Analysis of Current and Future Forest Disturbances Dynamics in Central Europe

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Abstract: The area of forests and the standing volume per hectare are constantly increasing in Europe, and this trend is expected to continue for several more decades; the aim of this paper was to provide an empirical overview of the development of disturbances in selected countries of central Europe and based on this overview to empirically model and predict the development and intensity of disturbances in the future. Statistical methods (Holt–Winters) and predictive risk models of the growth simulator SIBYLA were used for prediction. From the statistically predicted values by this method, it follows that, in the next three years, it is possible to assume that stagnation will result in declining volumes of incidental fellings in all countries. Forecast from the growth simulator SIBYLA shows a substantial increase in the predicted volume of incidental fellings for the years 2021 and 2022, compared with 2020. The volumes of incidental fellings should grow most significantly, especially in Germany, Poland, and Austria. The performed analysis and predictions suggest that the peak of wood volumes damaged by disturbances in the next decade will probably be reached already in the reports for 2021 or 2022. However, the risk of disturbances remains high, and other large-scale area disturbances in forest ecosystems cannot be completely ruled out.

Keywords: natural disturbances; climate change; growth simulator SIBYLA; damage; dynamics; management

1. Introduction

Calamity can be characterized as extensive disturbance and damage to forest stands or entire forest complexes by one or more harmful factors, which has an accidental occurrence of varying magnitude [1–3]. Although forest areas and standing volumes per hectare are steadily increasing in Europe, and this trend is expected to continue for several more decades [4], the dynamics and extent of disturbances, which play key roles in forest vegetation dynamics, are a cause for concern [5]. The disturbance is defined as a random event over time that disrupts forest ecosystems, population structure, and environmental conditions [6–8]. Natural disturbances are a common part of nature, and often their natural development in biocenosis depends on their occurrence [9–13]. Extensive disturbances cause unexpected economic damage, reduced forest value, and degraded timber production. Disturbances caused by natural factors have occurred in the past and cannot be avoided in the future. In the years 1950–2000, the annual average timber volume damaged by disturbances was 35 million m³ [14–16].

Global climate change is causing major changes in the course and dynamics of forest ecosystem disturbances [17], so understanding their nature and modeling the dynamics is important for forestry. In terms of the action of harmful factors, we divide them into mechanical and physiological factors. Mechanical damage is mainly caused by wind, snow, fire, and freezing. Drought, frost, bacteria, viruses, insects, and air pollution are physiologically active. The risk of disturbance depends on the threat, exposure, and vulnerability of the ecosystem [2,18,19]. The most frequent harmful factors in the territory of 30 European

countries in the period 1850–2000 were strong wind storms, which caused 53% of the volume of incidental fellings. The second most common harmful factor was forest fires, which caused 16% of all damage. There were also bark beetles and wood-destroying insects (8%) and other abiotic factors (8%) [14]. In the context of climate change, droughts, forest fires, windstorms, and pest multiplication can be expected to occur more frequently [12,20,21]. The attributes of a particular disturbance regime, such as the recurrence period, the severity and extent of the different types of disturbances occurring in the country, are currently the subject of intensive research [3,22]. There are natural cases in which the primary disturbance caused by one factor, e.g., the wind, gradually grows into subsequent disturbance caused by other factors, e.g., bark beetles, which can increase the original extent of the damage several times [2,23,24].

The extent and negative impact of disturbances and the current occurrence of harmful factors also fundamentally affect how forest ecosystems have been managed in the past. The negative consequences of past forest silviculture and management methods may persist for a relatively long period [25]. Changes in atmospheric temperature and rainfall will have an impact on forest production in the coming decades, as well as the representation and mortality of the main tree species [26–28].

The basic precondition for successful forest management in the future is risk assessment and prediction of disturbance development. Mathematically speaking, the risk of destruction of a forest stand by harmful factors increases with the age of its establishment. Several factors affect the risk assessment of a particular harmful factor [29–32]. An important tool for the analysis of relations between disturbances and the environment in forest management are quantitative models because, by using mathematical and statistical tools, they make it possible to explain and understand the processes that occur in the forest ecosystem and, at the same time, test theoretical hypotheses to improve and streamline forest management [2,9]. From the point of view of the simulation method, we recognize two basic types of models. The first is mechanistic (process) models, which are based on understanding and describing the relationships and processes ongoing in ecosystems. The second is empirical models, which are derived from empirical data and are based on the quantification of disturbances based on a statistical analysis of empirical observations in the past. They are, therefore, based on data and measurements made in previous periods, which form the basis for deriving and describing the dependencies between disturbances and the status of the forest ecosystem, as well as the sources of variability of these data [2]. In terms of time, models can simulate individual disturbances or a set of disturbances, or cumulative disturbances over some time [33].

