LATVIJAS VALSTS MEŽZINĀTNES INSTITŪTS “SILAVA”
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LATVIJAS LAUKSAIMNIECĪBAS UNIVERSITĀTE
LATVIA UNIVERSITY OF LIFE SCIENCES AND TECHNOLOGIES

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PARASTĀS EGLES (*PICEA ABIES* (L.) H. KARST.) VĒJA NOTURĪBAS IZMAIŅAS SAKŅU TRUPES UN STUMBRA MIZAS BOJĀJUMU IETEKMĒ

THE EFFECT OF ROOT ROT AND BARK-STRIPPING ON WIND STABILITY OF NORWAY SPRUCE (*PICEA ABIES* (L.) H. KARST.)

PROMOCIJAS DARBS

Zinātniskā doktora grāda zinātnes doktors (*Ph.D.*) Lauksaimniecības un zivsaimniecības zinātnēs, mežzinātnē iegūšanai

DOCTORAL THESIS

for the doctoral degree Doctor of Science (Ph.D.) in Agriculture, Forestry and Fisheries

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Salaspils 2020

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The PhD thesis was prepared in Latvian State Forest Research Institute “Silava”. The PhD studies was carried out in Latvia University of Life Sciences and Technologies, Forestry Faculty in period from 2012 to 2015. Data collection was conducted in projects, carried out in Latvian State Forest Research Institute “Silava” and financed by JSC “Latvia’s State Forests” and ERDF. Preparation of the thesis was carried out in ERDF project “Birch and aspen stand management decision support tool for reduction of wind damages” (No. 1.1.1.1/18/A/134).

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ANOTĀCIJA

Klimata pārmaiņu dēļ parastās egles mežsaimnieciskais potenciāls Eiropā turpinās samazināties, izņemot Eiropā ziemeļu daļā, kur boreālo un hemiboreālo mežu zonā sagaidāms, ka arī nākotnē saglabāsies šai koku sugai piemēroti augšanas apstākļi. Tomēr arī šajās teritorijās egles audzēs ir sagaidāmi dabisko traucējumu izraisīti bojājumi. Egles audzes Latvijā saglabās savu līdzšinējo nozīmi tautsaimniecībā un oglekļa piesaistē, ja mežsaimniecības prakse tiks pielāgota dabisko traucējumu negatīvās ietekmes prevencijai un iespējamo seku mazināšanai. Informācija par dažādu dabisko traucējumu un to mijiedarbības ietekmi ir nozīmīga rekomendāciju izstrādei adaptācijai klimata pārmaiņām. Darba mērķis ir novērtēt biotisko traucējumu ietekmi uz vēja bojājumu iespējamību parastās egles audzēs.

Biotisko aģentu izraisītie bojājumi neatkarīgi no bojājuma apjoma īpatsvara un augsnes veida būtiski samazināja egļu noturību, kas galvenokārt ir atkarīga no stumbra tilpuma. Egles stumbra un sakņu-augsnes kamola morfometriskie parametri mežaudzēs ar nosusinātām kūdras augsnēm būtiski atšķīrās no mežaudzēm ar minerālaugsnēm.

Sakņu trupe izraisa statistiski būtisku un nozīmīgu parastās egles stabilitātes samazinājumu neatkarīgi no augsnes veida un mitruma, un sakņu-augsnes kamola tilpuma, līdzīgi ietekmējot kā primāro, tā sekundāro lūšanu.

Stumbra mizas bojājumiem nozīmīgāka ietekme bija uz augsnes-sakņu sasaisti, nevis stumbra koksnes mehānisko izturību, statistiski būtiski pazeminot slodzes, kas nepieciešamas kā koka primārajai, tā sekundārajai lūšanai. Izteiktāka ietekme konstatēta tieši uz primāro lūšanu. Tātad šādas audzes nākotnē, mainoties vēja klimatam un saglabājoties augstam briežu dzimtas dzīvnieku populāciju blīvumam, būs pastiprināti pakļautas bojāejai kā tiešā, atkārtotas vēja iedarbības, tā sekundāro faktoru ietekmē. Jau šobrīd konstatēts nozīmīgs egles audžu saglabāšanās kritums, kokiem sasniedzot trešo vecumklasi.

