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Analysis of Spatial and Temporal Dynamics of Finland's Boreal Forests and Types over the Past Four Decades

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Abstract: In the context of global warming, the study of the long-term spatial change characteristics of boreal forest cover is not only important for global climate change and sustainable development research but can also provide support for further research on the response of boreal forest changes to climate change. Using Landsat TM/OLI images from 1980 to 2020 as the data source and Google Earth Engine (GEE) as the platform, Finland was selected as the study area of boreal forests, and typical sample points of different features were chosen to classify forested and non-forested land using the random forest algorithm combined with spectral indices and classified feature sets of tasseled cap transform to obtain the four-phase forest cover change maps of the region. GEE test sample points and random selection points of images from the GF-2 and GF-7 satellites were used for verification. The classification accuracy was 97.17% and 88.9%. The five-phase forest cover images were segmented by a 2° latitude zone, and the spatial and temporal dynamic changes in forest cover in the whole area and each latitude zone were quantified by pixel superposition analysis. The results showed that, in the past 40 years, the boreal forest cover in Finland changed significantly, and the forest cover decreased from 75.79% to 65.36%, by 10.43%. Forest change mainly occurs in coniferous forests, whereas broadleaf forests are more stable. The forest coverage in each latitude zone decreased to varying degrees, with higher changes occurring in high-latitude areas above 64° N between 1980 and 2000, and higher and more severe changes occurring in low-latitude areas below 64° N between 2000 and 2020. Coniferous forests are the dominant type of forest in Finland, and the degradation of coniferous forests in the south is likely to become more severe, whereas the north and above is likely to become more favorable for coniferous forests. More monitoring and research are needed to follow up on the very different changes in the north and south regions.

Keywords: boreal forest; forest types; forest cover; GEE; Landsat satellite

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1. Introduction

Forests are the main part of the terrestrial ecosystem and the largest carbon storage reservoir on land, fixing carbon dioxide absorbed in the atmosphere in the vegetation or soil to reduce the concentration of carbon dioxide in the atmosphere [1], and they have an important strategic position in global climate regulation and sustainable development [2].

The global climate balance is being affected by the growing magnitude of greenhouse gas emissions and their increasing concentration in the atmosphere [3]. The global average temperature by 2100 will increase by about 1, 2, and 4 °C compared to temperatures in the period 1986–2005 [4]. Unlike the imagined feedback mechanisms of the climate system, warming in the high latitudes of northern Europe will be greater than near the equator, and warming in winter will be greater than in summer. Precipitation in the Arctic Circle has also increased over the last century, especially during the cold season [5].

The global climate has changed significantly since the beginning of the last century, and anthropogenic and natural factors have made climate warming a topic of pressing concern, since it has a great impact on economic development, social stability, and the survival and development of all human beings [6]. Climate change makes forests highly susceptible to damage, breaking the ecological balance. As a result, the distribution of forests has changed significantly. In the context of rising temperatures, the growth cover of forest vegetation has increased, and the alpine tundra at the edge of the Arctic is being replaced by trees and shrubs, while temperate forests in the southern part of the boreal forest are being replaced by subtropical or tropical forests [7].

The boreal forest region accounts for about 14.4% of the Earth's total land area and 30% of its forest area, mainly in North America and Eurasia, and is one of the most sensitive regions to climate change [8–10]. The unique cold climatic conditions of the boreal forest make it a huge carbon reservoir for terrestrial ecosystems (30%~35% globally), the carbon being stored in the organic matter of forest soils. Boreal forests are largely unmanaged landscapes, and overall levels of human disturbance and population densities are kept low. However, these forests have become homogenized over long periods of management; global warming has degraded forests in some regions, while at the same time, forests distributed from south to north are advancing northward and mountain forests are moving upward [11]. Changes in boreal forests vary according to region, indicating that boreal forests, as one of the regions that is most sensitive to climate, interact differently with climate in different regions. Therefore, the study of the spatial change characteristics of boreal forests over a long period of time and on a large scale is of great practical significance for the study of global climate change issues and sustainable development. From past research, it is obvious that climate change has a negative impact on boreal forests and forestry, but there are positives as well [12–16]. Forests in the Nordic countries are likely to increase [17,18], where the growing season is relatively short and low summer temperatures and nutrient availability currently limit growth. Increasing temperatures and drought events may also worsen the growing conditions for certain tree species, such as Norway spruce (Picea abies), which is very common in northern Europe. It is more prominent in the northern and southern regions [12,13,19].

Finland has the highest forest cover in Europe and the densest forests in the world, and research on the effects of climate change on Finland's boreal forests is important for monitoring boreal forests on a global scale. The effects of climate change on boreal forest areas can be excellently studied in Finland, which is a typical boreal forest region. Today, the mean annual temperature in Finland is already about 2.3 °C higher than it was two centuries ago [20] Mikkonen et al. 2015. By the 2080s, mean annual temperatures are projected to be 1.9, 3.3, and 5.6 °C higher than in 1981–2010, with mean annual precipitation projected to increase by 6%, 11%, and 18%, respectively, with a projected rise in mean temperatures of about 1–5 °C and a projected increase in precipitation of 5%–11% [5]. Rising temperatures may lead to conditions in the south becoming less suitable for forests, while in northern Finland, there is a tendency for forests to increase, but overall forest growth will still be declining [13].

The development of remote sensing technology has realized the extension of people's observation of objects in terms of distance and spectral dimension. Traditional forest survey technology has the disadvantages of field work intensity, high cost, time consumption, low precision, etc. The macro, dynamic, convenient, periodic, and low-cost characteristics of remote sensing technology are very consistent with the characteristics of forest resources, such as being vast, complex, and having poor access, and this technology has become the ideal means of research on the dynamic changes in forest resources [21]. Remote sensing image classification has been developed since the late twentieth century, many scholars have conducted extensive and in-depth research on the use of remote sensing imagery for forest cover monitoring, and the combination of vegetation indices and classification algorithms can effectively extract forested and non-forested land, broadleaf forests, and coniferous forests [22–24]. Moreover, with the development of the cloud platform Google Earth Engine (GEE) and satellites, the efficiency of long time-series forest change monitoring has been greatly improved in recent years and can be programmed online to accomplish natural and anthropogenic changes in an area over decades. It is also easier to study the response mechanisms between forests and climate factors [25,26].

Currently, some results have been obtained in the qualitative monitoring of overall forest changes, but there is less monitoring and quantitative analysis of dynamic changes in boreal forests at large scales, high spatial and temporal resolutions, and spatial and temporal scales at different latitudes, and there are fewer studies of changes in coniferous and broadleaf forests. In this work, a spectral feature set was constructed based on multitemporal geodetic remote sensing imagery and geographic data, and a random forest algorithm was utilized in conjunction with local data analysis for the quantitative analysis of changes in forest cover and different forest types in the Finland boreal forest during the last four decades, as well as the patterns of spatial change at different latitudes. The aim was to reveal which latitudinal band is more sensitive to forest changes and to provide information for studying the response of boreal forest areas to global climate change.