The aim of this paper was to provide an empirical overview of the development of disturbances in selected countries of central Europe and, based on this overview, to empirically model and predict the development and intensity of disturbances in the future. The development of disturbances was assessed mainly through the volume of incidental fellings. For the purposes of this study, incidental fellings are fellings that were caused by an accident by a harmful factor. Therefore, we implemented the felling of wood damaged by harmful factors, which was not planned (intentional), as an incidental event.

2. Materials and Methods

Selected countries in the central European region (Slovakia, Czech Republic, Germany, Austria, Switzerland, Poland) were included in the analysis. Data on total timber harvesting and incidental fellings were obtained from public information sources, national statistical institutes, or summary forestry reports at national levels (overview in Table 1) [34–40]. The accuracy of the analysis may have been partly affected by inconsistencies in the data reported at different levels by the professional institutions in each country. In Switzerland, for example, only data about incidental fellings due to insects were available until 1998 [38]. The overall period analyzed in all selected countries was 2000–2020. This time period was chosen because relatively accurate data on total harvesting volumes were available in all countries over these years. Part of the problem was also the inconsistency of data

on volumes of incidental fellings, especially in the years 1990–2000 for some countries (e.g., statistics reported only for 1990, 1995, and 1999, with missing data for other years). Therefore, the modeling of the volumes of incidental fellings was based only on time series for the period 2000–2020. Data from the countries of the Czech Republic, Slovakia, Germany, Austria, and Poland were used to model the development predictions, where consistent and accurate data on the volumes of incidental fellings since 2000 were available.

Table 1. Overview of the information sources about incidental fellings for the analysis database according to references.

Country	Information Source	Reference Number
Slovakia	Forestry Green report from the Ministry of Agriculture and Rural Development of the Slovak Republic	[34]
Czech Republic	Czech Statistical Office—Forestry datasheet	[35]
Germany	Federal Statistical Office of Germany—Forestry and Wood Statistics	[36]
Austria	Federal Ministry Republic of Austria Agriculture, Regions and Tourism—Timber harvesting Data	[37]
Switzerland	Federal Office for the Environment Switzerland. Yearbook Forests and Wood (Swiss Federal Research Institute); insect infestation Ips typographus remains high	[38,39]
Poland	State Forests of Poland—Forest report in Poland	[40]

The growth simulator "SIBYLA TRIQUETRA", which is available as freely distributable software [41], was used to model the prediction of the development of incidental fellings and possible scenarios. The construction, accuracy, and use of this growth model for predicting random events in forest stands have already been described in previous studies [42–45]. Information on forest ecosystems (area, tree composition, etc.) from available information sources of individual countries was inserted into the model [34–40].

Additional software modules called "Agressor" and "Prophet" were used to predict the threat and development of the volume of incidental fellings by the SIBYLA TRIQUETRA growth simulator. A database was used to quantify the risks from the territory of Slovakia for the groups of trees spruce, fir, pine, beech, and oak. Among the harmful factors, it contains a module for quantifying risks for wind, insects, snow, freeze, fungi, drought, fire, wood theft, and unidentified causes. The sector of the analytical module for risk quantification "Agressor" is shown in Figure 1, and the sector of the forest growth and damage prediction module "Prophet" with ongoing simulation is shown in Figure 2. Models created from Slovak and German stand databases were used for modeling. For each country, the appropriate tree composition and forest structure were selected, which was up to date until 2020. This age and tree species structure was fundamentally influenced by the results of the predicted volumes of incidental fellings for the next decade.

All data on mining and incidental fellings show signs of a seasonal component. Most statistical models are based on the quantification and modeling of the factors that cause incidental felling (wind, insects, fires). As the quantification and continuity of these data varied from country to country, it was not possible to use most of the empirical statistical models that are standardly used in predicting natural disturbances. Due to the lower number of observations on an annual basis (20), the Holt–Winters method [46] based on exponential smoothing was chosen for statistical analysis and prediction of future developments. A similar method, classified by Box and Jenkins [47], was not suitable for this analysis due to the low number of observations. The Holt–Winters method belongs to the so-called adaptive time-series balancing methods designed for short-term forecasts for one-dimensional data. The method has the ability to respond quickly to changes in time series values. Exponentially decreasing weights are assigned to past observations in exponential equalization. Recent observations have been given relatively greater weight in forecasting than older observations [48], which is particularly important for the dynamic changes brought about by global climate change over the last decade. Winters [46] generalized this