Mērķtiecīga mežkopība, nodrošinot atjaunošanu ar ģenētiski kvalitatīvu stādmateriālu, zemāku sākotnējo biezumu un savlaicīgu rekomendēto jaunaudžu kopšanu, nodrošinās iespēju ātrāk sasniegt mērķa caurmēru un līdz ar to nozīmīgi mazināt kumulatīvo bojājumu varbūtību egles audzēs, paaugstinot to monetāro un citu ekosistēmas pakalpojumu vērtību.

Šis promocijas darbs sastāv no tematiski vienotām piecām zinātniskām publikācijām.

ABSTRACT

Climate change causes gradual decline of economic value of Norway spruce forestry except in boreal and hemiboreal forest zones that will remain suitable for this tree species. However, also in this region frequency and scale of damages caused by natural disturbances (abiotic and biotic factors) are expected to increase. Norway spruce will remain its economic significance and role in carbon sequestration in Latvia, if forest management practices will be changed to prevent or minimize the damages caused by natural disturbances. Information on effect of natural disturbances and their interactions on trees is vital for development of recommendations for adaptation of forestry to climate change. The aim of the thesis is to assess the effect of root rot and bark-stripping on possibility of wind induced damages in Norway spruce stands.

Tree mechanical stability was primarily determined by its stem volume; however, the presence of damages, caused by biotic agents, such as root rot and bark-stripping, significantly reduced it. Morphometric parameters of Norway spruce stem and root plate differed significantly between stands on drained peat and mineral soils.

Root-rot notably and significantly affected mechanical stability of trees regardless of soil type and volume of root-soil plate, resulting in similar reduction of wind load necessary to cause both primary and secondary failure. Consequences of bark-stripping primarily affected root-soil anchorage, more commonly causing uprooting than stem fracture. Most pronounced was reduction of resistance against primary failure. Changing wind climate, high population density of cervids and presence of root-rot will lead to increased risk of damages caused by (repeated) storms and subsequent legacy effects. The survival of forest stands depends on dimensions of trees and exposure time to different damaging agents, and, at current climate and silvicultural practice, was significantly reduced when transitioning into third age class (41-60 years).

Targeted forestry, ensuring planting of improved material, lower initial density, timely precommercial thinning and thus ensuring faster reach of the tree dimension required for final harvest will reduce the time when stands are subjected to significant wind damage risk, thus minimizing the possibility of such disturbance and boosting value of Norway spruce stands.

SATURS / *CONTENT*

PUBLIKĀCIJU SARAKSTS / *LIST OF PUBLICATIONS*

Promocijas darba rezultāti ir apkopoti piecās publikācijās.

The results of thesis are compiled in five publications.

I **Krisans O**., Saleniece R., Rust S., Elferts D., Kapostins R, Jansons A., Matisons R. (2020) Effect of bark-stripping on mechanical stability of Norway spruce. Forests, 11(3), 357; doi:10.3390/f11030357

II **Krisans O**., Matisons R., Rust S., Burnevica N., Bruna L., Elferts D., Kalvane L., Jansons A. (2020) Presence of root rot reduces stability of Norway spruce (Picea abies): results of static pulling tests in Latvia. Forests, 11(4), 416; doi:10.3390/f11040416

III **Krišāns O**., Samariks V., Matisons R., Jansons Ā. (2020) Model of above-ground biomass distribution of Norway spruce (Picea abies L. (Karst.)). BioResources, 15(2), 4314-4322

IV Bāders E., **Krišāns O.**, Donis J., Elferts D., Jaunslaviete I., Jansons Ā. (2020) Norway Spruce Survival Rate in Two Forested Landscapes, 1975–2016. Forests, 11(7), 745; doi.org/10.3390/f11070745

V **Krišāns O.,** Samariks V., Donis J., Jansons Ā. (2020). Structural Root-Plate Characteristics of Wind-Thrown Norway Spruce in Hemiboreal Forests of Latvia. Forests, 11(11), 1143; doi.org/10.3390/f11111143