2. Materials and Methods

2.1. Study Area

Finland's forests are predominantly coniferous, with 81% spruce and red pine, 15% birch, and only 4% broadleaf trees [27], making it one of the most typical boreal forest regions in the world (Figure 1). Boreal forest ecosystems are relatively intact and stable, but the trend of change in the context of global climate change is more drastic than that of the rest of the world. In Finland, human activities are concentrated in the area from 60° N to 64° N, and there is less human activity at higher latitudes. In this paper, the spatial and temporal dynamics of forests in Finland are investigated in relation to latitude in the context of climate change. Therefore, the Arctic Circle is used as a criterion for classifying and analyzing forests, with the forests being divided into latitudinal bands at two-degree intervals within the Finland study area.

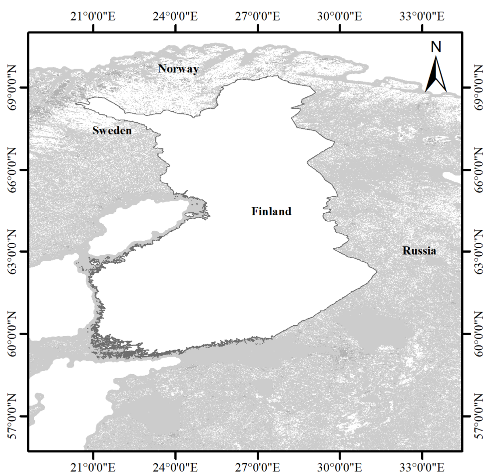


Figure 1. Study area.

In recent decades, Finland has suffered fewer natural disasters than any other European country, including Sweden. However, as the climate warms, the risk of forest destruction is expected to increase both in summer and in winter [28,29]. Such disturbances may affect extensive coniferous forests in northern Europe, especially in the boreal cold zone. A comprehensive understanding of how climate change affects the environment at different spatial and temporal scales is needed in order to ensure sustainable multifunctional forest management and to utilize the prerequisites of different ecosystem services. Therefore, it is important to study the dynamics of typical boreal forests in Finland at different latitudes.

2.2. Data Acquisition and Processing

According to Finnish climate characteristics, satellite images from Landsat5 TM and Landsat8 OLI, which were provided by the GEE platform, were mainly utilized for the analysis of five periods of June–September remote sensing images in the years 1980, 1990, 2000, 2010, and 2020. The selected images are Landsat T1 products, i.e., they have been radiometrically and geometrically corrected. The overall cloudiness of the image is reduced to less than 5% by masking the cloud snow pixels. Finally, multiple images were medianized and mosaicked to obtain complete image data for the study area. The missing images were supplemented with data from adjacent years to obtain the full coverage of images in the study area. Data in shp format for Finnish administrative districts, the Global 30 m surface coverage product dataset, and Google Earth high-resolution imagery were collected to facilitate the selection of classification samples. Gaofen-2 (GF-2) and Gaofen-7 (GF-7) satellite images in 2015 and the Esri | Sentinel-2 10 m Land Cover forest category dataset were used for accuracy assessment.

2.3. Forest Classification Methods

The GEE platform was used to select time series image data, complete image preprocessing, and construct a spectral classification feature set based on the characteristics of forest and vegetation cover in Finland. By combining the spatial distribution of vegetation data with the platform's forest reality map, uniform sample points covering the whole country of Finland were selected to form a five-phase sample set, which was then trained and classified using the random forest algorithm. First, the classification of forested and non-forested land was completed; then, the forested land was pruned to complete the classification of coniferous and broadleaved forests. Finally, accuracy and algorithms were evaluated, and mapping and data analysis were completed. (Figure 2).

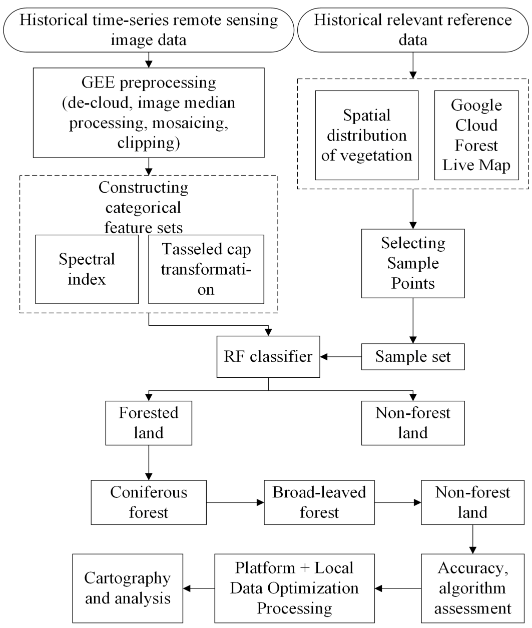


Figure 2. Research workflow.

The vegetation index is a simple and effective measure of surface vegetation, it is also an effective means of distinguishing between vegetated and non-vegetated features [30], and a variety of vegetation indices are obtained by combining different bands of imagery to form a classified feature set. In this paper, the following combinations of vegetation indices were selected to construct a feature classification set based on the north–south characteristics of Finnish vegetation. The normalized difference vegetation index (NDVI), the most commonly used vegetation index [31], is designed to detect vegetation growth status and vegetation cover and to eliminate some of the radiometric errors, etc. The enhanced vegetation index (EVI) can attenuate the effects of atmospheric and soil noise [32], improving the ability to detect sparsely vegetated areas. The modified soil adjustment vegetation index (MSAVI) mitigates the influence of soil on crop monitoring results [33] and is very suitable for situations where the NDVI is not effective in providing accurate values, especially where there is a high proportion of bare soil and sparse vegetation. The modified normalized difference water index (MNDWI) largely improves the effect of shadows such as buildings in water extraction [34], and the differentiation effect is good. The normalized difference built-up index (NDBI) is used to distinguish vegetation from buildings and urban areas [35]. It is worth stating that when classifying the study area, NDBI was found to be effective in extracting man-made surfaces, bare ground, snow, and ice and integrating them into the unforested land samples. The inclusion of MSAVI improved the classification accuracy of grassland and broadleaf forest.

Tasseled cap transform (TCT), also known as Kauth–Thomas transform (K-T transform), is a special principal component analysis (PCA) transform with the transfer matrix fixed to serve a single image. For the TM image, the information of the six bands of visible light and infrared light is mainly reflected in the three feature vectors of greenness, brightness, and wetness after the K-T transform, which compresses the number of features and focuses on the image information, and it can more fully express the information of the vegetation, water bodies, and rocky bare soil. The transformation matrix coefficients are related to image sensors, and different satellite sensor images have different transformation matrix coefficients. In this paper, Landsat5 TM and Landsat8 OLI satellite images are used, along with the transformation matrix that was proposed by Crist et al. [36] and Baig et al. [37]. Based on the band information and matrix coefficients, the encoding is completed to achieve the computation and construction of tasseled cap transformation features on the GEE platform.