method and included a seasonal component for forecasting in the model. The method uses simple exponential smoothing of the trend (T_t) and seasonal (S_t) components of time series. The model can be in either additive (linear) or multiplicative (non-linear) form. The method of choice was chosen as a suitable additive model. It is based on the additive model of time series components [49]:
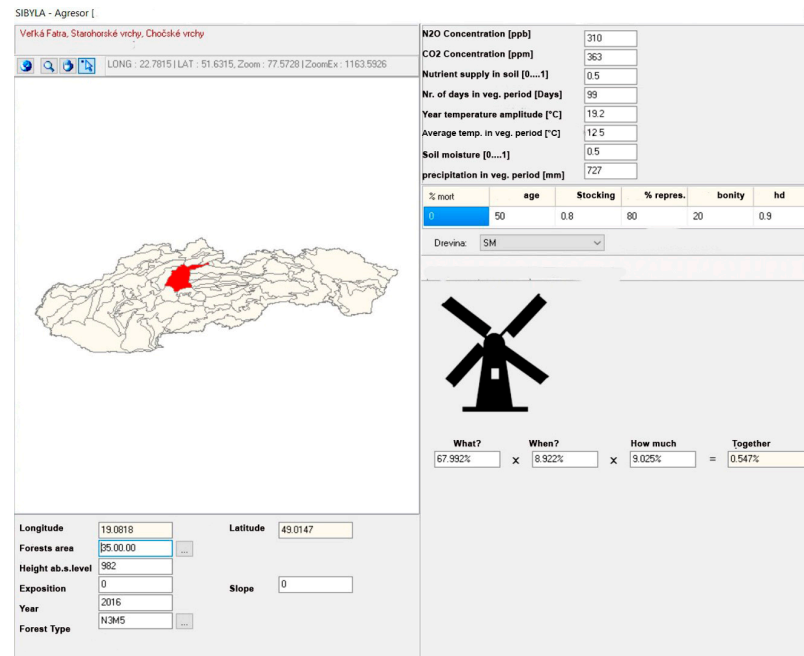
Figure 1. Section of module "Agressor" from software SIBYLA TRIQUETRA.
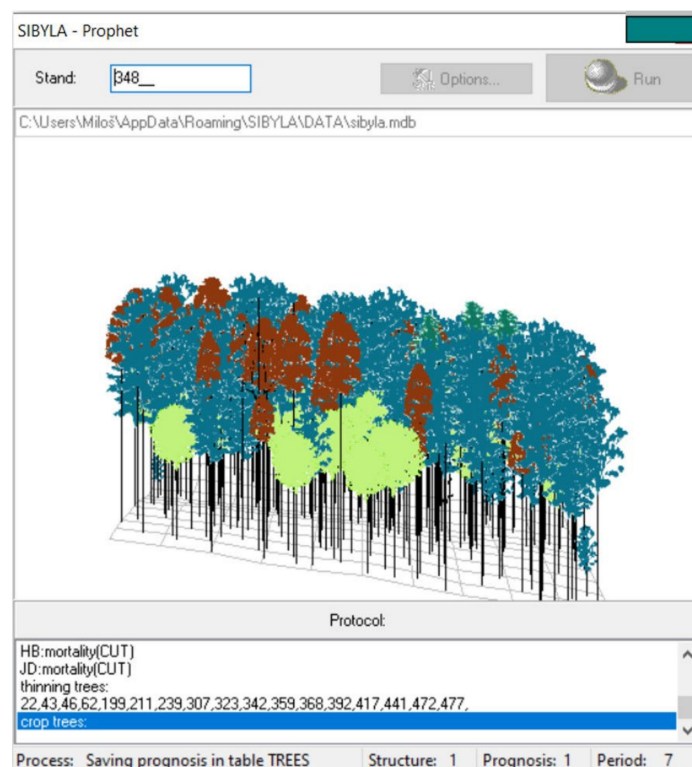
Figure 2. Section of module "Prophet" with running simulation from software SIBYLA TRIQUETRA.

$$Y_t = \mu_t + \beta_t t + s_p(t) + \varepsilon_t, \tag{1}$$

where

μ_t—The mean value of the trend component that changes at time t;
β_t—The slope of the trend that changes at time t;
$s_p(t)$—Seasonal component for one of the "p" periods;
ε_t—Residual component;
t—Time variable.