AUTORA IEGULDĪJUMS PUBLIKĀCIJĀS / *THE CONTRIBUTION OF THE AUTHOR*

Publikācijas nosaukums / *Title of the publication*	Autora ieguldījums, % / *Contribution of the author, %*
Krisans O., Saleniece R., Rust S., Elferts D., Kapostins R, Jansons A., Matisons R. (2020) Effect of bark-stripping on mechanical stability of Norway spruce. Forests, 11(3), 357; doi:10.3390/f11030357	70 %
Krisans O., Matisons R., Rust S., Burnevica N., Bruna L., Elferts D., Kalvane L., Jansons A. (2020) Presence of root rot reduces stability of Norway spruce (Picea abies): results of static pulling tests in Latvia. Forests, 11(4), 416; doi:10.3390/f11040416	75 %
Krišāns O., Samariks V., Matisons R., Jansons Ā. (2020) Model of above-ground biomass distribution of Norway spruce (Picea abies L. (Karst.)). BioResources, 15(2), 4314-4322	55 %
Bāders E., **Krišāns O**., Donis J., Elferts D., Jaunslaviete I., Jansons Ā. (2020) Norway Spruce Survival Rate in Two Forested Landscapes, 1975–2016. Forests, 11(7), 745; doi.org/10.3390/f11070745	55 %
Krišāns, O., Samariks, V., Donis, J., Jansons, Ā. (2020). Structural Root-Plate Characteristics of Wind-Thrown Norway Spruce in Hemiboreal Forests of Latvia. Forests, 11(11), 1143; doi.org/10.3390/f11111143	55 %

SAĪSINĀJUMI / *ABBREVIATIONS*

BBM – lieces moments stumbra pamatnē / *basal bending moment*
BBM$_{PF}$ – lieces moments stumbra pamatnē pie primārās lūšanas / *basal bending moment at primary failure*
BBM$_{SF}$ – lieces moments stumbra pamatnē pie sekundārās lūšanas / *basal bending moment at secondary failure*
DBH – stumbra diametrs krūšu augstumā / *stem diameter at breast height*
Dm – damaksnis / *Hylocomiosa forest type*
EEA – Eiropas Vides aģentūra / *European Environmental Agency*
ERAF – Eiropas Reģionālās attīstības fonds / *European Regional Development Fund*
H – koka kopējais augstums / *tree total height*
H/DBH – koka augstuma un caurmēra krūšu augstumā attiecība / *the relation of tree height and diameter at breast height*
HDBH^2 – koka augstuma un caurmēra krūšu augstumā kvadrāta reizinājums / *tree height was multiplied by diameter at breast height squared*
H$_{mp}$ – koka masas centrs / *height of tree mass point*
Ks – šaurlapju kūdrenis / *Myrtillosa turf.mel. forest type*
Kp – platlapju kūdrenis / *Oxalidosa turf. mel. forest type*
LVĢMC – Latvijas Vides, ģeoloģijas un meteoroloģijas centrs / *Latvian Environment, Geology and Meteorology Centre*
NMM – Nacionālais meža monitorings / *National forest inventory*
PF – primārā lūšana / *primary failure*
SF – sekundārā lūšana / *secondary failure*
UNECE – Apvienoto Nāciju Organizācijas Eiropas Ekonomikas komisija / *United Nations Economic Commission for Europe*

