Solar Cycles in Salvage Logging: National Data from the Czech Republic Confirm Significant Correlation

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Abstract: Forest ecosystems in Europe undergo cyclic fluctuations with alternating periods of forest prosperity and disturbances. Forest disturbances are caused by large-scale calamities (climate-induced and unforeseen events) resulting in an increased volume of salvage logging. In recent decades, climate change (warming, long-term droughts, more frequent storms, bark beetle outbreaks) has contributed to an increased frequency of salvage logging. However, until now, it has not been revealed what triggers national-scale forest calamities. All of the above-mentioned natural disturbances are connected to solar activity, which is the driver of climate change. This research relates the total volume of harvested timber and salvage logging to the climate and cosmic factors in the Czech Republic, Central Europe. Data of total and salvage logging are compared with air temperatures, precipitation, extreme climatic events, sunspot areas, and cosmic ray intensities. The results document a significant effect of average annual temperatures on the total and salvage logging for the entire period of observations since 1961. A significant correlation of salvage logging to the sunspot area and cosmic ray intensity was observed. The link between salvage logging and sunspots and cosmic ray intensity is supported by spectral analysis in which a significant 11-year cycle was observed since 1973. The results also show an increasing significant effect of sunspots and cosmic ray intensity on logging in recent years in connection with synergism of extreme climate events and the subsequent bark beetle outbreaks. Space and cosmic effects are factors that substantially influence forest ecosystems. Therefore, this paper provides new knowledge about, and possible predictions of, the forest response under climate change.

Keywords: solar cosmic rays; sunspot area; climate change; disturbance cyclicity; Central Europe

1. Introduction

Forest ecosystems play a crucial role in climate stabilization and in the mitigation of global climate changes on the earth [1–3]. Better comprehension of how and to what extent different cultural practices in forests can affect their ecological stability under ongoing global climate change will lead to mitigation of climate change [4,5]. Climate change increasingly influences the capacity of forests to provide ecosystem services essential for humans, such as biomass production, regulation of the air quality, and the water regime in the catchment [6,7]. Particularly important effects include so-called indirect impacts of climate change that may increase the frequency of abiotic disturbances (e.g., windstorms, drought, floods, forest fires) and the occurrence and population dynamics of insect pests and fungal diseases [8,9]. Forest disturbances caused by climate changes are progressing over time [10–12]. In the period 1950–2000 in Europe, 35 million m^3 of timber per year was damaged and subsequently harvested, accounting for ca. 8% of total logging [13]. In the Czech Republic during the same period, harvesting of damaged timber accounted for 37% [14], and in the period 2007–2018, because of forest disturbances (salvage logging), 8.9 million m^3 of timber were harvested per year on average, i.e., 51%

of total logging [15]. In 2019, salvage logging reached 92% (25.5 million m^3) of total harvested timber and the losses in the forestry sector were around EUR 1.12 billion in the Czech Republic [16].

Active silvicultural practices can mitigate the impact of climate change [17,18]. The so-called mitigation measures include an increase in the amount of carbon accumulated in the forest (including the soil), an increase in the carbon amount bound in products made from wood, and biomass production for energy purposes, which can be used to partly replace fossil fuels [19–22]. By contrast, adaptation measures contribute to changes in management that alleviate the adverse impacts of climate change and utilize them in a positive way [6,13,23]. The key instruments are a change in the tree species composition, including the introduction of new tree species, an increase in biodiversity, a reduction in the rotation period of less tolerant tree species, and the use of uneven-aged forest management [24–26].

In Europe, climate change has the greatest impact on the forest sector in relation to the silviculture of coniferous tree species that have recently suffered damage by periodically recurring drought. This is most obvious in the widespread Norway spruce (*Picea abies* (L.) Karst) [27–30]. Norway spruce, as the dominant tree species (50.5%) in Czech forests, experienced large-scale damage in recent years due to climate change [15]. The poor condition of spruce stands is also accompanied by mass outbreaks of bark beetles that occur in parallel with dry years and increase the forests' disintegration [31,32]. Spruce stands in the Czech Republic have been stressed by fluctuations caused by changes in climatic conditions over the last two to three decades [33]. These climatic fluctuations harm coniferous tree species, therefore, more resistant deciduous tree species are promoted more by forest management [34]. The negative stress factors causing the decline of spruce forests are reflected in large-scale salvage logging [35], which leads to the adjustment of silviculture procedures in forest management to favor the ecological stability of forest stands [36,37].

Solar cycles affect the earth's climatic conditions at approximately eleven-year intervals. In addition, the influence of CO_2 has also increased recently, exacerbated by global climate change [38,39]. An important role of the sun's influence on climate change is exerted by the solar radiation in the invisible part of the spectrum that distinctly and strongly fluctuates within periodic changes of the sun [40,41]. Direct physical effects of high-energy solar radiation, particularly during solar flares, have a global impact on the planet's climate [42–44]. Climate change is associated with the activity of sunspots, darker regions on the surface of the sun that have a lower temperature than the surrounding regions (less than 5000 K) [45,46]. The activity of sunspot formation influences the electromagnetic activity of the sun [47,48], which also impacts the natural variability of the planet's climate [49]. Sunspots affect the temperature of the earth's surface both in the northern and southern hemisphere [50]. In the southern hemisphere, sunspots influence the water cycle through the El Niño impact [51,52]. In the northern hemisphere, it has been proven that solar cycles can initiate pronounced long-term temperature fluctuations on the surface of the planet [40,53]. Solar cycles were found to manifest their activity in the air temperature at altitudes of 1.5 to 8 km. [54]. Drought periods are also characteristic of climate change when precipitation is lower. This phenomenon is influenced by solar activity, e.g., in the forests of the Rocky Mts. in Montana and in Canada [55]. Furthermore, the activity of sunspots can be linked to the occurrence of forest fires, volcanic eruptions, and earthquakes [56–58].

Air circulation at around 1000 m from the lower part of the troposphere is linked with the sunspot cycle above the northern hemisphere of the Atlantic Ocean, and this effect influences Europe [59]. The cyclic formation of sunspots is also obvious in the cycle of cosmic rays [60,61]. Sunspots reflect cosmic rays due to their magnetic activity, and the larger the sunspot area, the smaller the impact of cosmic rays on the planet's atmosphere [47]. Through ionization, cosmic rays influence the formation of aerosols that change properties of the cloud cover in the atmosphere, affecting their formation processes [62]. Subsequently, the solar radiation impinging on the planet's surface is altered. Atmospheric aerosols belong to the most variable factors influencing climate models [63,64]. Cosmic rays are also associated with the periodicity of winds, storms events, and rainy seasons [65,66], and thus form an integral part of the formation of the water cycle [67].

In this paper, unique climate factors, particularly sunspots, cosmic rays, air temperatures, and precipitation, are evaluated in relation to the development of salvage logging and total harvested timber in the Czech Republic. The total and salvage logging volumes are interrelated in the Czech Republic because the volume of planned logging and that of salvage logging make up the total volume of harvested timber. In this relationship, the volume of planned logging might be reduced in the case of a greater volume of salvage logging caused by negative climate fluctuations such as drought, air pollution, or damage by windstorms to forest stands. Thus, if salvage logging is higher, it is caused particularly by extreme climate fluctuations. Therefore, it is very important to know whether and how climate changes influence the growth and development of forest stands and whether different scenarios of forest management can increase their ecological stability and reduce the amount of salvage logging [68,69].

No study on solar cycles and their possible impact on forestry has been published yet. There is a large number of factors that affect salvage and total logging, and this work is mainly focused on the simplifying of the issue to clarify the natural cyclical phenomena that affect logging in the Czech Republic. Precipitation, air temperatures, sunspot area, and cosmic ray intensity were selected as the main climatic effects in this study. The main purpose of our study is to determine whether there is a relationship between salvage and total logging to the sunspot area, cosmic ray intensity, and climatic factors (precipitation, air temperatures, extreme climatic events). This work evaluates the aforementioned natural and climatic factors in relation to salvage and total logging in the Czech Republic. Particular time periods during the historical development of salvage and total logging are also evaluated. Our study deals with the important issues of forestry in Central Europe, and its unusual approach might contribute to the understanding of climate change and its impact on forestry.

