, C.; Larrieu, L.; Lopez-Vaamonde, C.; Wen, Q.; Yu, D.W. The Ecological Impact of Pest-Induced Tree Dieback on Insect Biodiversity in Yunnan Pine Plantations, China. *For. Ecol. Manag.* **2021**, 491, 119173. [CrossRef]
- Mohapatra, M.; Yadav, R.; Rajput, V.; Dharne, M.S.; Rastogi, G. Metagenomic Analysis Reveals Genetic Insights on Biogeochemical Cycling, Xenobiotic Degradation, and Stress Resistance in Mudflat Microbiome. J. Environ. Manag. 2021, 292, 112738. [CrossRef]
- 27. Azis, M.N.; Abas, A. The Determinant Factors for Macroinvertebrate Assemblages in a Recreational River in Negeri Sembilan, Malaysia. *Environ. Monit. Assess.* 2021, 193, 394. [CrossRef] [PubMed]

- 28. Badraghi, A.; Marek, M.V. Species Mixing Effect on Norway Spruce Response to Elevated CO₂ and Climatic Variables: Root and Radial Growth Response. *Forstwiss. Cent.* **2021**, *140*, 1363–1376. [CrossRef]
- 29. Zhang, C.; Ye, Y.; Xiao, D.; Qi, L.; Yin, J. Rapid Detection and Identification of Major Vegetable Pests Based on Machine Learning. *Int. J. Wirel. Mob. Comput.* 2022, 22, 223–235. [CrossRef]
- Hamdane, Y.; Gracia-Romero, A.; Buchaillot, M.L.; Sanchez-Bragado, R.; Fullana, A.M.; Sorribas, F.J.; Araus, J.L.; Kefauver, S.C. Comparison of Proximal Remote Sensing Devices of Vegetable Crops to Determine the Role of Grafting in Plant Resistance to Meloidogyne incognita. *Agronomy* 2022, *12*, 1098. [CrossRef]