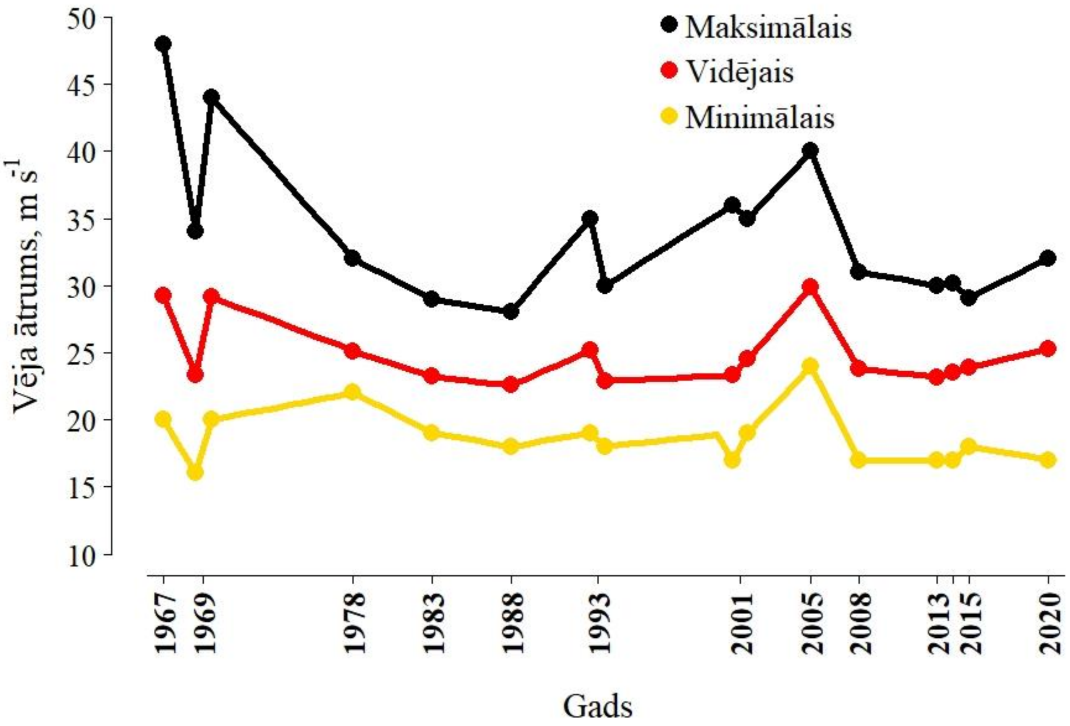
1. IEVADS

Parastās egles (turpmāk – egles) nākotnes mežsaimnieciskā nozīme pēdējo desmitgažu laikā rietumu un centrālajā Eiropā ir pakāpeniski samazinājusies līdz ar klimata pārmaiņu izraisīto augšanas apstākļu pasliktināšanos (Yousefpour et al., 2010; Hanewinkel et al., 2013; Cermák et al., 2019). Prognozēts, ka eglei piemēroti augšanas apstākļi Eiropā saglabāsies tās ziemeļu daļā—boreālo un hemiboreālo mežu zonā (Hickler et al., 2012; Suvanto et al., 2016; Kapeller et al., 2017; Marini et al., 2017). Tomēr arī šajās teritorijās nav izslēgta dabisko traucējumu negatīvā ietekme uz egļu nākotnes audzēm, un jau šobrīd ir vērojama vēja, patogēnu un dendrofāgo kukaiņu izraisītu bojājumu atkārtošanās biežuma un bojājumu apjoma palielināšanās (Marini et al., 2017), jo īpaši, vecākās audzēs ar bojātiem vai novājinātiem kokiem (Jakuš et al., 2011). Ņemot vērā egļu audžu augsto ražību (Pretzsch et al., 2014) un līdz ar to ievērojamo lomu ekonomikā un oglekļa piesaistē (Ķēniņa et al., 2018), egles audzēšana Latvijā saglabās savu līdzšinējo nozīmi, ja mežsaimnieciskā prakse tiks pielāgota dabisko traucējumu negatīvo ietekmju prevencijai un iespējamo seku mazināšanai.

