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Norway Spruce Survival Rate in Two Forested Landscapes, 1975–2016

Endijs Bāders [1,*], Oskars Krišāns [1], Jānis Donis [1], Didzis Elferts [1,2], Ieva Jaunslaviete [1] and Āris Jansons [1]

[1] Latvian State Forest Research Institute 'Silava', Rigas 111, LV–2169 Salaspils, Latvia; oskars.krisans@silava.lv (O.K.); janis.donis@silava.lv (J.D.); didzis.elferts@lu.lv (D.E.); ieva.jaunslaviete@silava.lv (I.J.); aris.jansons@silava.lv (Ā.J.)

[2] Faculty of Biology, University of Latvia, Jelgavas street 1, LV–1004 Rīga, Latvia

* Correspondence: endijs.baders@silava.lv

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Abstract: The increasing frequency and severity of natural disturbances (e.g., storms and insect outbreaks) due to climate change are expected to reduce the abundance of Norway spruce stands in the European forests. Under such conditions, the assessment of *status quo* on focusing on survival of Norway spruce stands are essential for the agility of forest management strategies. The dynamics (mortality rate) of Norway spruce stands in hemiboreal forests based on forest inventories for the period from 1975 to 2016 (inventories of 1975, 1985, 1999, 2011 and 2016) were analyzed in two forest landscapes in the western and eastern parts of Latvia (Vane and Dviete, respectively). The spatiotemporal changes in age-dependent mortality differing by abundance of Norway spruce and disturbance regime were assessed, focusing on the transitions of stands between age groups (inventories). The age-related changes in probability of stands transitioning into the next age group contrasted ($p < 0.001$) between sites. In Vane, the survival of stands between inventories was constant (ca. 90%), while in Dviete, it decreased sharply from 85.7% during 1985–1999 inventories to 49.3% in 2011–2016. Age-related decreases in stand survival showed local dependencies between both landscapes, namely, in Vane, notable decreases started from 61 years, while in Dviete, the downward trends started already from 31 years, probably due to different disturbance regimes. This suggests that, in forest management planning, the different outcomes for mortality patterns between both landscapes must be considered and should not be generalized for a whole country.

Keywords: landscape; stand dynamics; forest inventory; mortality; survival rate

1. Introduction

In the context of global climate change, simulation of future forests in support of forest planning and decision making may become more challenging [1,2]. Critical knowledge gaps are associated with forest disturbances that must be considered in modelling forest dynamics [3,4]. In particular, the lack of long-term empirical data to compare similar conditions over time is a significant problem [5]. Consequently, projection systems must evolve to better reflect the mortality of a stand in a landscape due to primary disturbance forces [6]. In general, current forest resource projection systems are created by combining the multitude of factors that affect forest growth [7,8]. Many uncertainties and unknowns remain, and many forest modelling studies do not adequately account for the disturbance effects [9]. Therefore, identification of the potential effects of disturbance-driven changes may assist in evaluating forest dynamics [10].

The capability to simulate the effects of large-scale natural disturbances on forest landscapes is limited [11]. Although many models have incorporated tree mortality, the calibrations have been based on unsupported assumptions and short-term empirical data [12]. Some simulation models already include large-scale events (such as complete stand destruction) caused by natural or anthropogenic disturbances [13–15]. Natural disturbance events are highly variable in intensity, extent, and spatial and temporal occurrence [16]. Therefore, the mortality algorithms for applications over a restricted spatial extent and under the current climate should be calibrated based on datasets from the same region, even if they are minimal [17]. The analysis of long-term data such as forest inventories can provide new knowledge of the dynamics of forest stands and information on stand mortality rates.

To improve our understanding of forest landscape dynamics, we analysed data on stands of Norway spruce (*Picea abies* (L.) Karst.), one of the most common and economically important tree species in the nemoral and boreal regions of Europe [18,19]. It is susceptible to both abiotic and biotic disturbances, among which windstorms are the most important [20], ranging from periodic small-scale events to infrequent major, large-scale disturbances that have determined forest structure over the landscapes in the Baltic Sea region [21]. Biotic factors such as pests, herbivores and pathogens may also significantly influence Norway spruce stand mortality rate, which is reflected in the landscape patterns [14,22,23]. Moreover, the interaction between abiotic and biotic factors also is important in determining the amount and severity of damage [24,25]. Climatic conditions in Norway spruce forests are identified as the dominant growth-determining factor [26]. Changes in precipitation patterns and increased summer temperatures have also been associated with drought stress in Norway spruce stands and may cause mortality [27]. Projected future environmental conditions suggest growth, vitality and particularly regeneration challenges for Norway spruce [28]. Although the present final cutting of Norway spruce in Latvia are allowed from the age of 81 years, earlier research pointed out that Norway spruce are at great risk for being damaged before it reaches the allowed age to be felled in the final cut [29]. The analysis we propose in this study may serve in future discussions of the documentation needed to reduce Norway spruce stand losses and to increase their resistance to disturbance, as the species is of great practical importance for forest owners and the forest sector. The aim of this study was to characterize the decline and natural mortality of Norway spruce stands in two hemiboreal forest landscapes over a 40-year period. Data from five consecutive forest inventories were analysed to assess the cumulative impact of various factors on the stand mortality rate over the longer period.