2. Materials and Methods

2.1. Study Area

The area of interest covers the whole territory of the Czech Republic, which has a forest cover of 34.1% (2.67 million ha). The area of forests has been steadily increasing since the 1950s. Coniferous forests account for 71.6% and deciduous for 27.2% of the tree species composition. The main tree species is Norway spruce with a share of 50.0% (Figure 1a), while it comprised only 11.2% in the original tree species composition. Commercial forests make up 74.3% of forests. The majority of forest is owned by the state (56.0%), followed by private owners (19.2%), and municipalities and cities (17.1%). The predominant form of forest management in the Czech Republic is the clear-felling method, followed by the shelterwood and the selection felling methods. Artificial forest regeneration dominates (81.7%) over natural regeneration (18.3%). In terms of the age structure of forests, there is a higher proportion of over-mature stands to normal-aged stands (Figure 1b). The mean age of forest stands increased by 9.0 years (from 52 to 61 years) and the mean rotation age by 11.7 years (from 101.2 to 112.9 years) in 1960–2018 (Figure 2a). The total stand volume of timber in the Czech Republic reached 703 million m^3 in 2018. The mean stand volume per 1 ha of forest land is 269 m^3. The total stand volume is constantly increasing. Compared to 1960, the total stand volume has more than doubled. Similarly, there is an increase in the mean annual timber increment, which currently reaches 4.9 m^3 ha^{-1} year^{-1} (Figure 2b) [15].

The climate in the Czech Republic is mild, characterized by continental influences. According to Koppen's climate classification, most of the territory of the Czech Republic belongs to the Dfb climatic region—a humid continental climate, characterized by hot summers and cold winters. Annual air temperature ranges from +9.5 to −0.4 °C (mean 7.9 °C) and the annual sum of precipitation from 410 to 1705 mm (mean 650 mm) in relation to the altitude (115–1603 m a.s.l.). The average altitude of the Czech Republic is 430 m a.s.l. The lowest mean temperature in January is −2.0 °C, the highest in July 17.8 °C. Similarly, the precipitation minimum is in January (40 mm) and maximum in July (85 mm). The average number of days with snow cover in most areas (depending on altitude) is

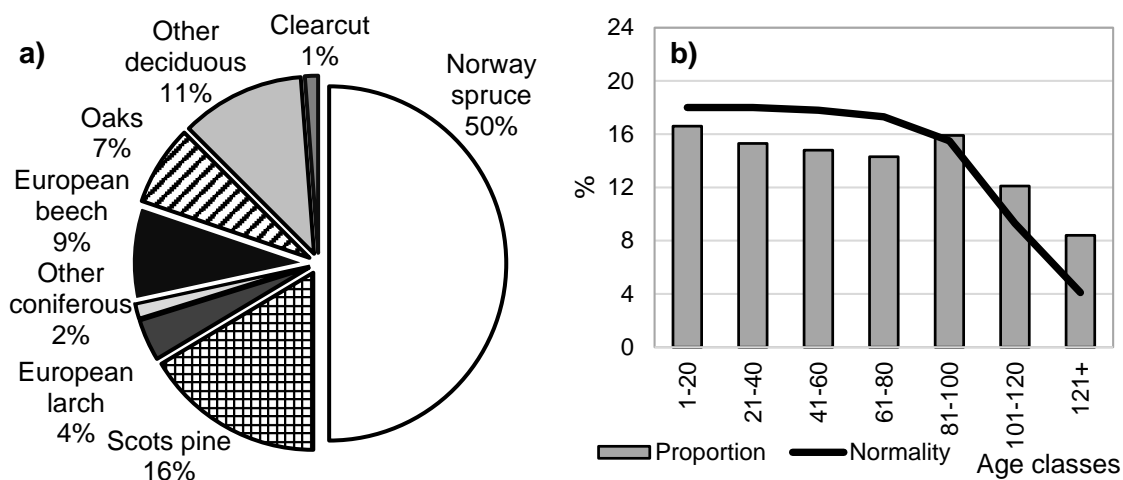40–100 days. The average wind speed is in the range of 10–18 km h^{-1}. The average time of sunshine is 1200–1720 h year^{-1} [70].

Figure 1. Current status (2018) of (**a**) tree species composition and (**b**) proportion of age classes to normality in the Czech Republic.
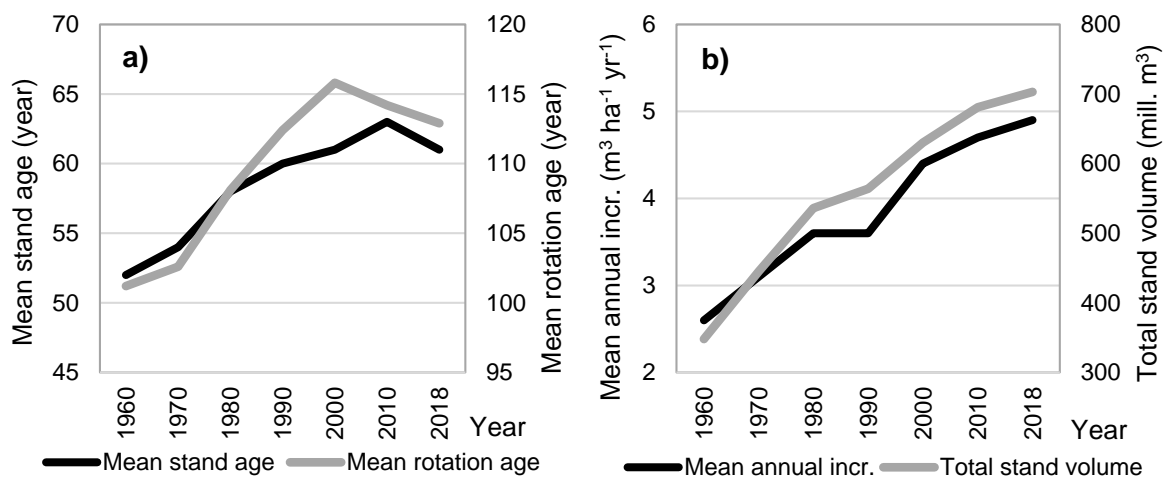

Figure 2. Development of (**a**) mean stand age and mean rotation age of forests and (**b**) mean annual timber increment and total stand volume in the Czech Republic.

2.2. Data Source and Collection

The data on the total volume of harvested timber and on groups of salvage logging (elemental disturbances, air pollution, insects), differentiated by particular tree species and their groups were taken (unchanged) from the Forest Management Institute (ÚHÚL) in Brandýs nad Labem, Czech Republic and the Czech Statistical Office (ČSÚ) in Prague, Czech Republic. These logging data cover the whole territory of the Czech Republic for the period 1961–2018. The total logging (total harvested timber) is the volume of large timber (logging residues are not included) and include self-production. Large timber is the timber volume of the aboveground part of a tree with a minimum diameter of 7 cm over bark. The timber from logging or silvicultural operations is counted including the salvage logging. Salvage logging includes the data for all kinds of salvage logging and calamities caused by abiotic and biotic factors. It includes also dead standing trees, isolated breaks, uprootings, all of the volume of trap trees felled for trapping bark beetles, and individual trees in which harmful insects (bark beetles, etc.) spend winter. Salvage logging (processed) comprises the volume of timber processed within salvage logging [71].

The annual air temperature, annual sum of precipitation, and storm event data were taken directly without changes from the Czech Hydrometeorological Institute (ČHMÚ) in Prague and cover the whole state area. The values of territorial temperatures and precipitation were recalculated for the whole period from 1961 to 2018 to obtain a time series calculated by a uniform interpolation method [70].