The smoothing equations for error correction are in the following forms [49]:

$$L_t = \alpha(Y_t - S_{t-p}) + (1 - \alpha)(L_{t-1} + T_{t-1}), \tag{2}$$

$$T_t = \gamma(L_t - L_{t-1}) + (1 - \gamma)T_{t-1}, \tag{3}$$

$$S_t = \delta(Y_t - L_t) + (1 - \delta)S_{t-p}, \tag{4}$$

The equation for calculating the prediction [49] is

$$\hat{Y}_t(k) = L_t + kT_t + S_{t-p+k}, \tag{5}$$

where

L_t—Estimate of the mean value of the time series μ_t;
T_t—Estimate of the trend component β_t;
S_t–Estimate of the seasonal component;
α, γ, δ—Balancing the model weights with values from the interval between 0 and 1;
p—Number of periods per year.

In the final part, we focused on the analysis of the current development of total and incidental fellings in selected European countries. Subsequently, the empirical algorithms of the SIBYLA growth simulator software were used to forecast the further development of forest ecosystems in these countries and, through statistical models, to empirically predict the development of incidental felling volumes in the future.

3. Results

3.1. Development of Timber Harvesting in Selected European Countries

Figure 3 shows the development of timber harvesting in selected central European countries. The volume of harvesting naturally reflects the size of the country, its forest cover, as well as the tree species composition. However, it also reflects the extensive disturbances that have hit European forests in previous decades (e.g., Germany in 1990, the Lothar and Martin windstorms, or the large-scale bark beetles attack in the Czech Republic in the last 3 years). In smaller countries such as Slovakia, Austria, and Switzerland, a decline in total timber harvesting has been evident over the last three years, mainly due to a higher share of incidental fellings in the previous two decades.

In most countries, the volume of incidental fellings caused by a wide range of harmful factors contributes significantly to the total volume of timber harvesting. The percentage of incidental fellings from the total volume of timber harvesting in selected countries for the period 2000–2020 is shown in Figure 4.

Developments show that the harmful factors that caused incidental fellings had various intensity impacts in selected European countries over the past two decades. The lowest share of incidental fellings was in almost all countries at the turn of the decade (2011–2013). Since then, the share of incidental felling volumes has increased in most countries until 2019. The exception is the Czech Republic, where, in the past three years (2018–2020), the share of incidental fellings has exceeded 90%. However, this is due to known causes of deforestation by bark beetles. The increase in development has continued in the past three years in Germany as well. In Slovakia and Austria, the share of incidental fellings fell below 60% in 2020. In the long run, the share of incidental felling is low in Poland, but in the period 2015–2018, it also grew slightly. It has been declining slightly again in the last two