2. Materials and Methods

2.1. Study Area

We obtained forest stand inventory data from two landscapes in different regions of Latvia: in the west near Vane and the east near Dviete, with areas of 3490.6 and 7190.1 ha, respectively. In both areas, the land is mainly used for forestry (Figure 1); detailed descriptions about the study areas are available in Table 1. In both areas, the climate is moist with moderate winters and is continental (although influenced by the proximity of the Baltic sea). The mean annual precipitation is 713 mm in Dviete and 650 mm in Vane. The temperature ranges from 16.9 °C in July to –3.6 °C in February with annual means of 5.9 °C in Dviete and 6.2 °C in Vane. The large-scale windthrow caused substantial forest damage in both landscapes on October 1967. The storms on November 1969 and January 2005 also caused a great damage. Another severe summer windstorm on August 2010 occurred in Dviete, that was followed by a spruce bud scale (*Physokermes piceae* Schrank.) outbreak in 2011.

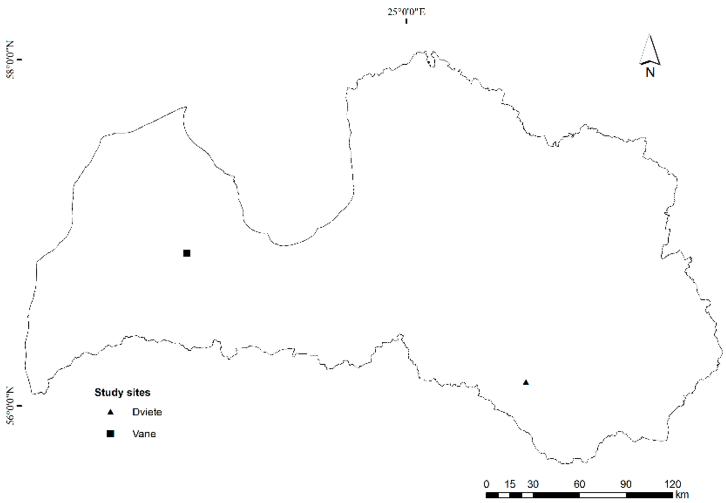

Figure 1. Location of the two study sites in Latvia.

Table 1. The characterization of forest massif by dominant species in 1975.

Landscape	Latitude	Longitude	Species	Area, ha	Area, %	Mean Annual Precipitation, mm	Mean Annual Temperature, °C
Vane	56°53′ N	22°38′ E	*Picea abies* ((L.) Karst.)	1307.1	37%	650	6.2
			Pinus sylvestris L.	784.2	22%		
			Non-forest	764.8	22%		
			Betula pendula Roth	513.7	15%		
			Populus tremula L.	101.0	3%		
			Alnus glutinosa (L.) Gaertn.	9.9	0%		
			Alnus incana (L.)	9.9	0%		
			Total area	**3490.5**			
Dviete	56°08′ N	26°15′ E	*Pinus sylvestris* L.	3086.3	43%	713	5.9
			Betula pendula Roth	1534.7	21%		
			Picea abies (L.) Karst.)	1404.0	20%		
			Non-forest	709.4	10%		
			Alnus glutinosa (L.) Gaertn.	420.9	6%		
			Populus tremula L.	26.1	0%		
			Alnus incana (L.)	8.0	0%		
			Total area	**7189.2**			

2.2. Data

The forest stand dynamics between 1975 and 2016 were based on stand-wise forest inventories since limited changes have been made in regulations concerning forest inventory (i.e., no changes in forest type classification and decision criteria for delineation of the new stand). The information (available in all inventories) about stand dominant tree species (according to basal area) and stand age were determined from forest inventories. The forest inventories for 1975, 1985 and 1999 were obtained from archives at the Latvian State Forest Research Institute. The archived forest plans were scanned and rectified to the LKS-92 coordinate system. The selected forested landscapes were digitized, and the boundaries of each stand were mapped in a GIS database using ArcGIS 10.2. Software (ESRI Inc., Redlands, CA, USA, 2014). Spatial data (polygon shapefiles) on forest stands digitized up to 2011 and 2016 were obtained from the State Forest Service.