The data on the sunspot area were acquired from the National Oceanic Atmospheric Administration (NOAA, Silver Spring, MD, USA) [72]. The data on the sunspot area were expressed as arithmetic means from the average monthly data from NOAA. The data on cosmic rays were obtained from the Lomnický štít measuring station in Slovakia affiliated to the Institute of Experimental Physics SAS [73]. Data on cosmic rays were corrected for pressure when the year 1969 was added as the arithmetic mean between the previous and the next year.

2.3. Data Processing

Using the R software, an eight-year spline was fitted to all data to remove short-time influences. The computations of Pearson's correlations and 3D charts were performed in the Statistica 13 software (Statsoft, Tulsa, OK, USA) to analyze salvage logging, air temperature, precipitation, cosmic ray intensity, and sunspot area. The computation of spectral analysis was done as a Fourier transform in the R software [74], when the redfit function or Schulz's REDFIT (version 3.8c) was used; this function estimates the red-noise spectrum of a time series [75] with an optimum test spectrum against the red-noise background using a Monte Carlo simulation. This computation was conducted according to the instructions for R according to Bunn and Miko [76].

Overall, annual data on the total and salvage logging throughout the Czech Republic were compared with average annual temperatures, total annual precipitation, average annual sunspot areas, and average annual cosmic ray intensity. In addition, the volume of logging was compared with the ten driest years (lowest annual precipitation), the warmest years (years with the highest average annual temperature), and the years with the strongest occurrence of storm events in the period 1961–2018. Storm events were sorted and selected according to the WEI index Storm (Weather Extremity Index) [77]. Logging volumes were also compared with large outbreaks of pests (bark beetle, larch tortrix) and the periods of air pollution (high SO_2 concentrations). Salvage logging was further divided into elemental disturbance (drought, storm, fire, etc.) logging, insect logging, and air pollution logging.

3. Results

3.1. Development of Timber Harvest in the Czech Republic and Studied Factors

In the period 1961–1969, the mean total amount of logging was around 8.9 million m^3 of timber, with salvage logging accounting for 24% on average (Figure 3). In 1970–1989, when clear-felling systems were mostly used, and exterior and interior spatial forest planning was rather neglected, the total average annual logging was around 12.7 million m^3 and salvage logging 5.0 million m^3 (i.e., 39% of total logging). In 1976, after the Cappela windstorm, 5.6 million m^3 had to be logged. In the second half of this period, the air pollution load culminated, being characterized by high concentrations of SO_2 (3× larger concentrations than the limit value). In 1990–2005, when transformation and renewal of close-to-nature forest management were gradually introduced, the total average annual logging was around 13.3 million m^3 and salvage logging amounted to 5.7 million m^3 (i.e., 43% of salvage logging). In 1990, windstorms Vivian and Wiebke caused salvage logging in the amount of 8.7 million m^3. The years 2006–2014 experienced frequent severe windstorms, when total average annual logging was around 16.5 million m^3 and salvage logging 9.0 million m^3 (i.e., 55% of salvage logging). After the historically largest windstorm Kyrill in 2007 (in which the wind speed exceeded 40 m s^{-1}), salvage logging reached 80% and, in the following year of 2008, total logging reached the maximum volume to date—19.19 million m^3. Pronounced climate changes with serious drought periods in the growing season were typical of the years 2015–2018, when the total average annual logging was around

19.7 million m^3 and salvage logging amounted to 13.1 million m^3 (i.e., 66% of salvage logging). The last two years were the most critical, with a total annual harvest of around 27.0 million m^3 and salvage logging of 23.0 million m^3 (i.e., 90% of salvage logging) in 2018, and 95% of salvage logging in 2019 (30.9 million m^3).
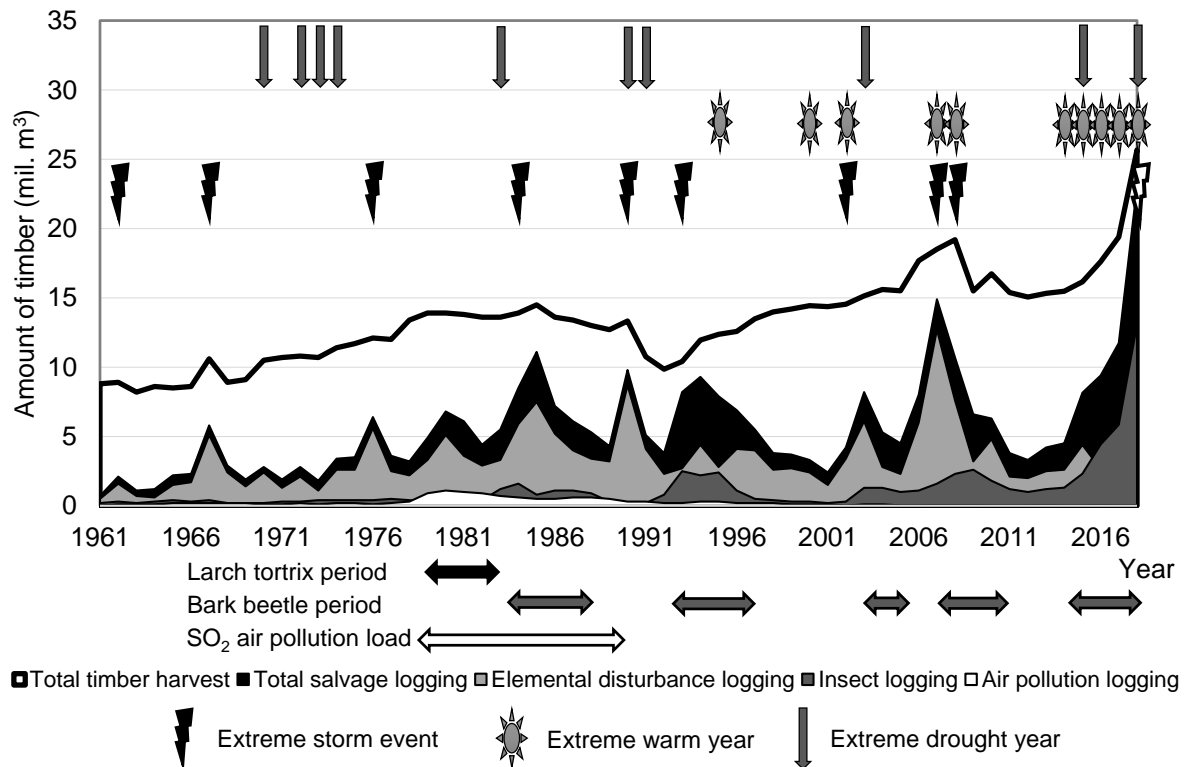
Figure 3. Dynamics of total timber harvest and salvage logging (elemental disturbance logging, insect logging, air pollution logging) in relation to extreme events in the Czech Republic.

During the observed period (1961–2018), extreme storm events most often reappeared in cycles of 8–11 years (Figure 3). These wind calamities were frequently followed by bark beetle outbreaks, especially of the spruce bark beetle (*Ips typographus*), because the amounts of windthrown timber were too large to allow timely processing. The first significant bark beetle outbreak occurred in 1983–1988 (5.8 million m^3 of timber), and others followed in 1993–1996 (8.2 million m^3), 2003–2004 (2.6 million m^3), 2007–2010 (8.3 million m^3), and 2015–2018 (23.3 million m^3). The largest amount of salvage logging in 2018 was caused by a single year in which there was a synergism of the effects of the storm Friederike, extreme drought (22% less precipitation), above-average warm weather (historically warmest year: 9.6 °C, average 7.8 °C), and the associated outbreak of bark beetle. There was no cyclicity in extremely dry years, unlike in the case of extreme storm events. Extremely warm years occurred only in the second half of the observed period, i.e., during the last 5 years. Overall, the largest share of salvage logging was found in the occurrence of extreme storm events, followed by an extremely warm year, and the smallest effect was found in an extremely dry year.