3. Results

3.1. Random Forest Classification and Accuracy Assessment

In this study, the Global 30 m surface coverage product dataset and Google Earth high-resolution imagery were chosen for the uniform selection of sample points along the north–south longitudinal direction of Finland, and a training set was formed with the above-mentioned feature set. To ensure the classification accuracy and reliability, the sample points were disrupted and randomly arranged, and 70% of the sample points were randomly selected for training, while 30% of the sample points were used as test validation. After the random forest algorithm completed the classification, the confusion matrix was automatically generated by coding, while the Esri | Sentinel-2 10 m Land Cover forest category dataset was selected, and the GF-2 and GF-7 satellite images were used to validate the classification results. The overall classification accuracy and Kappa coefficient were selected as the validation indices.

The random forest algorithm was used to classify Finnish images from 1980, 1990, 2000, 2010, and 2020. The accuracy validation of the test sample points in the GEE platform showed that the overall classification accuracy of the random forest algorithm for Finnish forested land classification was 97.17%, with a Kappa coefficient of 95.17%. Using the Esri | Sentinel-2 10 m Land Cover forest data and forested land classification results for spatial superposition analysis, spatial cross-validation results show that the spatial overlap between Sentinel-2 10 m Land Cover and 2010 forested land classification results is 82.70%, and the overlap with the 2020 results is 79.50%, which indicates that the classification feature set and the random forest algorithm are reliable and can meet the needs of vegetation monitoring in large-scale and topographically complex areas.

Meanwhile, in total, 1240 sample points of coniferous forests, broadleaf forests, and unforested land were randomly and uniformly selected using the three-scene data of GF-2 and GF-7 imagery to validate the accuracy. The validation was completed by randomly selecting various types of validation points in the three high-resolution images to compare with the regions and some pixel points in the classification results. The overall classification accuracy was 88.9%, with a Kappa coefficient of 82.67%. Among the sample points, the F1-scores of the above three land types were 0.91, 0.86, and 0.87. The results are shown in Table 1. Considering the consistency of national imagery over the years, the validation results are also considered valid for the period 1980–2000. An example of the classification is presented in Figure 3. It can be noticed that broadleaf forests have the highest number of misclassifications, which may be due to the fact that broadleaf forests tend to grow in urban areas, on the borders of cultivated land, and intermixed with coniferous forests.

Table 1. Accuracy assessment using GF-2 and GF-7 images.

Land Classification	Coniferous Forest	Broadleaved Forest	Non-Forest Land	Total
Coniferous forest	525	3	34	562
Broadleaved forest	43	266	35	344
Non-forest Land	15	8	311	334
Total	583	277	380	1240
F1-score	0.91	0.86	0.87	
		overall accuracy = 88.9%		

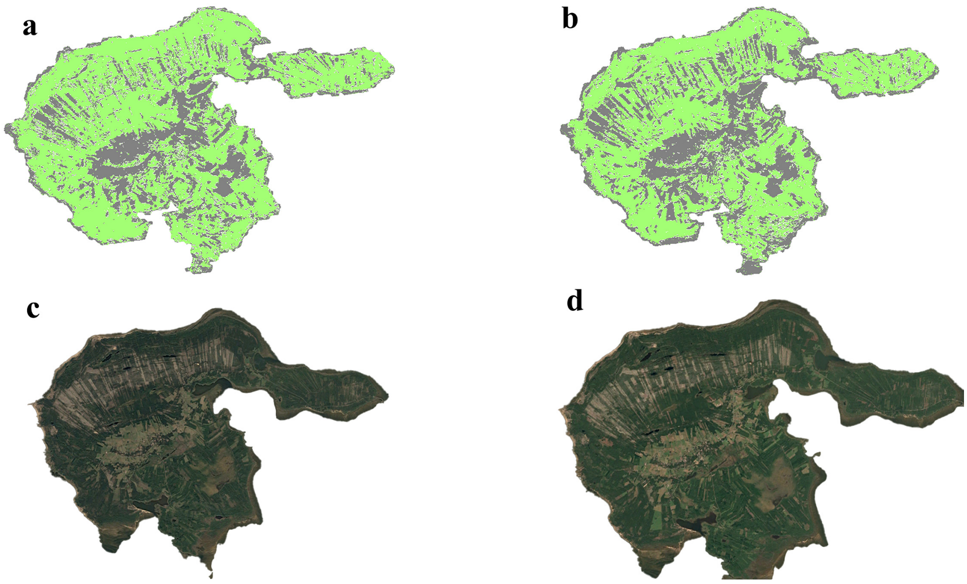
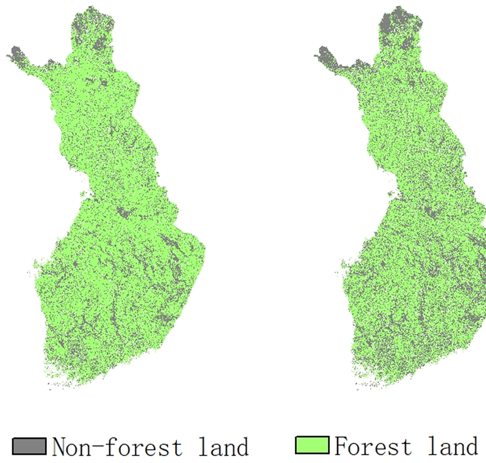


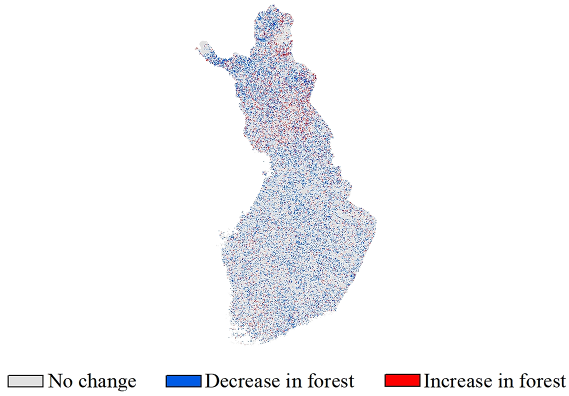
Figure 3. Regional classification results (**a**,**c**) in 2010 and (**b**,**d**) in 2020.

3.2. Spatial Change in Boreal Forest Cover

The random forest algorithm was used to classify the 1980, 1990, 2000, 2010, and 2020 images of Finland, and Figure 4a shows the spatial distribution of Finnish forests in 1980 and 2020. The five periods of Finnish forest cover information were analyzed by image meta-stacking to obtain the results of monitoring changes in the dynamics of the Finnish boreal forest cover from 1980 to 2020, as shown in Figure 4b. It can clearly be seen that the forest area in Finland has changed over the four decades. Overall, the forest coverage in the Finnish study area was 75.79% in 1980. Finland's forest cover was 65.36% in 2020. From 1980 to 2020, Finland had a net loss of 37,615.15 km^2 of forest area and a net decrease in coverage of 10.43%, and the overall trend of forest area and cover area is decreasing.



(**a**)



(**b**)

Figure 4. Forest and non-forested land classification (**a**) in 1980 and 2020; (**b**) the spatial change in forested land and non-forested land from 1980 to 2020.