Based on the spatial relationships between different forest inventories (1975, 1985, 1999, 2011 and 2016), we generated forest change maps for Norway spruce stands in Vane (Figure 2) and Dviete (Figure 3) landscapes. The maps consisted of the locations of Norway spruce stands in both landscapes. The map of 1975 was used as a base, and each stand was overlaid within exact boundaries for each of the studied periods. The Norway spruce stand dynamics over 40 years were analysed by dividing the stands into groups based on their age during each inventory. The first group "0" comprised stands with age zero, and there was a mark to denote clear-cut provided in the attribute table. Norway spruce was marked as the future planned species (in 1975, that meant mandatory regeneration). Whereas the second stand age group "1–10" comprised 1 to 10-year-old stands, the third group "11–20" comprised 11 to 20-year-old stands, and so on.

To reduce the offset of boundaries among studied periods (e.g., due to different rules for demarcation among forest inventories), we created core areas for each forest stand in each map. The core area represented the area of the stands as the distance (up to 15 m) from the stand perimeter. However, we could not obtain accurate data (such as area) of the dynamics of forest stand inventory over the observation period due to boundaries offsets.

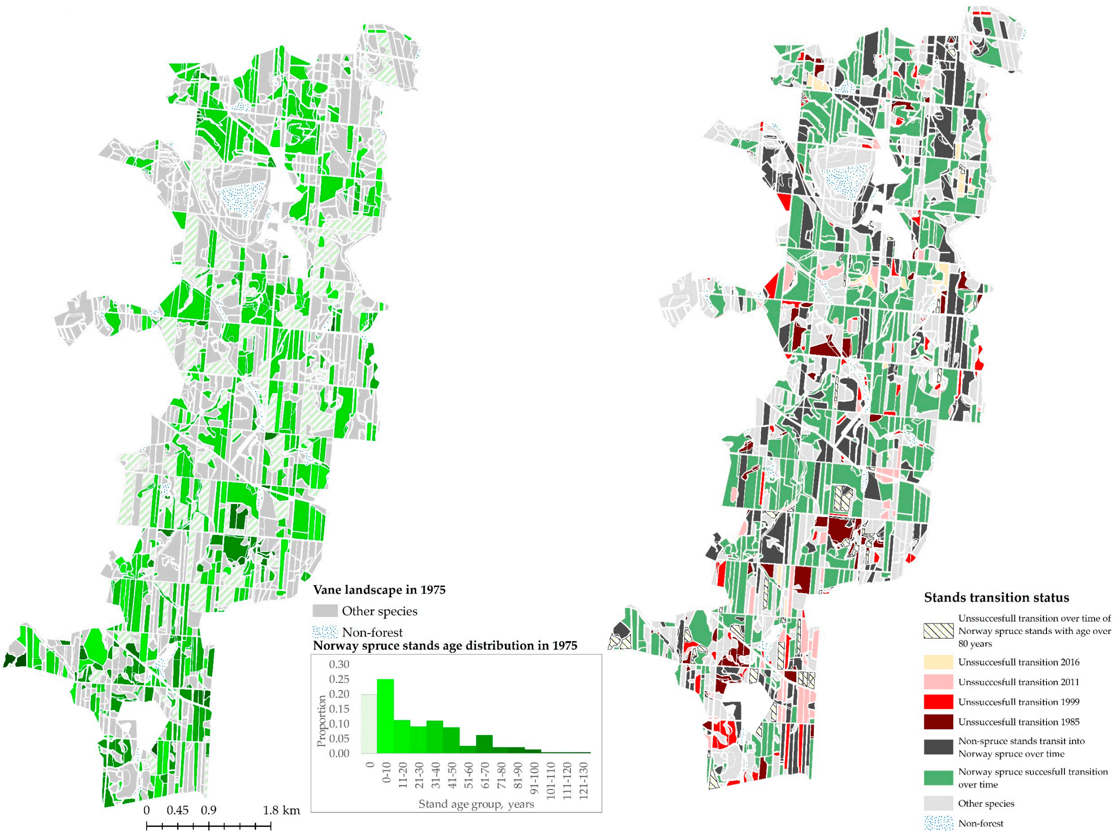

Figure 2. Norway spruce stands dynamics in Vane over 40 years (1975–2016).