Correlations between the studied factors are clearly summarized in a simple table of correlation coefficients (Table 1). The table shows that the correlations of all studied factors with salvage logging and total timber harvested in the Czech Republic significantly increased in a shorter time period. Thus, in the latter period (2000–2018), the correlation of salvage logging with sunspot area and cosmic ray intensity was strong. Another important result is a significant correlation between average annual temperatures and the volume of salvage logging in all periods. Table 1 also shows that the correlations between temperature and precipitation in relation to sunspot area and cosmic ray intensity are not statistically significant.

Table 1. Correlation coefficients of salvage logging and total volume of harvested timber with sunspot area, cosmic ray intensity, average air temperatures, and average precipitation total; data are divided into time periods; significant results at $p < 0.05$ are in bold.

	Time Period 1961–2018	Time Period 1973–2018	Time Period 2000–2018
	Sunspot area		
Salvage logging	−0.0932	**−0.3263**	**−0.7800**
Total timber harvest	−0.2045	−0.2224	**−0.6550**
	Cosmic ray		
Salvage logging	−0.1221	**0.3620**	**0.7575**
Total timber harvest	0.0608	0.1519	**0.6307**
	Temperature		
Salvage logging	**0.5269**	0.0994	0.4374
Total timber harvest	**0.3122**	**0.3650**	**0.5080**
Sunspot area	0.0610	0.0005	0.1048
Cosmic ray	−0.1895	−0.0263	0.2399
	Precipitation		
Salvage logging	0.1099	0.1541	−0.3885
Total timber harvest	0.0135	−0.0434	−0.4438
Sunspot area	−0.1450	−0.1549	0.1315
Cosmic ray	−0.0240	0.0395	−0.2816

3.2. Effect of Annual Precipitation and Annual Air Temperatures on Development of Timber Harvest

Measurements of the annual sum of precipitation and average annual air temperatures have previously been compared with the development of forest stands in the Czech Republic. Therefore, these two climate factors should be mentioned in this study. The combination of these two factors creates a clearer picture of the relationship of the salvage and total logging to the climate in the Czech Republic, which is illustrated in Figure 4a,b. When annual precipitation decreases, a water balance deficit occurs which, in combination with higher average temperatures, leads to an increase in salvage logging and, at the same time, a reduction in planned logging, which is reflected in the total volume of timber harvested. These relations are evident in Figure 4a, e.g., in the period from 2011 to 2018, but the situation might differ in other periods. For example, in 1982–1989 salvage logging increased with an increase in total precipitation according to Figure 4a, while this period was characterized by high air pollution, particularly of SO_2. In Figure 4b, where an eight-year spline is fitted to the data, precipitation does not obviously correlate with the data on salvage or total logging. On the contrary, average temperatures are rising in line with total and salvage logging when the maturation of forest stands should be taken into account, which is caused by forest aging in the Czech Republic.

A scatter plot (Figure 5) illustrates the relationship between the data on the volume of harvested timber and the climate data (average annual temperatures and annual sum of precipitation). At a glance it can be noted that average annual temperatures in Figure 5a,b show a positive relationship with harvested timber, whereas they have a negative relationship with the annual precipitation total Figure 5c,d. It should also be accentuated that the correlation with R^2 has increased in the recent years, evidenced by an increase in R^2 in the time period 2000–2018 (Figure 5b,d). It is also true that temperatures show a higher R^2 than precipitation, and so they are in closer correlation with salvage and total logging. A comparison of salvage and total logging indicates that the R^2 of salvage logging with temperatures and precipitation is higher in most cases (Figure 5b–d), suggesting that salvage logging better reflects climate fluctuations.
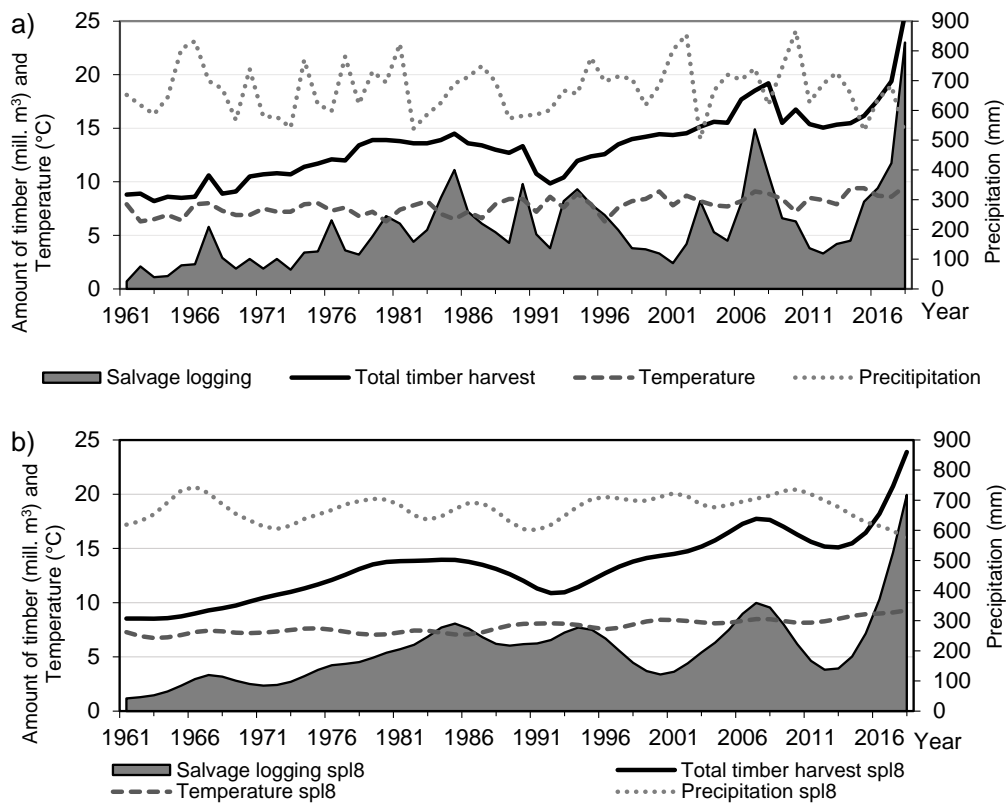
Figure 4. Average annual air temperatures and annual precipitation total in relation to the volume of timber harvested in the Czech Republic: (**a**) The trend of total timber harvest and salvage logging; (**b**) an eight-year spline (spl8) fitted to harvested timber and climate data.
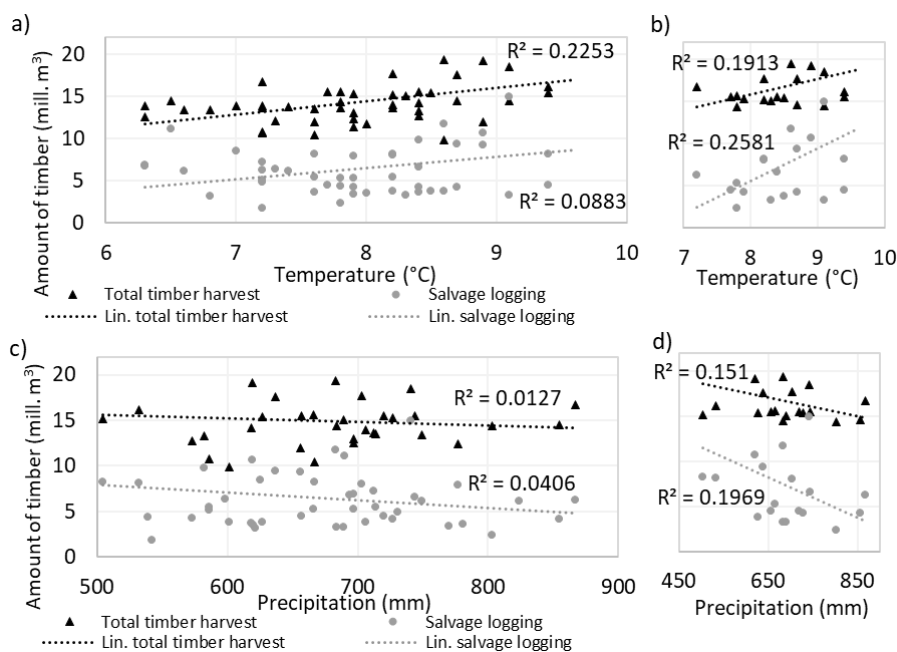

Figure 5. Scatter plot; average annual air temperatures in relation to salvage logging and total timber harvested in the Czech Republic in the periods (**a**) 1973–2018 and (**b**) 2000–2018; the annual sum of precipitation in relation to the volume of salvage logging and timber harvested in the Czech Republic in the periods (**c**) 1973–2018 and (**d**) 2000–2018; explanatory notes: Lin.—linear regression model; mill. m³—million cubic meters of harvested timber.