In view of Finland's geographical location and climatic characteristics, to better analyze and study the dynamics of boreal forests, the Finnish study area was divided into 2° latitudinal bands at intervals and information on forest cover in each latitudinal band was counted, as shown in Figures 5 and 6. To enable a more accurate analysis of the differences in forest types' cover across latitudinal bands, the regions of 58–60° N and 70–72° N, which are smaller in total area, were integrated into the 60–62° N and 68–70° N regions, respectively. This integration permitted the concentration of the northernmost and southernmost regions of Finland into a single latitudinal band.

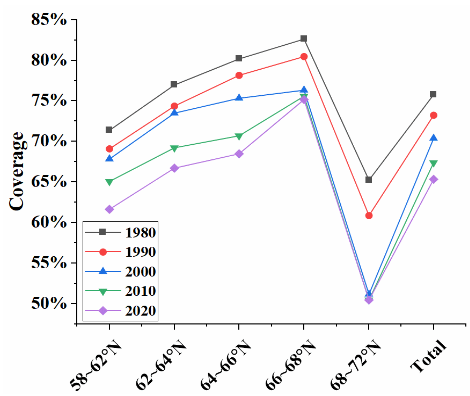


Figure 5. Statistics of forest cover information from 1980 to 2020.

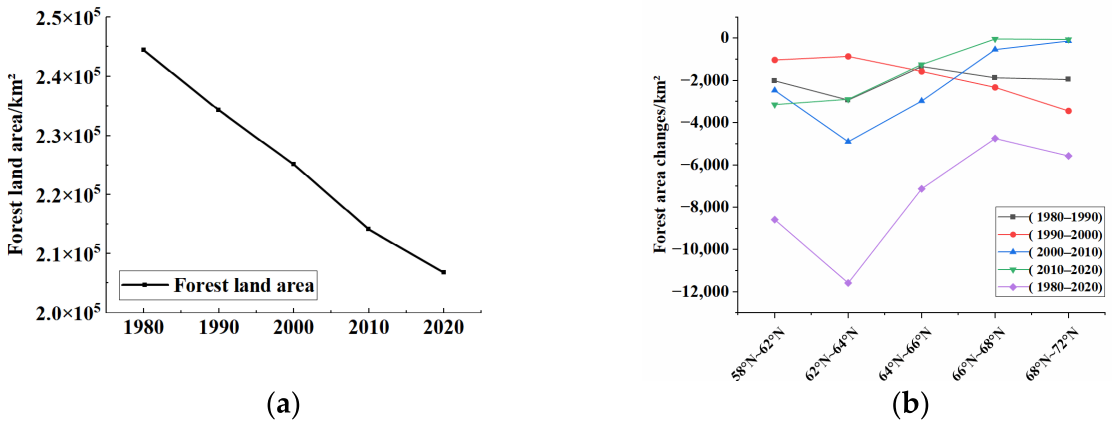


Figure 6. Changes in the area of forested land: (**a**) overall trends; (**b**) spatial and temporal changes in forests in the various latitudinal zones.

From a spatial point of view, the area and coverage of forested land in different latitudinal zones also showed a decreasing trend, with the area converted from forested to non-forested land being larger than the area converted from non-forested to forested land in all latitudinal zones, and the coverage of forested land in all latitudinal zones decreased by an average of 10.95 percent, which was a significant change. Among these zones, the study area has changed the most in the last 40 years in the region from 62° N to 64° N, with a decrease of 11,582.29 km^2 and a 10.24 percent reduction in cover; the area in the region from 68° N to 72° N had the greatest rate of change, with a reduction of 14.78 percent in forest cover, which suggests that forests are more affected by climate change in these latitudinal belts and are more sensitive to the climate.

Analyzed from a temporal perspective, it can be seen that changes in forests in each time interval over the past 40 years are consistent with the overall changes. The highest changes in forested areas between 1980 and 1990 and between 2000 and 2020 were in the latitudinal belt from 58° N to 64° N, with an average decrease in cover of 10.01 percent. In the region of 68° N to 72° N, where the highest change in forest area occurred between 1990 and 2000, there was a 9.73 percent reduction in cover.

In the region of the Arctic Circle, 66° N to 72° N, where there is less human activity, the change in area over the past 40 years has been reflected mainly in the reduction of 10,331.96 km^2 of forested land in the high-elevation mountainous region and the reduction in forest cover by 10.5 percent. In the eastern mountains, where there is perennially bare ground and rocky soils from 68° N to 72° N, there has been a significant increase in new forested areas, which is a clear departure from the trend of decreasing forested areas in the north-western part of the same latitudinal belt over the past 40 years. This is in contrast to the decreasing trend in forest area in the north-western study area of the same latitudinal belt over the last 40 years and suggests that climate change is having different effects on boreal forests in different regions of Finland.

In Finland, anthropogenic areas are concentrated below 64° N, and the changes in area are shown in Table 2. The analyses show that in the study area, the extent of change in area and the percentage reduction in cover were higher in areas above 64° N than in areas below 64° N during the period 1980–2000 and that the extent of change in area and the percentage reduction in cover were higher in areas below 64° N than in areas above 64° N during the period 2000–2020. This indicates that the high latitudes were more affected by climate change than the low latitudes in the period 1980–2000 and that the area and cover of Finland's boreal forests declined to a certain extent across the latitudinal bands in this period; the low latitudes were more affected by climate change in the period 2000–2020, and the trend of decreasing area and cover is still present. However, in the high latitudes, the reduction in forest area and cover has eased, and some degraded areas are regrowing forests, with a tendency to recover or increase. Consequently, in general, high latitudes, especially above the North Frigid Zone, are more suitable for boreal forests in Finland. The environment for growing forests in the lower latitudes is deteriorating and still shows a decreasing trend.

Table 2. Statistics of regional area changes.

Longitude	1980–1990		1990–2000		2000–2010		2010–2020		1980–2020	
	Change in Area/km^2	Reduction in Coverage/%	Change in Area/km^2	Reduction in Coverage/%	Change in Area/km^2	Reduction in Coverage/%	Change in Area/km^2	Reduction in Coverage/%	Change in Area/km^2	Reduction in Coverage/%
Below 64° N	−4930.58	2.46	−1894.88	1.03	−7309.94	3.62	−6030.72	2.90	−20,166.12	10.01
Above 64° N	−5155.10	2.66	−7326.34	5.08	−3633.72	2.23	−1333.87	0.98	−17,449.03	10.95

3.3. Spatial and Temporal Changes in Boreal Forest Types

Within the extent of forested land, coniferous and broadleaf forests were categorized. Over the last four decades, the total area of coniferous forests in the study area decreased by 30,646.54 km^2, and that of broadleaf forests decreased by 2280.08 km^2. Overall, both broadleaf and coniferous forest cover decreased in the study area. First, the R_{bl} of broadleaf forest area to total land area and R_{cl} of coniferous forest area to total land area were calculated; these two ratios can reflect the absolute cover of both forest types to total land. Figure 7 shows a line graph of changes in forest cover and forest types. The broadleaf forest cover in the study area decreased from 3.74% to 3.1%, a decrease of 0.64%; the coniferous forest cover decreased from 72.77% to 64.48%, a decrease of 8.29%. Coniferous forests remained dominant over the forty-year period but decreased much faster than broadleaf forests. The broadleaf forest cover has decreased slightly but was stable overall, which is consistent with the local climate and vegetation characteristics of Finland.