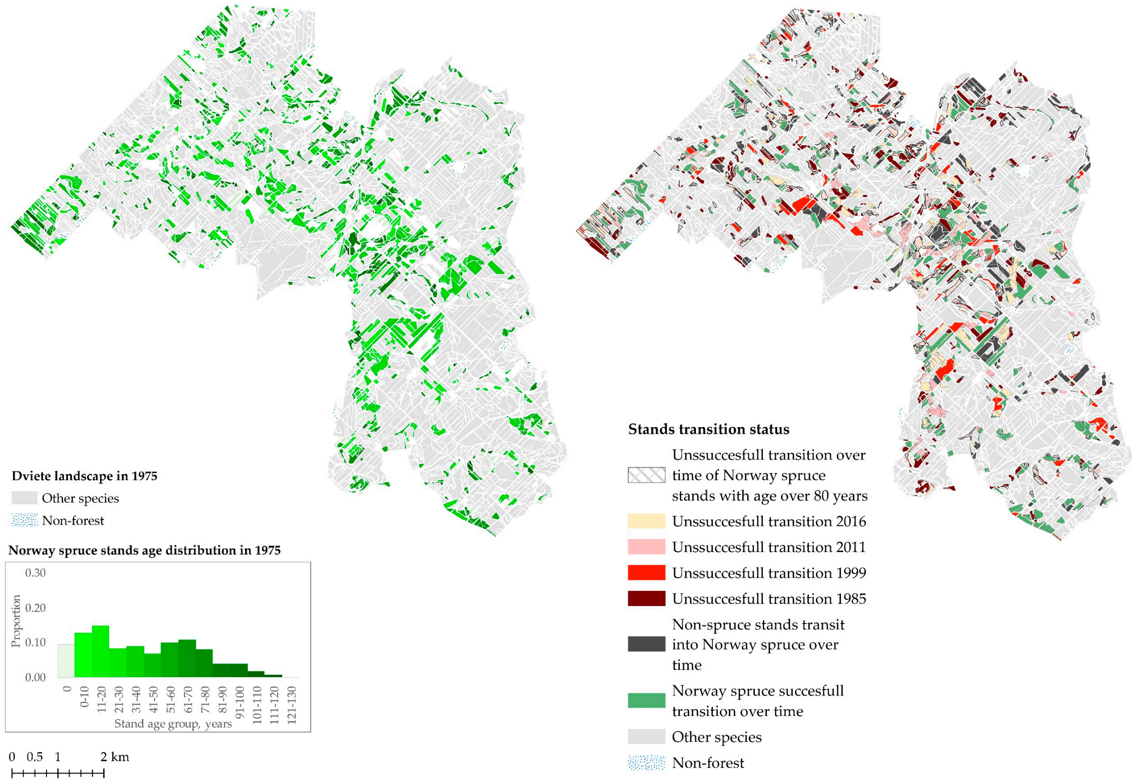

Figure 3. Norway spruce stand dynamics in Dviete over 40 years (1975–2016).

2.3. Data Analysis

To avoid possible bias in the characterization of the Norway spruce natural mortality due to the final harvest, we selected a subset of stands in which Norway spruce was the dominant tree species at the beginning of the observation period and Norway spruce stands up to and including the 71–80-year stand age group (at present, the final harvest of Norway spruce stands in Latvia is allowed if the trees have reached the age of 81). We assume that all mortality in stands younger than 81 years old was due to natural causes. The changes in the dominated species in the stand between maps were detected with the joins toolset in ArcGIS 10.2. [30]. Before joining, each stand was converted from a multipart feature to a single part feature. We added information about species and age to the actual map from the previous period.

We regarded stand mortality as a failure to transition from forest stand to the next age group and/or the stands that did not retain the same dominant species class. We determined the stands' status across selected periods from 1975 to 2016 for each forest stand. In the analysis, we included only Norway spruce stands of 1975 (non-spruce stands could not transition into spruce over the study period); thus, Norway spruce stands that once were declared as unsuccessfully transitioned stand were excluded from further analysis. We excluded from further analysis those stands in which there was a significant age discrepancy (greater than that between two inventories) between two subsequent forest inventories, thus indicating bias between forest inventories.

The change in stand status across different forest inventory times was determined. In our implementation, the variables were dominant tree species and stand age. In this approach, we analysed the dynamics of the percentage of the Norway spruce occupancy in the forest landscape and/or the changes in percentages of age-class distributions in the area that the Norway spruce occupied.

The percentage variation of Norway spruce stands as a response variable within age classes between forest inventories was tested using a binomial generalized linear mixed-effects model implemented in R 3.5.0 software (R Core Team 2018, Vienna, Austria). The age classes and forest inventories were used as predictor values in the model, while the stand identification was used as a random effect (if the stand appeared in subsequent forest inventories), and the spatial auto covariate was used to assess the spatial dependencies between independent variables (region, age-class and time of inventory).

3. Results

The total number of Norway spruce stands varied across studied areas and age groups from 1975 to 2016. Overall, in both landscapes, the total number of Norway spruce stands decreased over time (Figure 4). The greatest proportion of all stands in 1975 was up to 20 years old (56% of all stands in Vane and 37% in Dviete). The binomial generalized linear mixed-effects model indicated that the site ($p < 0.001$), age group, time of inventory and combination of characteristics ($p < 0.001$) significantly impacted the probability of stand transition into the next age group.