3.3. Sunspots as an Inversion Factor to Total Harvested Timber and Salvage Logging

The sunspot area shows interesting results in relation to salvage and total logging in the Czech Republic. During the solar minimum, salvage logging increased as shown in Figure 6a,b. This implies that during the solar minimum, when minimum sunspot areas occur on the Sun, there is an increase in salvage logging. Higher volumes of salvage logging occur in approx. ten-year intervals from the particular calamities that coincide with the solar minima, which is illustrated in Figure 6b.
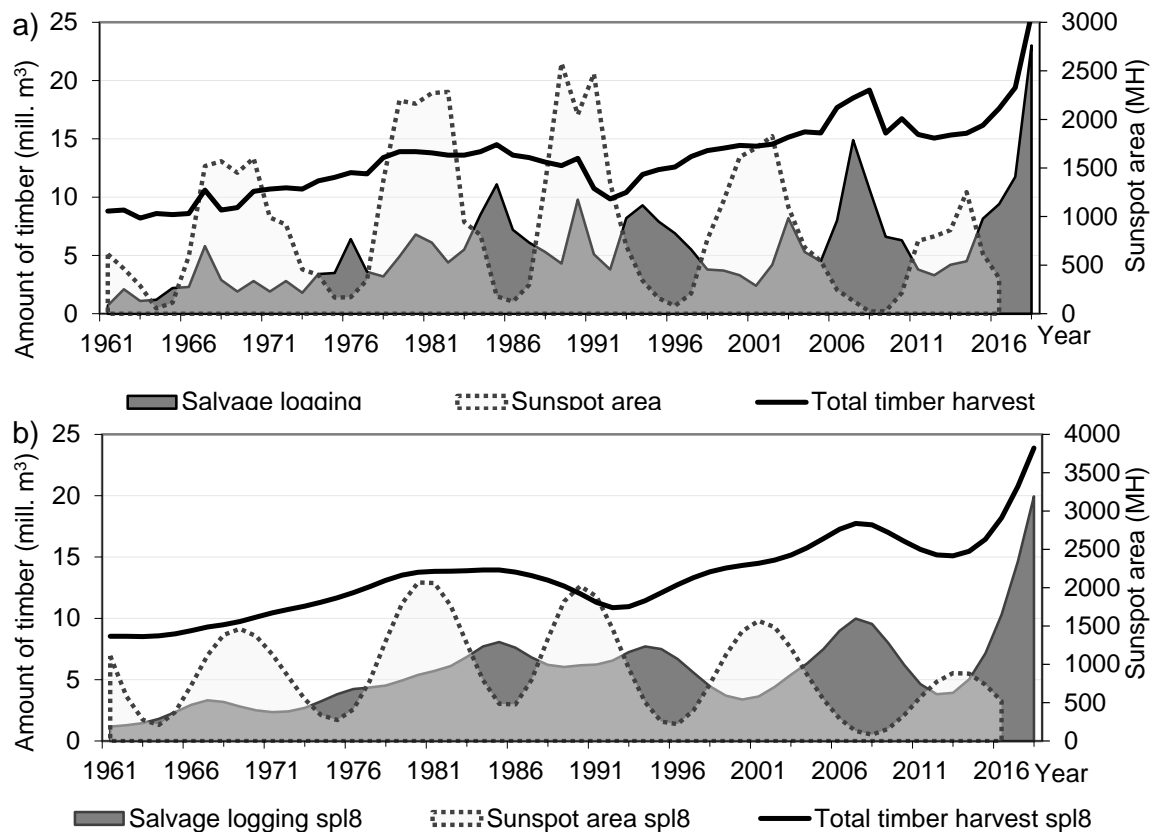

Figure 6. The average annual area of sunspots in relation to the volume of timber harvested in the Czech Republic: (**a**) The trend of total harvested timber and salvage logging according to their causes in relation to the sunspot area; (**b**) an eight-year spline (spl8) fitted to harvested timber and sunspot area; MH—millionths of a hemisphere; mill. m^3—million cubic meters of harvested timber.

The scatter plot in Figure 7a,b illustrates a negative correlation between the sunspot area and the volume of salvage logging and total harvested timber. It also documents that R^2 was higher in the time period 2000–2018 (Figure 7b) than in the period 1973–2018 (Figure 7a), suggesting a closer correlation between these factors. Another important factor is that the data on the sunspot area in relation to salvage logging document a much higher coefficient R^2 than in precipitation in Figure 5c,d or in temperatures in Figure 5a,b. The overall relationship between harvested timber and sunspot area is negative, which means if the sunspot area is small, the totals of harvested timber and salvage logging are higher.
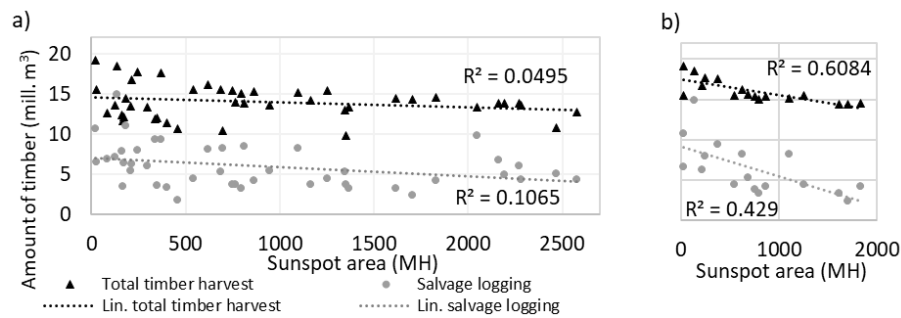
Figure 7. Scatter plot: Average annual sunspot area in relation to salvage logging and the total volume of timber harvested in the Czech Republic in the periods (**a**) 1973–2018 and (**b**) 2000–2018; explanatory notes: Lin.—linear regression model; MH—millionths of a hemisphere; mill. m^3—million cubic meters of harvested timber.