years. This is mainly due to the structure and tree species composition of Polish forests and partly also by the terrain and climatic conditions.
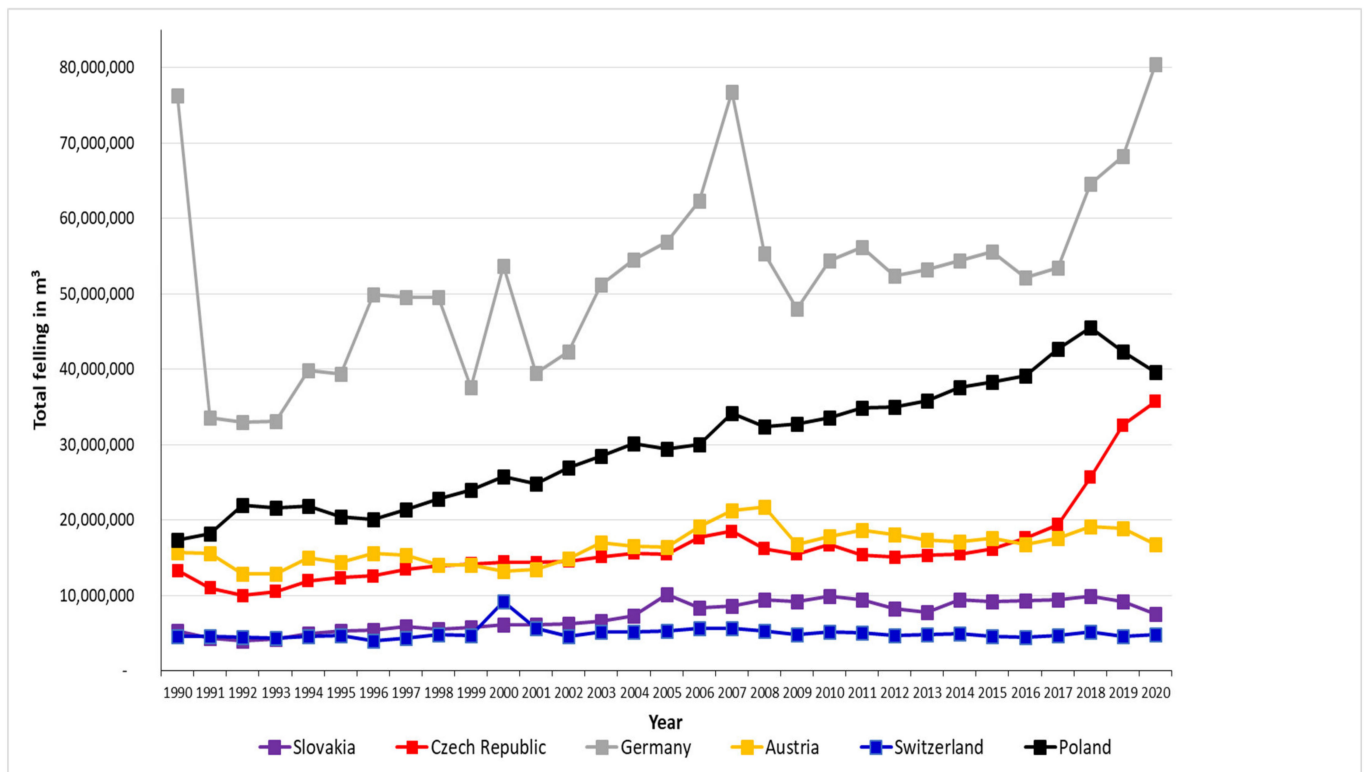
Figure 3. Time series development of total timber harvesting (m³) in central Europe selected countries.
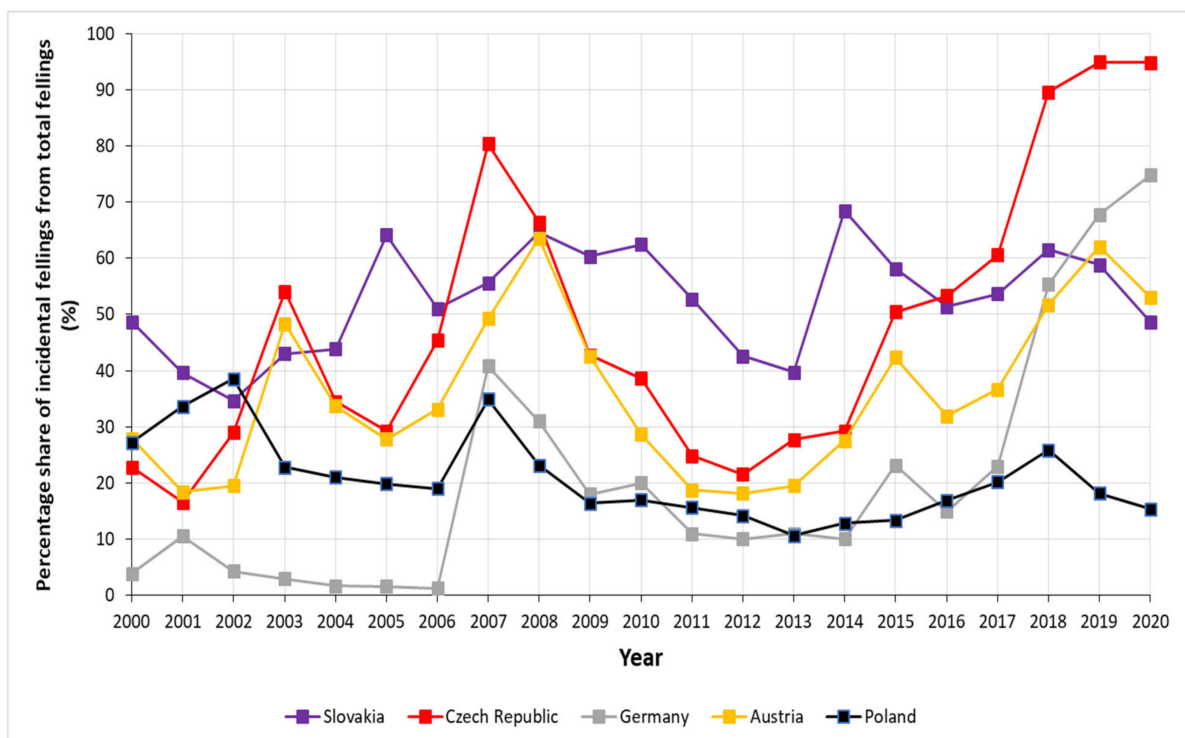
Figure 4. Percentage share of incidental fellings from the volume of total timber harvestings in selected European countries in the time range 2000–2020.

The volumes of incidental fellings from these countries represented the basic database for statistical prediction of future development, as well as the simulation of the development of forest ecosystems in the SIBYLA growth simulator.