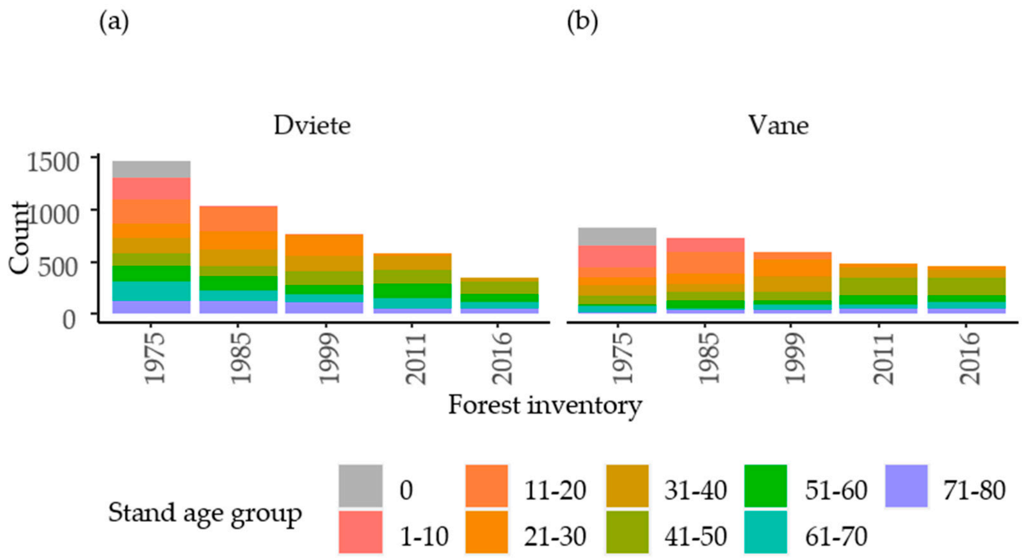

Figure 4. The dynamics of successfully transitioned Norway spruce stands (core areas) between inventories in two forested landscapes, Dviete (**a**) and Vane (**b**), respectively (only those stands that survived throughout the entire period are displayed).

The mean proportion of Norway spruce stands to survive to the next age group (i.e., not damaged or destroyed) over the first period from 1975 to 1985 was higher in the Vane site than in Dviete (93.1% and 76.5%, respectively). During the entire 40 years, the proportion of successfully transitioned stands between inventories remained high in Vane, reaching the highest 94.0% successfully transitioned stands for the period from 2011 to 2016. However, high decline and mortality of stands were observed in the Dviete site, where 50.7% Norway spruce stands did not survive between 2011 and 2016 forest inventories (Figure 5).

The highest decline and total mortality of Norway spruce stands were found in Dviete for each age group ($p < 0.001$). The distributions of the probability of stand transition presented in Figure 6 showed a relatively high proportions of successfully transitioned stands up to 30 years at both sites, whereas the slope of the continuous trend was highly different. With increasing age, from stand age groups 31–40 to 51–60, a relatively constant rate of successful transitioned stands remained in the Vane site, while a significant decrease in the proportions of survived stands was observed at the Dviete site for the same time. Subsequently, notable increase in the rates of decline and mortality were observed in Vane and Dviete from the age group 61–70 (Figure 6).