3.4. Cosmic Ray Intensity and Its Pronounced Effect on Timber Harvested

The relationship of cosmic rays to salvage logging and the total timber harvested in the Czech Republic can be described by parallel curves, mainly in the case of salvage logging, that were almost identical since 1982, as presented in Figure 8a,b. Since 1982, the values of cosmic ray intensity have increased and decreased in line with salvage logging, as documented in Figure 8a. Salvage logging and cosmic ray intensities developed almost simultaneously in recent years, which is confirmed by the high significant value ($r = 0.3620$) for the period 1973–2018. The data confirm that with an increasing cosmic ray intensity, there is also an increase in salvage logging. The total logging corresponds to the cosmic ray intensity to a smaller extent due to the efforts of forest managers to balance the volume of loggings during disturbances, which was obvious in the period 2006–2018. The data on cosmic ray intensity and salvage logging fitted with a spline show higher similarity without the short-term fluctuations that can be seen in Figure 8b.
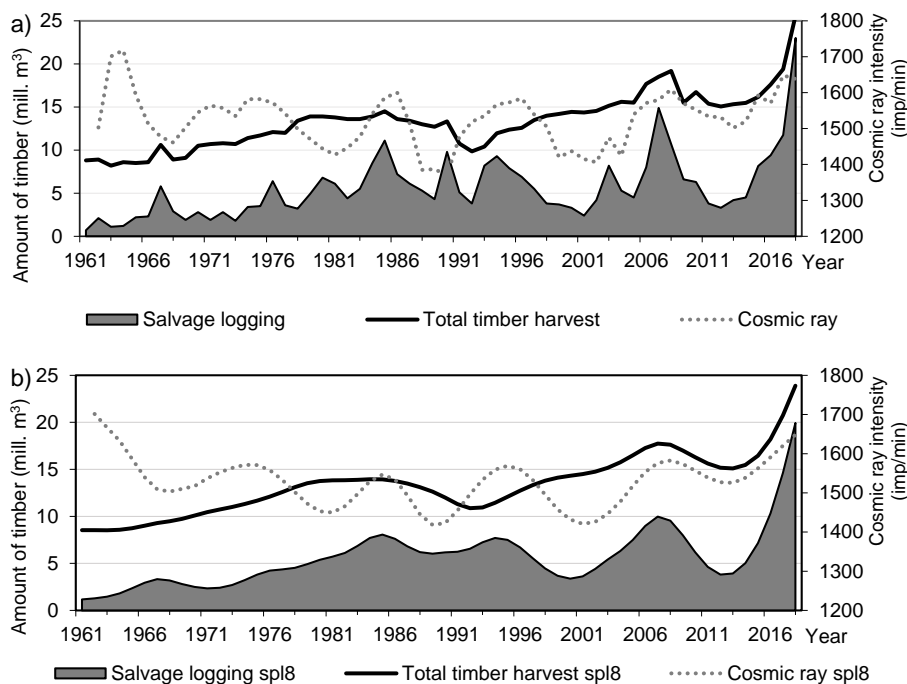

Figure 8. Average annual data on cosmic ray intensity in relation to the volume of timber harvested in the Czech Republic; (**a**) The trend of total and salvage logging according to their causes in relation to cosmic ray intensity; (**b**) an eight-year spline (spl8) fitted to harvested timber and cosmic ray intensity; imp/min—impulses/minute; mill. m^3—million cubic meters of harvested timber.

The scatter plot in Figure 9a,b documents the highest values of R^2 of all four factors studied in this research, especially in relation to salvage logging in the time period 1973–2018, which is illustrated in Figure 9a. The graphs in Figure 9a,b also show that with an increase in cosmic ray intensity impinging on the atmosphere, the volume of salvage logging increased while the growth of values was almost linear in all cases. These scatter plots show that there is a strong linear relationship between logging and cosmic ray intensity, which is useful information for the future.
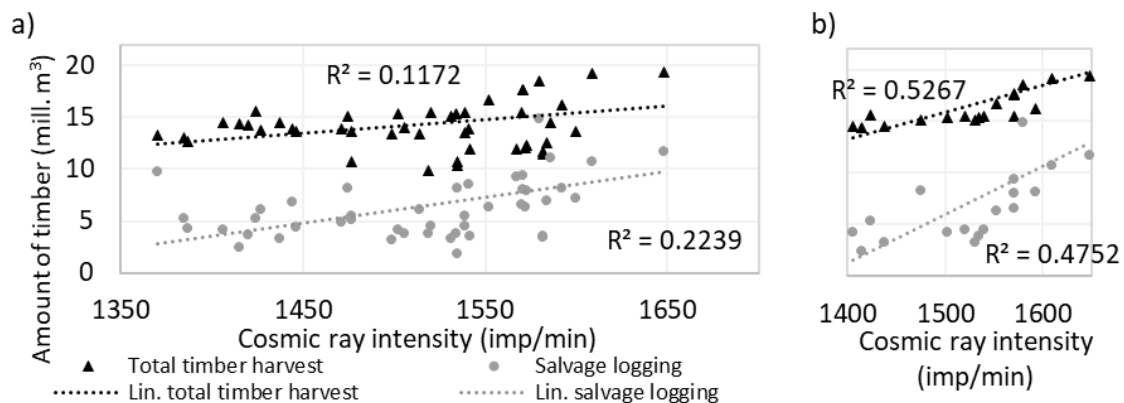

Figure 9. Scatter plot; average annual data on the cosmic ray intensity in relation to salvage logging and the total timber harvested in the Czech Republic in the periods (**a**) 1973–2018 and (**b**) 2000–2018; explanatory notes: Lin.—linear regression model; imp/min—impulses/minute; mill. m^3—million cubic meters of harvested timber.

3.5. Studied Factors in 3D Charts and Spectral Analysis

Three-dimensional line charts of salvage logging (Figure 10) document the relationships between relevant variants of all of the data used. Based on the correlation table (Table 1), four variants were created that work with the most significant options. The response of sunspot area (Figure 10a,b) to salvage logging is lower than that to cosmic ray intensity (Figure 10c,d). Nevertheless, the data on salvage logging and cosmic ray intensity are opposite to each other, but the correlation (Table 1) in the period 1973–2018 allows us to state that the response of the volume of harvested timber is negative and larger for cosmic ray intensity than for the positive response of sunspots. This is also confirmed by a visual difference between the sunspot area and the cosmic ray intensity, when the cosmic ray intensity creates a greater inclination of the 3D line chart than the sunspots. This is evident from the scale of 3D line charts when the sunspots are in the range from four to seven and the cosmic ray intensity is from 1 to 12. Furthermore, a greater inclination of the 3D chart is caused by temperatures than by precipitation when temperatures positively correlate with salvage logging while the correlation with precipitation is negative. In general, the most distinctive variant is the cosmic ray intensity in relation to average temperatures, which is well illustrated in Figure 10b. Cosmic rays are the most distinctive in all represented results (Figures 8–10). Average annual temperatures also correlate well across all time periods, which can be seen in Figure 4a and in Table 1.
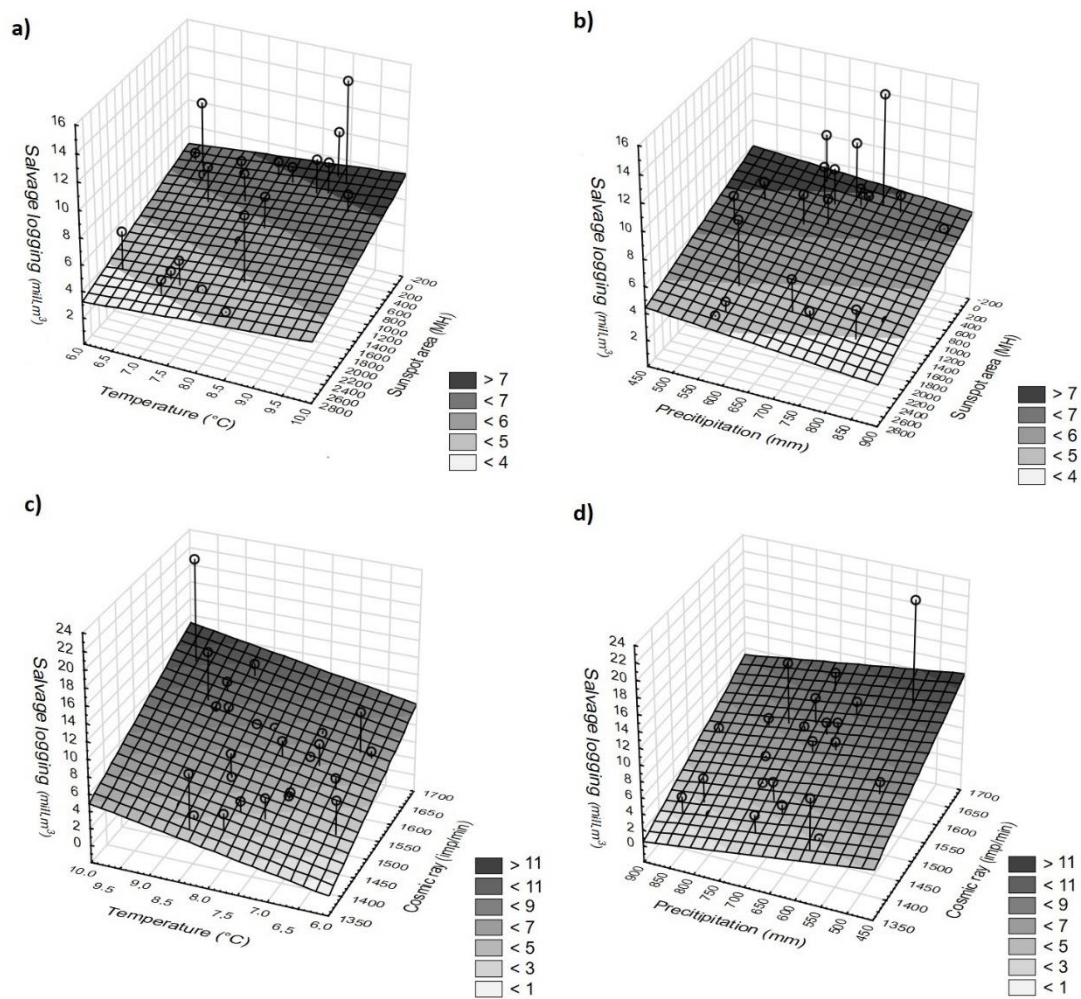
Figure 10. Three-dimensional line chart of salvage logging in relation to the particular factors in the period 1973–2018; (**a**) salvage logging in relation to average annual air temperatures and average annual sunspot area; (**b**) salvage logging in relation to the sum of precipitation and sunspot area; (**c**) salvage logging in relation to average annual air temperatures and average cosmic ray intensity; (**d**) salvage logging in relation to the sum of precipitation and average cosmic ray intensity; explanatory notes: mill. m^3—million cubic meters of harvested timber; imp/min—impulses/minute; MH—millionths of a hemisphere.