1.1. Potenciāli bīstama vēja atkārtošanās

Vējš ir nozīmīgākais dabiskais traucējums gan Latvijas, gan Eiropas mežos (Gardiner et al., 2013), kur divi galvenie potenciāli bīstama vēja izcelsmes veidi ir pērkona negaisi un vidējo platumu grādu cikloni (turpmāk – cikloni) (EEA, 2017; Taszarek et al., 2019;). Lai arī abu dabas parādību laikā vēja ātrums (vidējais 10 minūtēs, m s^{-1}) var sasniegt vismaz vētras spēku (pēc Boforta skalas 20,8 m s^{-1} (Barua, 2005)), dažkārt mežaudžu bojājumi veidojas jau ļoti stiprā vējā (pēc Boforta skalas 13,9 – 17,1 m s^{-1} (Barua, 2005)), jo vēja ātrums brāzmas nereti var būt par 10 m s^{-1} lielāks nekā vidējais vēja ātrums (Sheridan, 2011). Pērkona negaisu laikā var izveidoties ļoti spēcīgas un intensīvas lejupejošas gaisa plūsmas vai pat virpuļviesuļi, bet tie ir lokāli nozīmīgi, un to izveidošanos un pārvietošanos, tādējādi arī potenciālos postījumus, ir sarežģīti paredzēt (Schoen & Ashley, 2011). Pērkona negaisi nav novērojami platībās, kas lielākas par dažiem kvadrātkilometriem, tomēr skartās kokaudzes var tikt pilnībā iznīcinātas (Nagel et al., 2007, 2017). Lai arī pērkona negaisi ir ļoti lokāli un to sezona ir īsa, tomēr ir sagaidāms, ka to atkārtošanās biežums un intensitāte palielināsies (Rädler et al., 2019).

Nozīmīgākie mežaudžu vēja bojājumi gan Latvijā, gan Eiropā rodas rudens-ziemas sezonas ciklonos, kas skar daudz plašākas teritorijas nekā pērkona negaisi (vairāki tūkstoši km^2), un nereti tie nes līdzi lietusgāzes vai snigšanu (Stewart, 1985; Gardiner et al., 2013; Gregow et al., 2017). Nozīmīgākie ir Ziemeļatlantijas izcelsmes cikloni, kuru spēcīgākā ietekme ir vērojama Eiropas rietumu daļā, bet, virzoties dziļāk kontinentā, to spēks mazinās (Dravniece, 2007). Kopš 1871. gada Eiropā diennakts maksimālajam vēja ātrumam un vidējam gada vētraino dienu skaitam ir novērota tendence palielināties (Donat et al., 2011; Gardiner et al., 2013), un, sākot ar 1950. gadu, Eiropā ir fiksēti vairāk nekā 130 gadījumi ar 10 minūšu vidējo vēja ātrumu, kas sasniedz vētras spēku—20,8 m s^{-1} (Barua, 2005; Donat et al., 2011; Gregow et al., 2017). Lai arī šo ciklonu darbība ir bijusi lielākoties virs Britu salām, Ziemeļjūras dienvidu piekrastes un Fenoskandijas, nereti to pārvietošanās trajektorijas ir skārušas arī Latvijas teritoriju, un novērojumi liecina, ka arvien biežāk šīs atmosfēras sistēmas pārvietojas Eiropas kontinentālajā daļā, arī Baltijas valstīs (Gardiner et al., 2013). Pēdējo 60 gadu laikā stipra vēja gadījumu atkārtošanās biežums nav pārsniedzis 10 gadus (1.1. att.) (LVĢMC, 2020).