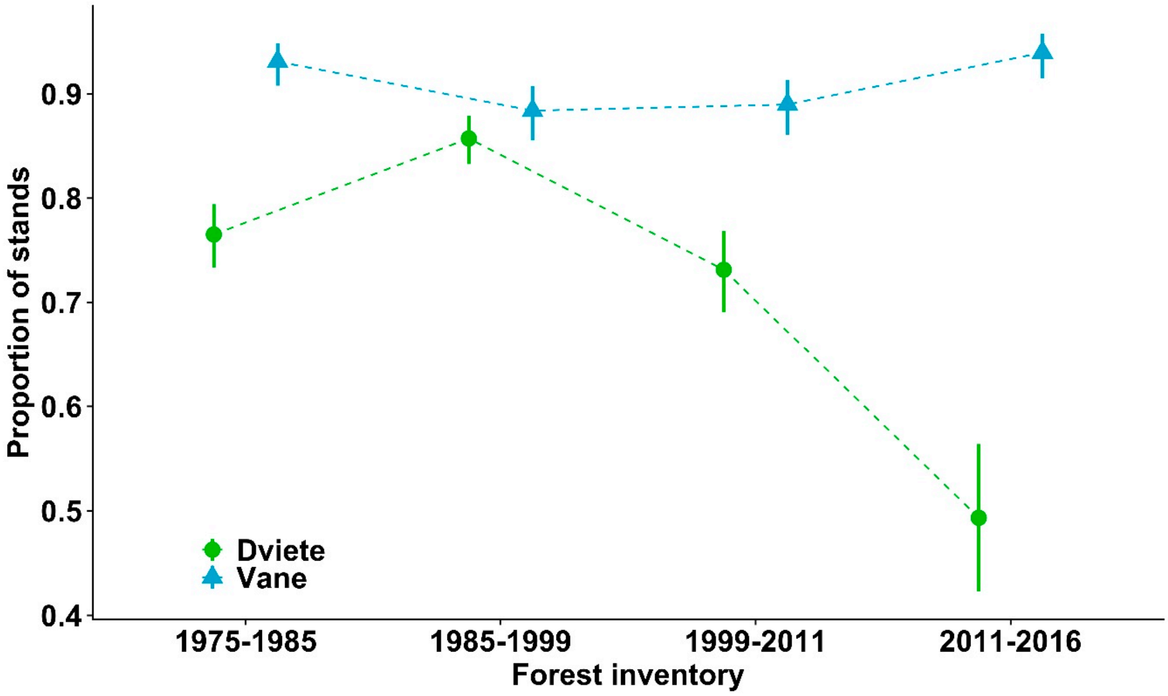

Figure 5. The transition of Norway spruce stands in two landscapes between two consecutive forest inventories (±95% confidence interval).

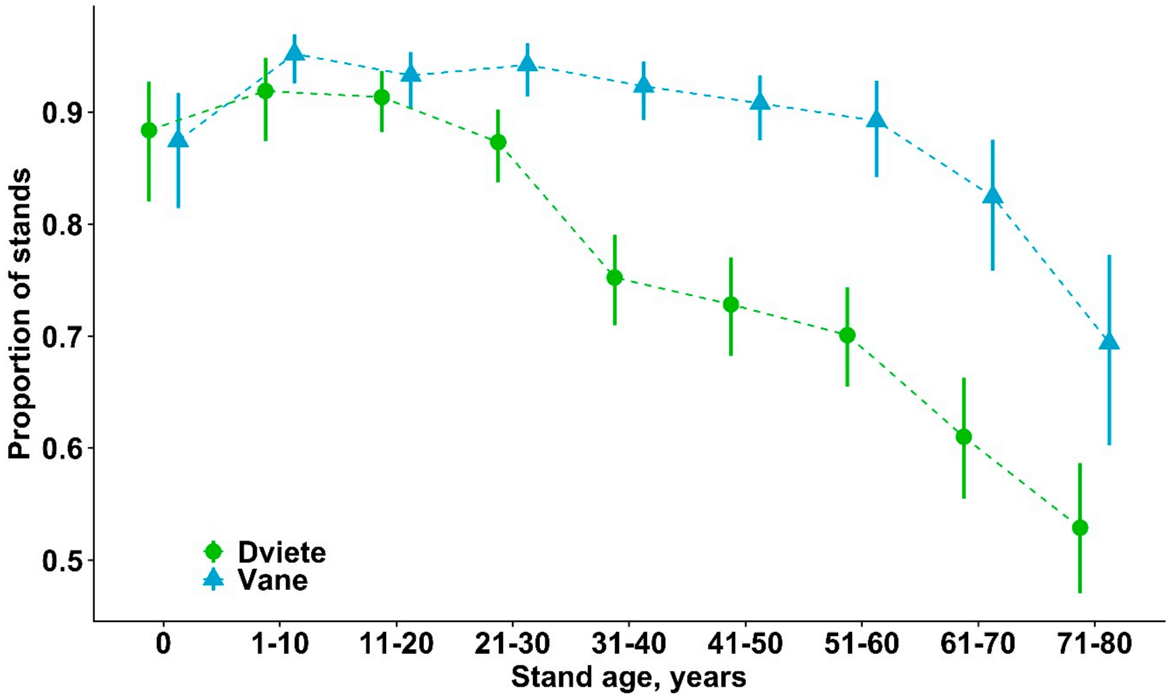

Figure 6. The site effect on the mean proportion of survival of Norway spruce stands between different age groups (±95% confidence interval).

The probability of the stand remaining alive as a Norway spruce dominated stand at the end of the observation period (in 2016) on average was higher in Vane than in Dviete for stands with ages at the beginning of the assessment period (1975) up to 50 years. A notable decline in survival for stands started after they exceeded the age of 30 years in Dviete and the age of 50 years in Vane. It was especially pronounced after the age of 70 years in both landscapes.

4. Discussion

The algorithms for forest modelling without a credible natural mortality function for long-term forecasts may be severely biased if assessed from forest inventory data [31,32]. For example, forest inventory data potentially describes forest structure very well but less so forest composition [33]. During the overlapping of the landscape maps, we encountered distortions due to stand boundary shifts between different inventories. In our study, the distortion of forest landscape composition was identified due to the different forest mapping regulations between inventory years. The increased precision of geodesic measurements and the development of remote sensing techniques have allowed for easy distinction of forest infrastructure objects, such as roads, ditches and cross-rides (in our study, these were distinguished starting in 2011), supporting the creation of more comprehensive maps. Another challenge may be linked to the stand age group "0" due to the different aspects of the forest inventory (see Section 2.2). The presence of senescent stand clear-felling due to its rotation period was ignored in this study, as we excluded stands over 80 years. Although we did not have data regarding the causes of these area losses, which thus precluded us from making inferences based on survey data, there are some important points of comparison with other studies.