Spectral analyses in Figure 11 illustrate the periodic behavior of the data. This type of analysis accurately demonstrates the occurrence of periodic events in the used data series. Average precipitation in the Czech Republic Figure 11a was significant (at a level of 90%) in 4-year periodic cycles. Average annual temperatures Figure 11b show significant (at 95%) results in a cycle once per 8 years. Cosmic rays and sunspot areas Figure 11c,d show significant (at 99%) results in an 11-year cycle. Salvage logging in the period 1961–2018 Figure 11e had significant results in the recurrence of 4-year cycles (at 99%) and 11-year cycles (at 90%) but if the data series is reduced to the period from 1973 to 2018, only 11-year cycles are significant. Hence salvage logging is significantly consistent with the 11-year periodic recurrence of sunspot area and cosmic ray intensity.
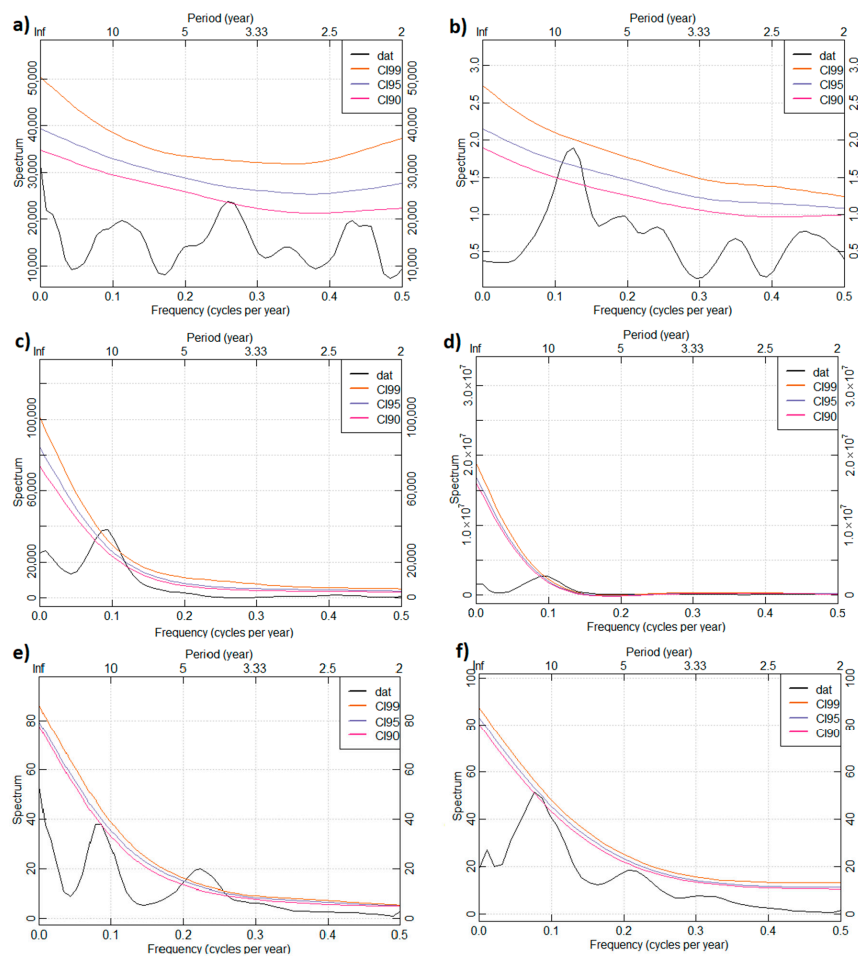
Figure 11. Spectral analyses of the used data in the period 1961–2018: (**a**) Annual precipitation total; (**b**) average annual temperatures; (**c**) cosmic ray intensity; (**d**) sunspot area; (**e**) salvage logging; (**f**) salvage logging in the period 1973–2018. Explanatory notes: the data used are represented by the black curve (dat); the lower, medium and upper parabolic line is significant at a level of 90% (CI90), 95% (CI95) and 99% (CI99), respectively; the period (year) shown on the upper x-axis ranges from 2 years to infinity (Inf).

4. Discussion

4.1. Anthropic Impacts and Climate Fluctuations Influencing Salvage Logging

Forest stands are influenced by a higher occurrence of extreme weather events during climate change. Such fluctuations include, e.g., severe storms, wind, drought, floods, or forest fires [13,78–80]. The greatest negative effects on the volume of salvage logging and also of timber harvested in the Czech Republic are imposed by wind, bark beetle, and air pollution disturbances [81–85]. In the Czech Republic, most prominent negative anthropic impacts on the environment resulting in salvage logging occurred during the air pollution calamity from the late 1970s to the late 1980s (see Figure 1) when, on average, 6.2 million m^3 of timber were annually harvested. As a consequence of the air pollution calamity, 47,300 m^3 of timber, i.e., 2% of the forest area, was harvested in the mountain areas of the Czech Republic, mainly in the Krušné hory Mts. and in the mountain ranges of the Sudetes system (Lužické hory, Jizerské hory, Krkonoše and Orlické hory Mts.) [14]. When the air pollution calamity culminated, average annual SO$_2$ concentrations in these mountain areas were in the range of 60–210 µg m^{-3} and maximum daily SO$_2$ concentrations reached 2500 µg m^{-3} [14]. In the course of the air pollution calamity, the declining spruce forests were often attacked by bark beetles, particularly by the eight-toothed spruce bark beetle [86–89].

In Europe, the Norway spruce decline was observed during climate change, e.g., in Germany [90], Austria [91], Poland [92], the Czech Republic, and Slovakia [15,93]. These forests are vulnerable to a number of secondary diseases and pests, and they are particularly sensitive to the warmer and drier climate [94,95]. Our data indicate that temperatures have a significant effect on the trend of salvage logging during the entire period 1961–2018, which is documented in Table 1, where r = 0.5269. The precipitation deficit is not significant in any variant in Table 1, but Figure 5b clearly shows that the precipitation deficit reduces the Norway spruce ability to resist bark beetle outbreaks, which was confirmed in previous research [96,97].