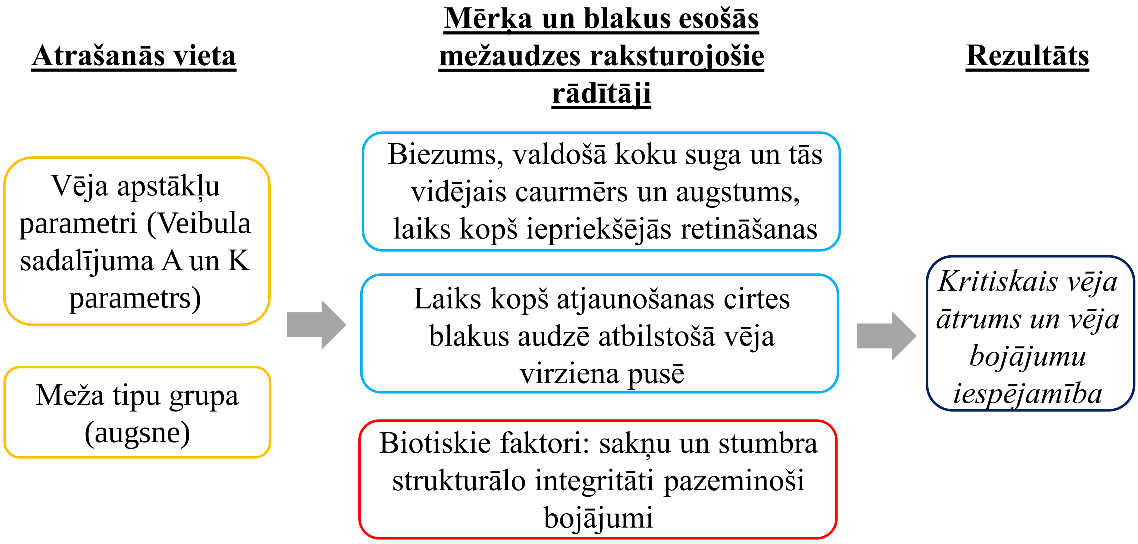


1.1. att. **Stipra vēja gadījumi Latvijā** (LVĢMC, 2020)
Līnijas attēlo minimālo (dzeltena), vidējo (sarkana) un maksimālo (melna) vēja ātrumu brāzmās, kas fiksēts katrā atsevišķajā vismaz stipra vēja gadījumā (LVĢMC, 2020)

1.2. Vēja izraisītie mežaudžu bojājumi

Cikloni spēj izraisīt būtiskus mežaudžu bojājumus arī Centrāleiropā un Ziemeļaustrumu Eiropā, un nereti viena gadījuma ietvaros kopējie mežaudžu bojājumi var sasniegt vairākus desmitus miljonu kubikmetrus koksnes (Gardiner et al., 2013). Vēja bojāto mežaudžu apjoms Eiropā ir pieaudzis, palielinoties kopējai krājai kopš Otrā pasaules kara beigām (UNECE, 2011). Aprēķināts, ka šobrīd Eiropā ir augstākā krāja kopš agrajiem viduslaikiem (UNECE, 2011; Nabuurs et al., 2013; EEA, 2017;), un lielu īpatsvaru veido vecas, pāraugušas mežaudzes, kuras ir potenciāli vairāk pakļautas dabiskajiem traucējumiem (Nabuurs et al., 2013). Pēdējo 20 gadu laikā Eiropā ir fiksēti vairāk nekā 89 tūkst. ziņojumu par mežaudžu bojājumiem, kopumā aptuveni vienu miljonu hektāru lielā platībā, un seši postošākie cikloni radīja mežaudžu bojājumus vairāk nekā 340 miljonu m^3 apjomā (Forzieri et al., 2020). Arī Latvijā ir vērojams mežaudžu krājas un bojājumu apjoma pieaugums, jo īpaši, palielinoties briestaudžu un ciršanas vecumu pārsniegušu audžu īpatsvaram (NMM, 2019). Latvijā pēdējo desmit gadu laikā novērtētais egļu audžu krājas pieaugums ir lielāks par 16 milj. m^3, bet platība palielinājusies par vairāk nekā 54 tūkst. ha (NMM, 2019). Savukārt vēja un dzīvnieku bojāto egļu audžu platības apjoms ir palielinājies attiecīgi par vairāk nekā 61 un 75 tūkst. ha (NMM, 2019; Šņepsts et al., 2018).