Predictive models in the simulation of forest management options and tree mortality or tree species succession are based on a limited set of assumptions [4,34,35], and long-term stand mortality data across landscapes has been an underutilised component in forest models. If mortality is included in planning systems, the simulated stand development (growth and yield models) could be underestimated as the potential disturbance effect may introduce considerable variability even in small regions due to local site-specific features such as topography and differences in forest landscape composition [36–38]. This result was also shown in our study, in which we found regional differences in the severity of damages between Dviete and Vane due to the 1967 and 1969 storms, reflected by the higher number of young stands in the following forest inventory (see Figure 5).

The dynamics of forest landscapes can potentially be sensitive to different external and internal factors. The current forest conditions are a result of the complex interaction of forest management roles and species capability to regenerate after large-scale disturbances, e.g., suitability of a species to its natural (fundamental) ecological niche. The importance of the local environment and the potential impact of new disturbances on Norway spruce growth is determined by regional differences, even on such a small scale as Latvia. Species resilience to individual small-scale disturbance is another key factor that may affect total species distribution over a landscape. Over the 40 years assessed by this study, the Norway spruce was no longer the dominant tree species or had been damaged, on average, in over a quarter of Norway spruce stands. The decline and natural mortality of Norway spruce stands has been observed, on average, from 6.5% to 38.9% in each age group (Figure 6) during the investigation period within both landscapes. This observation could be explained by the fact that, within the period of a decade, new disturbance events may occur and that individual stands may be damaged in the landscape. For example, Hanewinkel et al. (2008) [39] reported substantial damage (insect outbreaks) risks for Norway spruce or spruce-dominated forests 2 to 6 years after windthrow. In our study, the stand-replacing wind disturbance event of 2010 (based on the State Forest Service data) might be a cause of rapid decline of Norway spruce stands from 1999 to 2011 for stand age groups 21–30 to 51–60. Moreover, this storm was followed by the outbreak of the spruce bud scale (*Physokermes piceae* Schrank.) in 2011 [38,40], resulting in substantial damages in the stands, reflected in Dviete data between 2011 and 2016. Rapid decline of stands in Dviete for the age groups 61–70 and 71–80 from 1975 to 1985 might be linked as secondary damages after large storms in the middle of the 1960s. This observation is consistent with previous studies, which reported that the probability of damaged stands to be affected by another disturbance is greater [41,42]. Although the lack of large disturbance events in Vane leads to two different age structures of Norway spruce stands than in Dviete, in Vane, the highest declines of successful transitioning of stands from 1985 to 1999 inventories was observed for the initial age groups 61–70 and 71–80, but from 1999 to 2011, inventories for the age group 51–60 might be linked to the final harvest (Figure 7). Another significant aspect is tree ingrowth, which, in the context of global climate change, may become more challenging in the future [43]. Another study in Latvia demonstrated the difficulty in replanting Norway spruce stands after mortality due to a drought that had occurred two years after planting in 2015 and continued into 2016 [44]. The present study confirms this upward trend (of persistent difficulties with Norway spruce stand regeneration, as suggested by the relatively high decline of stand age group 0 being 12% of stands, was found unsuccessfully regenerated in subsequent forest inventories. Very often, however, stands subjected to delayed silvicultural treatments experienced reduced growth due to the loss of competition with deciduous trees that rapidly filled in the gaps and dominated in subsequent years.