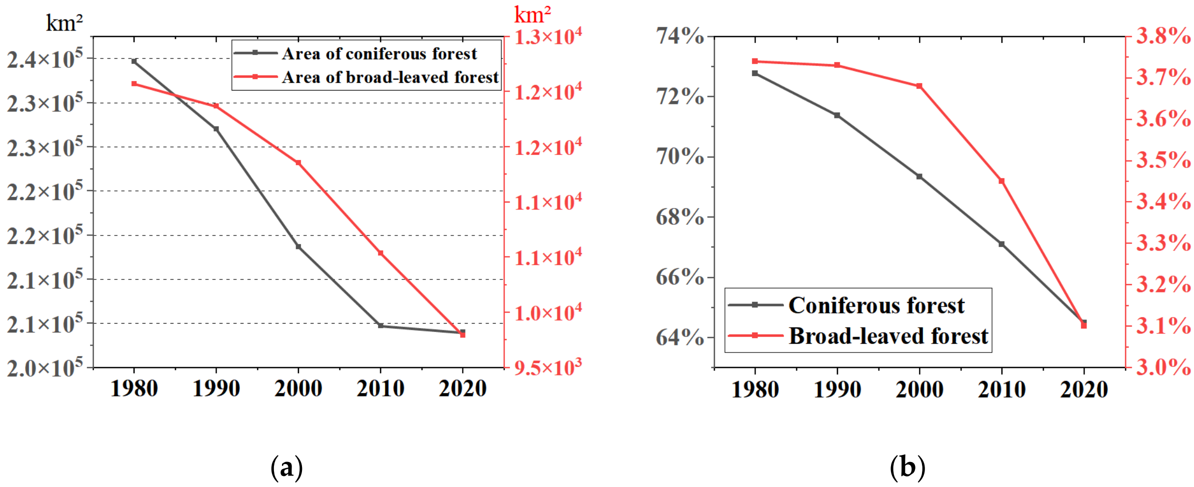


Figure 7. Changes in coniferous and broadleaf forests: (**a**) area change; (**b**) change in coverage.

Since the samples of coniferous and broadleaf forests were re-selected for classification and the number of image element statistics was changed, there was a small error in the statistics of coverage and other information, but the results were proved to be still valid by the accuracy assessment and trend comparison. The coverage of coniferous forests and broadleaf forests in each latitude in the last forty years is shown in Figure 8.

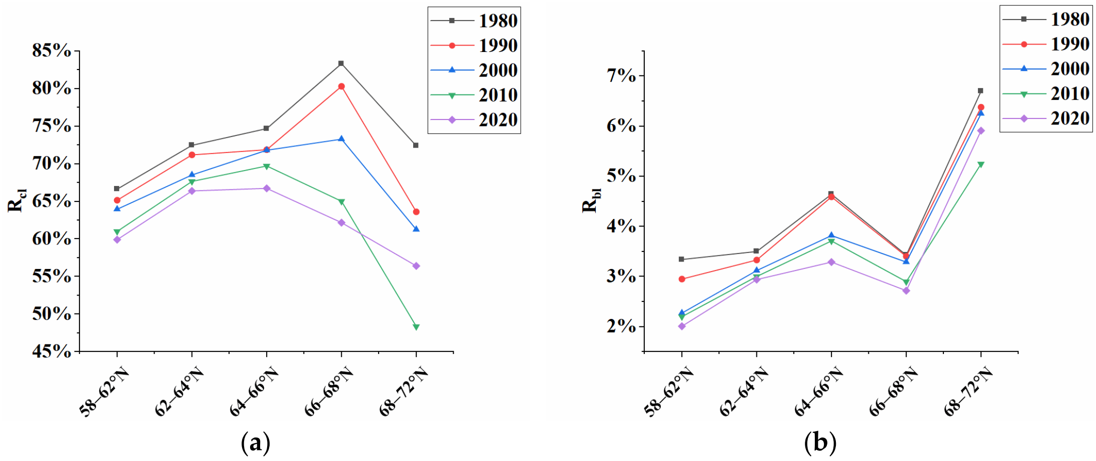


Figure 8. Regional coverage information of coniferous (**a**) and broadleaf (**b**) forests.

Spatially, R_{cl} is basically decreasing in all latitudinal zones. R_{bl} is decreasing in the 58° N–68° N and increasing in the 68° N–72° N region. In 1980, R_{cl} was the highest in the 66° N–68° N region, and R_{bl} was the highest in the 68° N–72° N region. In 2000, R_{cl} was the highest in the 66° N–68° N region, and R_{bl} was the highest in the 68° N–72° N region. In 2020, R_{cl} was the highest at 64° N–66° N and R_{bl} was the highest at 68° N–72° N.

From 1980 to 2020, the largest decreases in R_{cl} were in the 66° N–68° N and 68° N–72° N regions, with decreases of 21.16% and 15.98%, respectively. R_{bl} decreased the most in the 58° N–62° N region by 1.14%. It can be seen that in southern Finland, although human activity has been more frequent, changes in the natural forests of the northern boreal zone have been more prominent and have been mainly reflected in changes in the coniferous forests. The prominent decrease in coniferous forests and the increase in broadleaf forests in northern Finland also show that climate change has a strong impact on the boreal forests in the high latitudes of Finland.

Analyzed from a temporal perspective, the degree of change in cover is higher in the high-latitude areas of the study area than in the low-latitude areas for all time periods in the last four decades. Coniferous forests show the highest degree of change over four decades in the 68° N–72° N region, with an average decrease in cover of 8.01% per decade from 1980 to 2010 and an increase in cover of 8.05% from 2010 to 2020. The 66° N–68° N region with the highest R_{cl} reductions had the most dramatic change between 1990 and 2010, with a 15.29% reduction in R_{cl} during this period. The degree of change in R_{bl} in broadleaf forests was very small in all phases over the four decades and remained in a relatively stable state. It is interesting to note that the increase in R_{bl} was at its highest level of 0.62% in 2010–2020 in the 68° N–72° N region, which is the coldest part of Finland. The degree of change in R_{bl} per decade is also higher in the 64° N–66° N region. From 2010 to 2020, R_{cl} and R_{bl} increased in the 68° N–72° N region slightly.

3.4. Conversion between Forest Types

In order to further investigate the changes in forest types, the interconversion between coniferous forest (C), broadleaf forest (B), and unforested land (N) was counted using image element superposition and raster computation methods. The data were categorized into three phases, 1980–2000, 2000–2020, and 1980–2020, for the convenience of information statistics. Figure 9 shows the transformation of coniferous forests in two periods.