Such situations are well illustrated by typical examples of drought in 2003, when the precipitation total decreased to a below-average 504 mm, or in 2018, with only 522 mm of precipitation (Figure 1). A typical drought-induced outbreak of *Ips typographus* occurs when healthy trees are attacked [98,99] and there appear extensive foci of infested trees that fail to be cut in time [100]. In addition, the situation is made more complicated by mandatory tenders for logging operations performed by timber processing companies in the forest sector. The tenders considerably delay salvage logging, which contributes to the gradation of secondary pests. In 2019 the volume of salvage logging was 30.9 million m^3 (i.e., 95% of the total volume of harvested timber), mainly as a consequence of the enormous spread of bark beetles in Moravia and the Czech-Moravian Highlands [15].

4.2. Salvage Logging Versus Solar and Cosmic Factors

Forest disturbances in the Czech Republic are triggered by windstorms that initiate outbreaks of bark beetles. They subsequently start to destroy coniferous stands during the drought years [32,82]. This happened, e.g., in January 2007, when the windstorm Kyrill caused substantial damage to forest stands [101], triggering a domino effect of forest stand destruction, resulting in an increase in salvage logging of up to 15 million m^3 as shown in Figure 1, Figure 3, and Figure 5. The aforementioned drought periods belong to extreme weather fluctuations, again associated with the sunspot cycle. This was confirmed, e.g., in Kuwait [102] and China, where the solar cycles are associated not only with drought but also with floods [103]. An increase in the amount of precipitation is linked with the occurrence of high winds that also coincide with the occurrence of solar cycles, documented, e.g., in Spain [80]. Our data confirm that in the course of severe storms there is an increase in salvage logging (Figure 1), which occurred at the beginning of 2018 when, in the aftermath of the storm Friederike (with winds of up to 205 km h^{-1}), salvage logging increased to 23.01 million m^3. Impacts of 11-year solar cycles on the climate pattern in Europe have been proven for the last 250 years while the sunspot effect on climate increased during the 19th century [59]. This is also confirmed by our data in Table 1, which illustrate that salvage logging was higher during the solar minimum in recent years. Salvage logging amounted to 15 million m^3 of timber in 2007, but increased to almost 23 million m^3 in 2018, which also coincided with the solar minimum, i.e., the small or nearly zero sunspot area (Figure 6). In 2010–2012 (during the solar minimum) the occurrence of subcortical insects was successfully reduced in spruce monocultures to the level of the years 2004–2006 (Figure 1), which resulted in a decrease in salvage logging (on average 5.2 million m^3 salvage logging timber).

Salvage loggings are caused by climatic triggers. Furthermore, there are significant correlations with the sunspot area, which is evident from our significant correlations, e.g., in the period 2000–2018 (Table 1). Solar cycles can be linked with salvage logging through the North Atlantic Oscillation (NAO), which is closely associated, e.g., with the precipitation occurrence in Europe while precipitation is linked with the solar cycle [104]. However, our data (Table 1) did not show a significant correlation of sunspot numbers and solar cosmic ray intensity in relation to precipitation and temperature. An important fact completing our research is that the quantity of cosmic rays impinging on the Earth's atmosphere is influenced by the solar cycle, which also impacts the water cycle [105,106]. An inversion relationship between the sunspot area and cosmic ray intensity has been studied previously [47,107], and is also evident from Figures 6–9, when the response of salvage logging to cosmic ray intensity is the highest (Table 1). The relationship between salvage logging, sunspot area, and cosmic ray intensity is seen

in Figure 11, which shows that an 11-year solar cycle is projected in salvage logging and cosmic ray intensity. Cosmic rays are influenced by solar magnetism [108,109] but until now this effect has not been identified in relation with their real impacts on the forest environment and forest sector.

Our data illustrate a substantial effect of cosmic rays on the volume of salvage logging as shown in Table 1 and Figure 8 when the correlation with the time period 1973–2018 is significant. This fact is related with the formation of aerosols that are the basic component of cloud formation [63,65]. The solar cycle also influences radial increment of trees, which was suggested by dendrochronological researches in Siberia [110,111], Portugal [112], and China [113].

4.3. Relevant Context and Potencials

It is important to mention that logging operations in the course of salvage logging damage trees (log depots, abrasions, subsequent rot), disturb the soil (erosion), etc. [89]. Negative events and disturbances appear to show an increasing long-term trend which, in the future, will lead to a change in the species composition of forests in the Czech Republic, depending on the response of forest management. Proper management might reduce the impact of disturbance on forests [114,115].

Salvage logging largely comprises Norway spruce, which is negatively affected by disturbances such as higher temperatures and dry summers [35], and the coinciding influence of wind storms [11] places forest management under strong pressure (Figure 3—e.g., year 2018). The forestry sector must process a large amount of timber in a short period of time and this leads to financial losses. Timber loses value and is sold below cost [15]. The overall logical conclusion is that the fluctuations in the price of timber follow the fluctuations in total logging, and our study confirms that there is a significant correlation (Table 1) of logging with the solar 11-year cycle (Figure 11).

It is also worth noting that the highest significant correlation between sunspot number and total logging (Table 1) was recorded in the 21st century, and is associated with higher maturation of the forest stands to rotation age in the Czech Republic (Figure 2); therefore, total logging is undergoing an increasing trend. In contrast, solar activity significantly decreased in the 21st century, which is evident in the highest negative significant correlation against the increasing trend of total logging. Moreover, forest stands in the rotation age are more sensitive to negative climatic fluctuations [116], which is also connected with salvage logging. In the long run, salvage logging has not risen as significantly as total logging because in recent years there has been an increase in protected areas in which salvage logging is generally not carried out due to ecological concerns [117,118]. In addition, the economic factor affects salvage logging because it is not worthwhile to carry out salvage logging due to cheap timber prices, which in many cases leads to leaving the timber in the forest without rather than logging [119]. In recent years, there has been a significant relative decrease in the amount of salvage logging due to environmental and economic decisions [15,120], which is the reason for the reduction in the correlation between solar activity and salvage logging in the 21st century.

Carbon sequestration by forest ecosystems can be smoother if forest management succeeds in reducing salvage logging [121]. A study of the carbon stock in Europe also shows that forest disturbances in relation to salvage logging are part of the carbon cycle [122].

This study could provide forest management with a new concept of origin related to disturbances in salvage and total logging in forestry due to solar activity. The predictability of the solar cycles is associated with an 11-year solar period [123] and our results confirm that the 11-year period occurs even during salvage logging (Figure 11e,f). The next important note is that the next 11-year solar cycle can be lower or equal to the previous cycle in terms of solar activity [124]. Thus, the interesting observation of solar activity in parallel with the development of salvage logging can be beneficial for foresters. The total solar irradiance index (TSI), which includes climatic and solar effects [125,126], can also be used for future research of solar activity and its impact on forestry. This may lead to further in-depth research into the impact of the sun and climate change on forestry. Numerous factors influence forests and forest management, but salvage logging is a complex indicator of climate change which substantially restricts forest management.

5. Conclusions

Salvage logging and the total volume of harvested timber indicate the overall condition of the forest sector. These two factors respond to climatic, anthropic, and political impacts. Salvage logging and the total volume of harvested timber are in significant correlation with average annual temperatures, storm events, cosmic ray intensity, and sunspot area. The annual precipitation total does not significantly correlate with timber harvested. Among all of the studied variants, the response of salvage logging to cosmic ray intensity and average annual temperatures is the most evident. The response of salvage logging to the sunspot area is also highly distinct. Furthermore, there has been an increasing projection of the 11-year solar cycle in the volume of salvage logging, mostly in the last two decades in relation to the synergism of climatic extreme events. Salvage logging also significantly responded to average annual temperatures during the studied period. The results of this research are an important initiator of understanding particular natural fluctuations influencing the forest sector during climate change. However, further in-depth research is needed and should provide a link to a greater number of factors influencing salvage logging that play a role in forest silviculture and management (tree species composition, stand structure, etc.). This research should contribute to a profound knowledge and possible predictions of not only theoretical forest science but also practical principles of modern forestry.

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