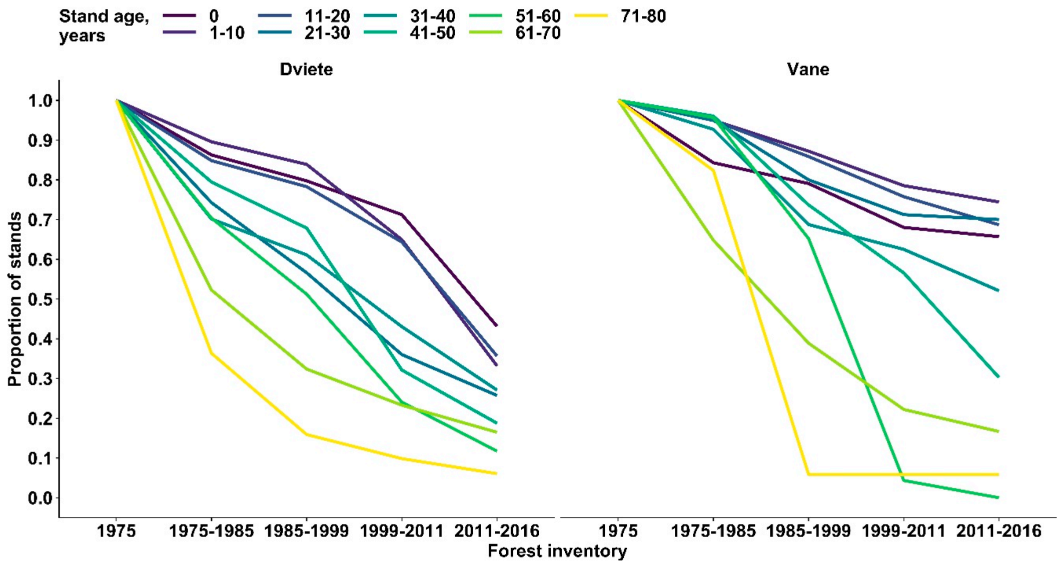

Figure 7. The proportion of successfully transitioned Norway spruce stands in both landscapes between observation periods by stand age group in 1975: In each forest inventory, the remaining part from the initial number of Norway spruce stands in a particular age group is shown.

The impacts of potential risks of the sudden destruction of Norway spruce stands by windthrow, epidemic pest infestation or other forces are largely determined by management decisions and actions such as planting (suitable environmental conditions, planting materials used and/or initial density), soil preparation, thinning, amelioration, clearing or other factors that span over long periods. In addition, the probability that stands will be damaged is higher when they reach a certain age and mean height [45,46]. Our study suggests a slight downward trend of stand survival starting from stand age group 31–40, with rapid decline in the 61–70 and 71–80 age groups. The decline of Norway spruce stands in age groups 0 to 11–20 (age at 1975) between 2011 and 2016 forest inventories (Figure 7) is in accordance with a previous study of spruce bud scale outbreak in 2011 [38], as they reported the greatest damage rate in 40- to 60-year-old Norway spruce stands. This rapid decline is consistent with previous studies that demonstrated the destruction of coniferous forests with increasing stand age [47]. Damages caused by fungi increases with age, especially compared to young and middle-aged stands [48,49]. This decline may also be explained by forest management decisions in the 1960s when the focus had changed to planting high-production Norway spruce monocultures [50,51]. Other studies suggest similar losses in Norway spruce productivity after the age of 45, and even mortality may be triggered by mismanaged silvicultural approaches, such as initially overstocked stands [29].

Optimal forest management decisions may increase the resistance and resilience of Norway spruce stands. However, in practice, treatments may not be feasible in maintaining main forest management strategies that require control over stand characteristics or otherwise may affect the risk levels to which the stands may become subjected [52]. Furthermore, the economic calculations of wind damage in Norway spruce stands indicate age as a major risk factor, thus encouraging the implementation of shorter rotation periods (50–60 years) in maintaining reasonable production and profitability [53] especially on high productivity soils and even in high wind risk zones [54,55]. Thus, forest owners have to be able to implement decisions that would be the best solution to reduce the potential ecological and economic losses. This indicates a need for legal regulations to cut down younger stands and not to wait until the age of 81 years at the end of the rotation period. For example, in Sweden, a study of the Norway spruce risks associated to climate change, such as major storms and their effects on the future of these stands, suggests that, if storms of Gudrun magnitude occurred once every fifth year, the expected land value would decrease by 20% with a 57-year rotation. In addition, they concluded that, if major windthrow affected Norway spruce stands once every fifth year, then almost no trees would reach the age of 87 years, while if storms occurred once every 20 years, then 60% of stand volume would be felled by a storm with an 87-year rotation cycle [56]. Still, both scenarios imply that Norway spruce would remain in the landscape as an admixture species. Although, uneven-aged management practices might be considered to gain some returns without clear-felling the stands, considering the negative effects (soil compaction, damage to remaining trees, etc.) [57] as the economic justification of such practice appears dubious.

5. Conclusions

The main finding of the dynamics of Norway spruce stands in two forested landscapes was a significant regional effect on the proportion of Norway spruce stands that survive between inventories as well as the strong variance between the age groups and combination of stand variables. Our findings suggest that the greatest decline and mortality in this study are associated with the negative effects of climate change. The windstorms and pest outbreaks as well as subsequent secondary damages resulted in a reduction in the total amount of Norway spruce stands in both landscapes. As expected, the Norway spruce stand survival rate decreased with stand age, indicating a downward trend starting from 31 years old, with very high decline of stands starting from 61 years old. Thus, we suggest that the consideration of optimized forest management decisions is needed to mitigate the Norway spruce decline and mortality in the near future. Although, the different outcomes of mortality patterns between both landscapes should be considered prior to maximize the harvesting.

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