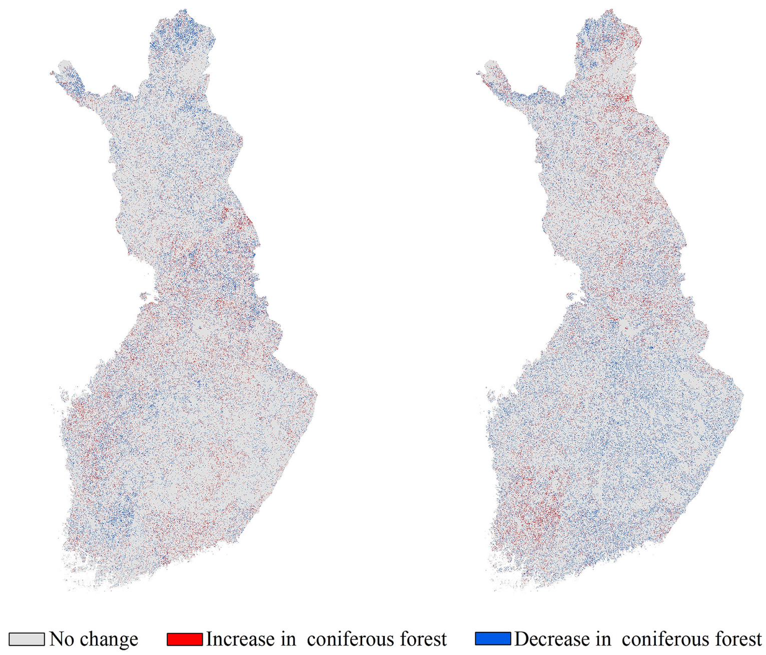


Figure 9. Information on the conversion of coniferous forest in 1980–2000 and 2000–2020.

From the graphs, it can be seen that the changes in the boreal forest in the study area are mainly concentrated in the conversion between coniferous forests and unforested land, and the conversion of broadleaf forests accounts for a relatively small proportion. It can also be seen that, in 1980–2000, the area of all six types of conversion was highest within the 62° N–64° N latitudinal band. The interconversion of coniferous and broadleaf forests and their degradation or reduction in 2000–2020 are also highest within the 62° N–64° N latitudinal band, but the area of conversion of forest-free land to coniferous and broadleaf forests is higher in the 58° N–62° N region. It is interesting to note that Finland's forests are spread all over the country, and tree conversions are relatively evenly distributed in the central region, but in the north and south, there are areas of concentrated conversions in both coniferous and broadleaf forests. It can clearly be seen that in the 68° N–72° N region, which is also the highest-altitude region in Finland, forest reduction mainly occurs in the central and western regions, while forest increase mainly occurs in the central and eastern regions. Based on the geographical characteristics of Finland, it can be inferred that tree conversion in the southern region is influenced by human activities and climate, climate also greatly affects tree conversion in high-altitude mountain forests in the northern region, and the impact is not consistent across different regions. The study area was still divided into upper and lower parts based on the 64° N latitude for the analysis of the degree of the conversion of forest types, and the distribution of statistics by the type of conversion is shown in Figure 10. The conversion of coniferous forests to unforested land was the highest in all three different time intervals and was most dramatic in the region below 64° N. The interconversion of coniferous and broadleaf forests is more frequent at higher latitudes. Overall, the degree of forest degradation is lower in high latitudes than in low latitudes, and the area of conversion between forest types and the area of new forest growth are higher than in low latitudes. Overall, the effects of climate change on coniferous forests are outstanding. Coniferous forests are the dominant forest types in Finland, and the degradation of coniferous forests in the south is likely to become more severe, whereas the boreal zone and above is likely to become more coniferous-friendly. Broadleaf forests have changed little, but the general trend is in line with that of coniferous forests.

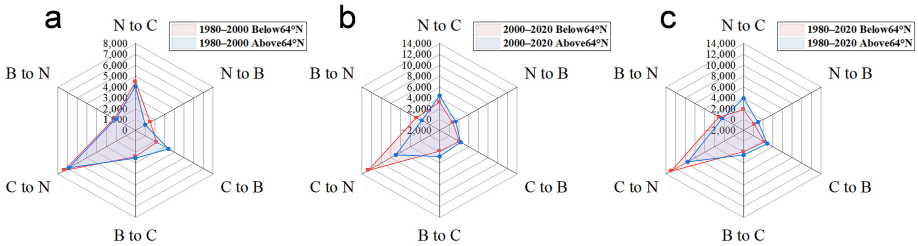


Figure 10. Comparison of area (km^2) conversions in different regions: (**a**) 1980–2000 period; (**b**) 2000–2020 period; (**c**) 1980–2020 period.

4. Discussion

Commonly used vegetation indices are effective in identifying water bodies, buildings, and extensive forests. It is also due to the fact that Finland has such a high forest cover that simple identification with only the commonly used vegetation indices will have very low accuracy. One reason for this is that these vegetation indices do not easily distinguish between low-density vegetation, cultivated land, grassland, and bare land. The second reason is that coniferous forests are extremely dominant in Finland. Broadleaf forests are scattered and mostly mixed with coniferous forests, and this is one of the most easily misidentified samples. Different commonly used vegetation index values for different feature types were extracted. However, for low-density vegetation, broadleaf forests, cropland, grassland, and bare ground, the unit of measurement for the interval difference in their vegetation indices is only 0.1 or 0.01. This leads to a very high number of misclassifications. The homogenization of forests is significant in Finland [11]. It has been found that when texture features are included in classifiers, they do not perform well and instead result in side effects. Moreover, the classification accuracy with texture features included is, on average, 10% lower than when texture features are not included.

The use of tasseled cap transformation and MSAVI is very helpful in vegetation identification in the study area. They make the intervals of vegetation indices for different feature types more distinct, which is reflected in the classification results in terms of improved classification accuracy and more distinct boundaries for different feature types. Not only can the five-phase data effectively differentiate between unforested and forested land, but the identification of broadleaf forests in the southern city, northern broadleaf forest clusters, and dispersed broadleaf forests is also very effective. When analyzing the differences in vegetation indices in different regions within the study area, it was found that the values of vegetation indices for different land cover types were significantly higher in northern Finland than in the south, which indicates that the classification could not be completed uniformly for the entire study area. This difference in values can be precisely bounded by the Arctic Circle. Categorizing the study area into two parts according to this principle gave good classification results. Therefore, too many indices and feature sets did not significantly improve classification accuracy. This also suggests that the rational application of vegetation indices according to the characteristics of different regions should be a key step in the classification of large-scale regional features.

The boreal forests of Siberia tend to increase in varying degrees from the temperate to the boreal zone [38]. In the same geographical location, forest growing conditions are deteriorating in southern Finland, and forests in the north have only begun to increase in the last decade. Studies show that Finland's forests are suffering from climate change and bioerosion risks [39–42]. In comparison to the boreal forest fires in Siberia and Canada, the Nordic forests seem much gentler [43]. Boreal forests in different regions do not reflect a very high degree of uniformity, but they share the common feature of expanding into the Arctic Ocean. The jury is also still out on the merits of this phenomenon [44]. The study demonstrated the significant impact of climate change on forest cover, as well as the impact of other factors on forest cover. In southern Finland, the interconversion of forests and arable land is the most pronounced. Land development also influences changes in forest cover. The forests of southern Finland are affected by climatic and anthropogenic factors, as well as other factors, and the situation is not optimistic.