3.2. Statistical Prediction of the Development of Incidental Felling Volumes

Figure 5 shows the development of incidental fellings in the countries of Slovakia, the Czech Republic, Germany, Austria, and Poland in the period 2000–2020. Continuous and accurate information on the volumes of incidental fellings in these countries was available for this period. Figure 5 also shows a prediction of the further development of incidental fellings in these countries, which is quantified by the Holt–Winters method. The prediction was calculated for 10 years ahead (period 2021–2030). In the individual time series of selected countries, the prediction in this period is shown by a dashed line.
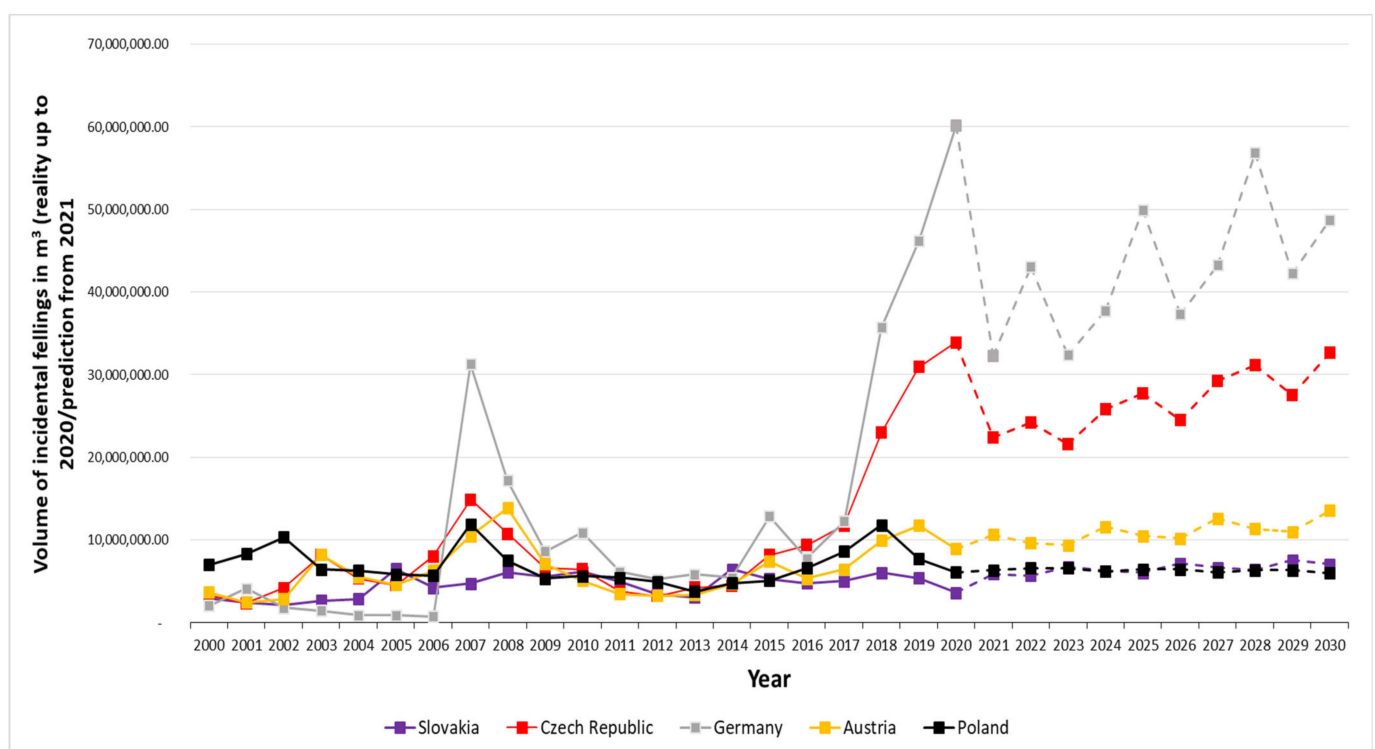
Figure 5. Volume development of incidental fellings and prediction from 2021 onward in selected European countries in the time range 2000–2030.

The volumes of incidental fellings predicted by this method show stagnation and a respective decline in the next three years in all countries. The most stable situation in terms of long-term forecasting will be in Poland, which logically follows from the relatively stabilized shares of incidental fellings in total timber harvesting. However, incidental fellings levels from 2020 will not be surpassed in most countries. The only exception is Slovakia, where the volumes of incidental fellings in 2030 will be higher by approximately 48.2%, compared with 2020. However, it should be added that in 2020 Slovakia had the lowest volume of incidental fellings since 2013, and compared with 2019, was about 33% lower. A lower volume of incidental fellings for the next decade is predicted for the countries of Germany, the Czech Republic, and Poland. In Austria, a higher volume of incidental fellings is forecast for 2030 by 35%, compared with 2020 (but only 15% higher than in 2019).