Jebkuras mežaudzes kritiskā vēja slodze (*critical wind load*), kas atbilst kritiskajam vēja ātrumam (*critical wind speed*), ir aprēķināma kā maksimālais lieces moments stumbra pamatnē, kā rezultātā iestājas neatgriezenisks bojājums (stumbra lūzums vai izgāšanās ar saknēm)—sekundārā lūšana (Detter et al., 2019; Peltola, 2006). Vēja ietekme nav statisks (punktveida) notikums, bet gan daudzas cita citai sekojošas brāzmas (Sheridan, 2011). Turbulences rezultātā vēja virziens un ātrums ir mainīgs, radot dinamisku slodzi, un tās izraisītu bojājumu summā reālais kritiskais vēja ātrums var būt zemāks. Nozīmīgi mežaudžu vēja bojājumi var veidoties pie 25 m s^{-1} liela vēja ātruma brāzmās (Spatz & Speck, 2000; Cullen, 2002; James et al., 2006). Mežaudzēm kritisko vēja ātrumu ietekmē meža ainavas reljefs un mežaudžu vainagu klāja virsmas nelīdzenumi, augsnes apstākļi, konkrētās, t.s. mērķa audzes, un blakus esošo kokaudžu morfometriskie parametri un saimniecisko darbību vēsture, kā arī biotisko traucējumu klātbūtne (Gardiner et al., 2013) (1.2. att.).



1.2. att. **Konceptuālā mežaudžu vēja noturības novērtēšanas shēma** (ERAF, 2019)

1.3. Sagaidāmo vēja izraisīto mežaudžu bojājumu novērtēšana

Sagaidāmo mežaudžu bojājumu apjomu un telpisko izvietojumu ir iespējams raksturot, analizējot meteoroloģisko novērojumu un prognožu datus (faktisko vēja ātrumu brāzmās, augsnes sasaluma dziļumu un mitrumu, sniega vai sasalstoša lietus masu koku vainagos u.c.), kā arī informāciju par meža tipu grupu un mērķa un blakus esošās mežaudzes raksturojošajiem rādītājiem. Tādējādi ir iespējams veikt paredzamo bojājumu seku mazināšanas vai novēršanas vairāku līmeņu plānošanu—operatīvo, taktisko un stratēģisko. Operatīvajā plānošanā, izmantojot meteoroloģisko novērojumu faktisko informāciju un mērķa un tai blakus esošo mežaudžu raksturojošo informāciju (meža tipu grupa un kokaudzes rādītāji), ir iespējams noteikt bojājumu vietas un apjomu seku novēršanas darbu organizēšanai. Taktiskajā plānošanā, izmantojot meteoroloģisko parametru vidējos rādītājus un to pašu mežaudžu informāciju, ko operatīvajā plānošanā, var pielāgot esošo mežaudžu apsaimniekošanas pasākumus atbilstoši sagaidāmajiem vēja bojājumu riskiem. Savukārt stratēģiskajā plānošanā papildus informācijai, ko izmanto taktiskajā plānošanā, izmanto datus no augšanas gaitas modeļiem, kas raksturo mērķa un blakus esošo mežaudžu parametru izmaiņu dinamikas prognozes (ERAF, 2019).

1.4. Mežaudžu vēja noturību ietekmējošie faktori

Vēja noturības raksturošana dažādvecuma mistraudzēs ir ļoti komplicēta, un to šobrīd nav iespējams veikt ar esošajiem vēja bojājumu modelēšanas rīkiem. Vienvecuma audzēs nozīmīgākie koku noturību ietekmējošie taksācijas rādītāji ir valdošā suga, audzes biezums (un laiks kopš iepriekšējās retināšanas), koku vidējais augstums un caurmērs (Donis et al., 2018). Visi šie rādītāji ietekmē vēja noturību gan tieši – koki ar lielāku augstumu vairāk pakļauti vēja ietekmei, koki ar lielāku caurmēru noturīgāki – gan mijiedarbojoties. Piemēram, augstāks audzes biezums palielina koku augstuma/caurmēra attiecību un sakņu konkurenci, kas savukārt samazina to individuālo vēja noturību (Gardiner et al., 2013). Lielākā daļa Latvijas egles audžu (88,8%, NMM, 2019) ir augstāko bonitāšu (Ia, I, II). Šo bonitāšu audzes otrajā-trešajā vecumklasē sasniedz tādu vidējo augstumu, ka tās var nozīmīgi ietekmēt vējš (Peltola et al., 2010). Vidējais egles audžu caurmērs ir 21,5 cm, un tas atbilst vidējam caurmēram trešās vecumklases sākumā (21,9 cm) (NMM, 2019).