The main role of forest management in Europe in the coming decades is not to protect the climate but to adapt the forest cover to changing climatic conditions [45]. In this study, the dynamics of forests at different latitudes in Finland were analyzed. The results of the analysis are a good representation of some of the characteristics of boreal forests. In this study, although we only analyzed the dynamics of Finnish forests at different latitudes, the results are clearly a good representation of some of the characteristics of boreal forests and are also relevant on a global scale. The consistency of the characteristics of the Nordic forests, the contrast with the boreal forests of Asia and the Americas, and the influence of climate on the forests will be the focus of the next studies. It is also necessary to improve the algorithm model to improve the large-scale forest recognition accuracy.

5. Conclusions

Remote sensing and GEE provide an ideal and fast method for monitoring the spatial and temporal dynamics of boreal forests. Using multiscene Landsat time-series images, a classified feature set was constructed based on the combination of spectral and tasseled cap transformations in a large-scale area. This feature set was then used with a random forest algorithm to complete the classification of forested land and forest types in a typical boreal forest area of Finland for the period 1980–2020, achieving a classification accuracy of about 90%. The results of this study show that Finland's boreal forest cover has changed significantly over the last 40 years, with a general downward trend, which has been dominated by changes in coniferous forests.

The long-term declining trend in forest area and cover in Finland is indicative of possible environmental pressures such as urbanization, industrialization, agricultural expansion, or deforestation. Latitudinal differences in forest decline may indicate different environmental and climatic pressures or anthropogenic effects. The rebound of forests in the northern part of the study area between 2000 and 2020 may indicate that climate change is positively affecting forest growth conditions, especially at higher elevations. This may be related to higher temperatures, changes in precipitation patterns, or increased carbon dioxide concentrations, which may have facilitated forest growth. The intensification of the declining trend in the southern forests and the rebound in the northern forests may signal that Finnish forest ecosystems are undergoing structural and compositional changes. Such a shift may affect the ecological functions of forests, such as carbon storage, the water cycle, and biodiversity. These observations point to the need for further research to better understand the interactions between climate change, human activities, and forest ecosystems and how to develop effective forest management and conservation strategies. Consideration needs to be given to how to adapt to and mitigate the effects of climate change while conserving biodiversity and maintaining ecological services. Finland's coniferous forests consist mainly of red pine and spruce, and the broadleaf forests consist of birch and other broadleaf species. In this paper, only the overall variation between coniferous and broadleaf forests has been investigated, and in future work, the variation between specific tree species should be studied in depth. More research is needed to determine which climatic factors are the main drivers of forest change in order to deepen the understanding of the mechanisms of response between forest vegetation and climatic factors in the context of global warming.

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References

1. Zhu, Z.S. Global forests face unprecedented crisis. *Environ. Edu.* **2006**, *12*, 65–67.
2. Chao, L. World environment day takes a look at the state of global forests. *Ecol. Econ.* **2011**, *27*, 8–13.
3. van Vuuren, D.P.; Edmonds, J.; Kainuma, M.; Riahi, K.; Thomson, A.; Hibbard, K.; Hurtt, G.C.; Kram, T.; Krey, V.; Lamarque, J.F.; et al. The representative concentration pathways: An overview. *Clim. Chang.* **2011**, *109*, 5–31. [CrossRef]
4. Stocker, T.F.; Qin, G.K.; Plattner, M.; Tignor, S.K.; Allen, J.; Boschung, A.; Nauels, Y.; Xia, V.B.; Midgley, P.M. *Climate Change 2013—The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK, 2013; p. 1535.
5. Ruosteenoja, K.; Jylhä, K.; Kämäräinen, M. Climate projections for Finland under the RCP forcing scenarios. *Geophysica* **2016**, *51*, 17–50. Available online: http://www.geophysica.fi/pdf/geophysica_2016_51_1-2_017_ruosteenoja.pdf (accessed on 15 March 2014).
6. Yang, Y.P. Global climate change and the function of forest carbon sinks. *J. Sichuan For. Sci. Technol.* **2010**, *31*, 14–17. [CrossRef]
7. Li, J.Q.; Li, Z.Y.; Yi, H.R. Interaction relation between forest and global climate change. *J. Northwest For. Univ.* **2010**, *25*, 23–28.
8. Kullman, L. Rapid recent range-margin rise of tree and shrub species in the Swedish scandes. *Ecology* **2002**, *90*, 68–77. [CrossRef]
9. Gower, S.T.; Krankina, O.; Olson, R.J.; Apps, M.; Linder, S.; Wang, C. Net primary production and carbon allocation patterns of boreal forest ecosystems. *Ecol. Appl.* **2001**, *11*, 1395–1411. [CrossRef]
10. Larsen, J.A. *The Boreal Ecosystem*; Academic Press: New York, NY, USA, 1980.
11. Stocks, B.J.; Lynham, T.J. *Fire Weather Climatology in Canada and Russia*; Kluwer Academic Publishers: Boston, MA, USA, 1996.
12. Kellomäki, S.; Peltola, H.; Nuutinen, T.; Korhonen, K.T.; Strandman, H. Sensitivity of managed boreal forests in Finland to climate change, with implications for adaptive management. *Philos. Trans. R. Soc. B Biol. Sci.* **2008**, *363*, 2341–2351. [CrossRef]
13. Kellomäki, S.; Strandman, H.; Heinonen, T.; Asikainen, A.; Venäläinen, A.; Peltola, H. Temporal and spatial change in diameter growth of boreal scots pine, Norway spruce and birch under recent-generation (CMIP5) global climate model 4 projections for the 21st century. *Forests* **2018**, *9*, 118. [CrossRef]
14. Reyer, C.; Lasch-Born, P.; Suckow, F.; Gutsch, M.; Murawski, A.; Pilz, T. Projections of regional changes in forest net primary productivity for different tree species in Europe driven by climate change and carbon dioxide. *Ann. For. Sci.* **2014**, *71*, 211–225. [CrossRef]
15. Reyer, C.; Bathgate, S.; Blennow, K.; Borges, J.G.; Bugmann, H.; Delzon, S.; Hanewinkel, M. Are forest disturbances amplifying or cancelling out climate change-induced productivity changes in European forests? *Environ. Res. Lett.* **2017**, *12*, 034027. [CrossRef]
16. Subramanian, N.; Bergh, J.; Johansson, U.; Nilsson, U.; Sallnäs, O. Adaptation of forest management regimes in southern Sweden to increased risks associated with climate change. *Forests* **2016**, *7*, 8. [CrossRef]
17. Poudel, B.C.; Sathre, R.; Gustavsson, L.; Bergh, J.; Lundström, A.; Hyvönen, R. Effects of climate change on biomass production and substitution in north-central Sweden. *Biomass Bioenergy* **2011**, *35*, 4340–4355. [CrossRef]
18. Poudel, B.C.; Sathre, R.; Bergh, J.; Gustavsson, L.; Lundström, A.; Hyvönen, R. Potential effects of intensive forestry on biomass production and total carbon balance in north-central Sweden. *Environ. Sci. Policy* **2012**, *15*, 106–124. [CrossRef]
19. Allen, C.D.; Macalady, A.K.; Chenchouni, H.; Bachelet, D.; McDowell, N.; Vennetier, M.; Kitzberger, T.; Rigling, A.; Breshears, D.D.; Hogg, E.T.; et al. A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. *For. Ecol. Manag.* **2010**, *259*, 660–684. [CrossRef]
20. Mikkonen, S.; Laine, M.; Mäkelä, H.M.; Gregow, H.; Tuomenvirta, H.; Lahtinen, M.; Laaksonen, A. Trends in the average temperature in Finland, 1847–2013. *Stoch. Environ. Res. Risk Assess.* **2015**, *29*, 1521–1529. [CrossRef]
21. Tong, Q.X.; Meng, Q.Y.; Yang, H. Development and prospect of the remote sensing technology. *City Disaster Reduct.* **2018**, *21*, 2–11.
22. Yuan, J.G. Study of forest vegetation classification with remote sensing. *J. Hebei Norm. Univ. (Nat. Sci.)* **1999**, *84*, 135–138.
23. Wu, Y.; Zeng, Y.; Wu, B.F. Retrieva1 and analysis of vegetation cover in the three-north regions of China based on MODIS data. *Chin. J. Ecol.* **2009**, *28*, 1712–1718.
24. Ma, Y.H. Study on extraction of coniferous forest information in southern China. *Cent. South Univ. For. Technol.* **2010**, *1*, 187–299. [CrossRef]
25. Chen, S.J.; Woodcock, C.E.; Bullock, E.L.; Arevalo, P.; Torchinava, P.; Peng, S.Q.; Olofsson, P. Monitoring temperate forest degradation on Google Earth Engine using Landsat time series analysis. *Remote Sens. Environ.* **2021**, *265*, 112648. [CrossRef]
26. Hou, M.T.; Ari, K.; Venäläinen, L.P.; Wang, P.; Pentti, Y.; Gao, S.F.; Jin, T.X.; Zhu, Y.; Qin, F.; Hu, Y.H. Spatio-temporal divergence in the responses of Finland's boreal forests to climate variables. *Appl. Earth. Obs. Geoinf.* **2020**, *92*, 102186. [CrossRef]
27. Office of National Greening Commission. Survey report on afforestation in Sweden and Finland. *Land Green.* **2004**, *20*, 4–5.
28. Jactel, H.; Petie, J.; Desprez-Loustau, M.L.; Delzon, S.; Piou, D.; Battisti, A.; Koricheva, J. Drought effects on damage by forest insects and pathogens: A meta-analysis. *Global Chang. Biol.* **2011**, *18*, 267–276. [CrossRef]
29. Seidl, R.; Thom, D.; Kautz, M.; Martin-Benito, D.; Peltoniemi, M.; Vacchiano, G.; Wild, J.; Ascoli, D.; Petr, M.; Honkaniemi, J.; et al. Forest disturbances under climate change. *Nat. Clim. Chang.* **2017**, *7*, 395–402. [CrossRef] [PubMed]