3.3. Prediction of the Development of Incidental Fellings Using the SIBYLA Growth Simulator

The growth simulator predicts a significant increase in the volume of incidental fellings for the years 2021 and 2022, compared with 2020 (Figure 6). The volumes of incidental fellings should grow most significantly, especially in the countries of Germany, Poland, and Austria. There will be more moderate growth in Slovakia and a decline in the Czech Republic. By 2030, the volumes of incidental fellings in all countries monitored should fall significantly below 2020 levels. This decline is naturally based on the current level of risk calculated from the occurrence of individual harmful factors to date. However, global climate change may significantly change the numerical parameters of their quantification models in the next decade. In some cases, the occurrence of the harmful factors is linked to the occurrence of the other harmful factor that precedes it and its extent (e.g., the risk of overgrowth of bark beetles following previous high timber volumes damaged by windstorms). It may also be the result of, for example, the multiplication of bark beetles insects related to climatic conditions in a given year, etc.
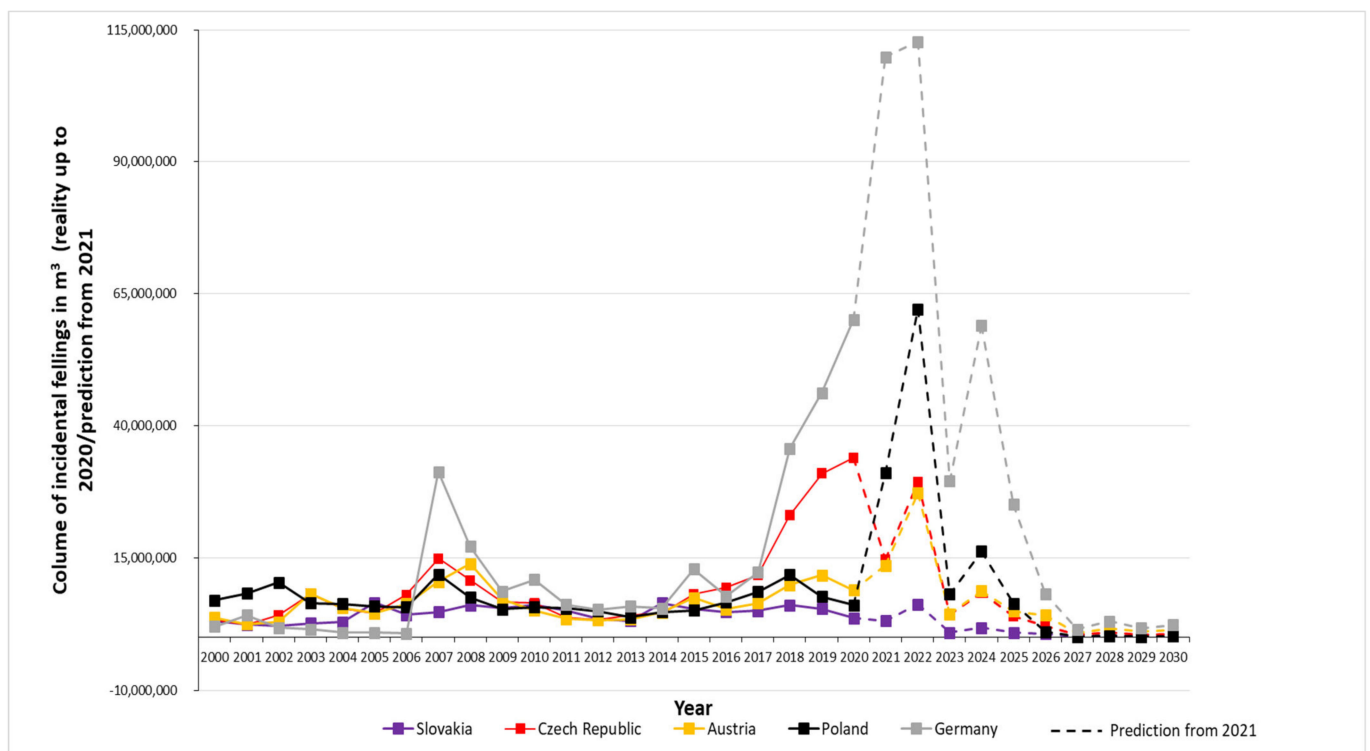
Figure 6. Volume development of Incidental fellings and SIBYLA TRIQUETRA prediction from 2021 onward in selected European countries in the time range 2000–2030.