30. Liu, L.L. Comparison and analysis of vegetation coverage of GF-1 based on different vegetation index. *Land Dev. Eng. Res.* **2018**, *18*, *7*.
31. Goward, S.N.; Markham, B.; Dye, D.G.; Dulaney, W.; Yang, J.L. Normalized difference vegetation index measurements from the advanced very high resolution radiometer. *Remote Sens. Environ.* **1991**, *35*, 257–277. [CrossRef]
32. Jiang, Z.Y.; Huete, A.R.; Didan, K.; Miura, T. Development of a two-band enhanced vegetation index without a blue band. *Remote Sens. Environ.* **2008**, *112*, 3833–3845. [CrossRef]
33. Yu, L.Y.; Cai, H.J.; Yao, F.Q. Applicability of vegetation indices to estimate fractional vegetation coverage. *Trans. Soc. Agric. Mach.* **2015**, *46*, 231–239.
34. Xu, H. Modification of normalized difference water index (NDWI) to enhance open water features in remotely sensed imagery. *Int. J. Remote Sens.* **2006**, *27*, 3025–3033. [CrossRef]
35. Zha, Y.; Ni, S.X.; Yang, S. An effective approach to automatically extract urban land-use from TM imagery. *Natl. Remote Sens. Bull.* **2003**, *18*, 37–40.
36. Crist, E.P.; Cicone, R.C. A physically-based transformation of thematic mapper data—The TM tasseled cap. *IEEE Trans. Geo. Remote Sens.* **1984**, *3*, 256–263. [CrossRef]
37. Baig, M.H.A.; Zhang, L.; Shuai, T.; Tong, Q.X. Derivation of a tasselled cap transformation based on Landsat 8 at-satellite reflectance. *Remote Sens. Lett.* **2014**, *5*, 423–431. [CrossRef]
38. Tian, L.; Fu, W.X. Bi-Temporal Analysis of Spatial Changes of Boreal Forest Cover and Species in Siberia for the Years 1985 and 2015. *Remote Sens.* **2020**, *12*, 4116. [CrossRef]
39. Ikonen, V.P.; Kilpeläinen, A.; Zubizarreta-Gerendiain, A.; Strandman, H.; Asikainen, A.; Venäläinen, A.; Kaurola, J.; Kangas, J.; Peltola, H. Regional risks of wind damage in boreal forests under changing management and climate projections. *Can. J. For. Res.* **2017**, *47*, 1632–1645. [CrossRef]
40. Lehtonen, I.; Hoppula, P.; Pirinen, P.; Gregow, H. Modelling crown snow loads in Finland: A comparison of two methods. *Silva Fennica* **2014**, *48*, 1120. [CrossRef]
41. Vajda, A.; Venäläinen, A.; Suomi, I.; Junila, P.; Mäkelä, H. Assessment of forest fire danger in a boreal forest environment: Description and evaluation of the operational system applied in Finland. *Meteorol. Appl.* **2014**, *21*, 879–887. [CrossRef]
42. Sierota, Z.; Grodzki, W.; Szczepkowski, A. Abiotic and biotic disturbances affecting forest health in Poland over the past 30 years: Impacts of climate and forest management. *Forests* **2019**, *10*, 75. [CrossRef]
43. Müller, M.M.; Hamberg, L.; Kuuskeri, J.; LaPorta, N.; Pavlov, I.; Korhonen, K. Respiration rate determinations suggest *Heterobasidion parviporum* subpopulations have potential to adapt to global warming. *For. Pathol.* **2015**, *45*, 515–524. [CrossRef]
44. Pearce, F. The forest forecast: Climate change could lead to a net expansion of global forests. But will a more forested world actually be cooler? *Science* **2022**, *20*, 788–791. [CrossRef]
45. Luyssaert, S.; Marie, G.; Valade, A.; Chen, Y.Y.; Njakou Djomo, S.; Ryder, J.; Otto, J.; Naudts, K.; Lansø, A.S.; Ghattas, J.; et al. Trade-offs in using European forests to meet climate objectives. *Nature* **2018**, *562*, 259–262. [CrossRef] [PubMed]