By 2030, the volumes of incidental fellings should fall most sharply in Germany (approximately 4% of accidental volumes in 2020), the Czech Republic (2% of 2020 volumes), and Poland (3.3% of 2020 volumes). In addition to the calculated risk of harmful factors on individual tree species, this prediction is also linked to the expected gradual and partial change in tree species composition in the forests of central Europe. The growth simulator prediction model also considers a change in the age structure in the forests of individual countries. The predicted volumes also reflect the partial risk reduction. The model assumes that if one harmful factor occurs in a certain year, the probability of its recurrence in the following year will be lower.

4. Discussion

There is a relatively few studies that model the future development and dynamics of natural disturbances in central Europe. However, a comparison of our results with those of the existing ones revealed that the statistical and software approaches that were used in our research can be used relatively well. However, such modeling is more important for shorter time periods in the future, also with regard to its accuracy.

Merganic et al. [2] predicted the development of disturbances in a selected forest subject in the model area using the neural network method. They indicated that it is not possible to determine generalized optimal management to increase the stability of the forest, but it is necessary to approach each forest stand individually. Based on the training model, they set a prediction of the risk of incidental felling at 28%. At the same time, they indicated that it is relatively difficult to describe incidental felling processes based on available data. In our first prediction method, the Holt–Winters method showed an average statistical error of 25%, concerning the difference between predicted and observed volume of incidental fellings.

Holécy and Hanewinkel [30] defined a risk model with application to coniferous stands in Germany. They calculated the highest level of risk in forest stands aged 30–70 years, while the premium surcharges for risk insurance before destruction decreased with the increasing size of the forest.

Aszalos et al. [48] predicted ice disturbance in European deciduous forests with generalized linear models, compared to field-based and airborne-based approaches. They found that both approaches can achieve relatively high accuracy in predicting ice damage (more than 90%). However, the accuracy of this method for other harmful factors has not been verified.

Building extensive information databases with information on their occurrence and extent in the past, such as wind disasters, can also be important for predicting disturbances [50]. The creation of such a database was also the basis for our prediction models and procedures.

On the basis of an ensemble of climate change scenarios, Seidl et al. [51] indicated that damages from wind, bark beetles, and forest fires are likely to increase further in coming decades, and estimated the rate of increase to be $+0.91 \times 10^6$ m^3 of timber per year until 2030. Our statistical forecast assumes a lower increase, at about the level of $+0.67 \times 10^6$ m^3. In a similar study, they also modeled the dynamics of damage caused by bark beetle insects using a two-stage multivariate statistical meta-model. They concluded that by the year 2099, damage to bark beetles could increase up to quadrupled [52]. However, predictions for the coming decades do not yet confirm such a dramatic scenario.

Melo et al. [53] modeled various disturbance development scenarios concerning spruce budworm and timber harvesting activities in Canada up to the year 2103 using a stochastic individual-based model. For the scenarios including spruce budworm, the variances were three to six times greater than those in the scenarios without outbreaks. Harvesting activities did not greatly contribute to the total variance. It is also clear from their results that the predictions are more important for a shorter period, as we also found in our research.

Schelhaas et al. [54] modeled the impact of climate change on forest resources in Switzerland, in three scenarios, until the year 2048. Under a simulated climate change scenario, the frequency of disturbances was assumed to increase, resulting in 25% higher damages. These results partially correlate with our overall results, except for some countries (e.g., Slovakia).

The number of approaches to forest disturbance modeling has increased significantly over the last 15 years. Statistical concepts for descriptive modeling are still largely prevalent over mechanistic concepts for explanatory and predictive applications [9].

5. Conclusions

With the increasing age of the forest stand since its establishment, the risk of its destruction due to disturbances caused by various harmful factors increases. This is a mathematical fact verified multiple times [31]. Therefore, maintaining a non-management regime in forest stands only makes sense in native and natural forest-type forest stands. In non-natural and previously managed forests, the risk of their destruction by some harmful factors increases with age.

The performed analysis and predictions in this study indicate that, in the next two years, we will probably have the peak of the volume of incidental fellings caused by disturbances in central Europe. This prediction can be described as realistic given the current developments in the effects of abiotic and biotic harmful factors in individual countries. The peak of the damaged volume of timber will probably be reached already in the reports for the years 2021 or 2022, which are not yet available.

If the trend of climate change continues to be dynamic in the future and forest management practices adapt to this trend, a slight decrease in the area of damaged forests, and thus in the volume of incidental fellings, can be expected in the next decade. However, the risk of large-scale incidents remains high, and further large-scale area disturbances in forest ecosystems cannot be completely ruled out. This risk is partially reduced mathematically only as a result of extensive forest damage caused in the last two decades, which was confirmed by the analyzed development in the period 2000–2020.

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