Parastās egles vēja noturības novērtējumā tās virszemes daļas biomasas sadalījuma un sakņu morfometrisko parametru dati ļauj raksturot augšanas apstākļu ietekmi uz koku stabilitātes nodrošināšanas iespējām (Cucchi et al., 2005; Nicoll et al., 2006). Līdzšinējos pētījumos par koku biomasu galvenokārt raksturota kopējā masa sausā stāvoklī, taču vēja ietekmes analīzei un modelēšanai nepieciešami dati par biomasas sadalījumu atkarībā no koka augstuma dabiski mitrai koksnei (Marklund, 1988; Repola, 2009; Lībiete et al., 2017; Kenina et al., 2018). Biomasas sadalījums nosaka gravitācijas spēka ietekmi uz kritisko vēja slodzi, to pazeminot līdz ar koka masas punkta paaugstināšanos, un otrādi (Gardiner et al., 2013). Koka noturību augsnē nosaka sakņu-augsnes sasaiste (*root-soil anchorage*) (Grime, 2001), kuru var raksturot ar sakņu-augsnes kamola morfometriskajiem parametriem (Nicoll et al., 2006; Štofko & Kodrík, 2008). Abi šie rādītāji—virszemes biomasas sadalījums un sakņu-augsnes kamola dimensijas – var atšķirties dažādos augšņu veidos, tomēr informācija par to ietekmes atšķirībām uz mežaudžu vēja noturību audzēs ar kūdras un minerālaugsnēm ir nepietiekama.

Koku sakņu sistēmas veic pielāgošanos augsnes mehāniskajām īpašībām, attīstot spēcīgākas stabilizējošās saknes pastāvīgu svārstību ietekmē (Coutts, 1986; Dumroese et al., 2019). Augstāka sakņu-augsnes sasaiste ir sausās minerālaugsnēs uz morēnas un māla cilmiežiem ar dziļu vidējo gruntsūdens līmeni, kā rezultātā kokiem attīstās dziļa sakņu sistēma (Štofko, 2010). Savukārt zemāka sakņu-augsnes sasaiste veidojas irdenās minerālaugsnēs, piemēram, uz grants-smilts cilmiežiem, bet jo īpaši – kūdras augsnēs (Štofko, 2010), lai arī sakņu sistēma šādās augsnēs attīstīta lielāku projekcijas laukumu un spēcīgākas stabilizējošās saknes (Coutts, 1986; Dumroese et al., 2019). Baltijas jūras reģionā ir plaši izplatītas mežaudzes ar kūdras augsnēm, starp kurām jo īpaši produktīvas ir egļu audzes, un to lielā saimnieciskā nozīme nosaka nepieciešamību veikt šādu mežaudžu vēja noturības novērtējumu (Päivänen un Hånell, 2012; Pretzsch et al., 2014). Latvijā īpaši augstražīgas egļu audzes sastopamas meža tipos ar kūdras augsnēm – šaurlapju un platlapju kūdreņos (Bušs, 1976). Pēc Nacionālā meža monitoringa datiem laika posmā no 2008. līdz 2019. gadam egļu audžu kopplatība un krāja šajos meža tipos ir palielinājusies attiecīgi par 1,78 tūkst. ha un 0,86 milj. m^3 (NMM, 2019).

Sakņu-augsnes sasaiste būtiski samazinās, paaugstinoties augsnes mitrumam, kas veicina sakņu izslīdēšanu koka stumbra kustību laikā (Mickovski, 2002). Rudens-ziemas sezonas ciklonu laikā paaugstināta nokrišņu apjoma un nesasalušas augsnes apstākļos vēja izraisītie mežaudžu bojājumi ievērojami palielinās, kā, piemēram, triju postošāko vētru pēdējo 60 gadu laikā gadījumā — 1967., 1969. un 2005. gadā (LVĢMC, 2020). Nākotnē sagaidāmo mežaudžu vēja bojājumu risku paaugstinošs faktors ir prognozētā augsnes sasaluma perioda saīsināšanās siltāku ziemu apstākļos hemiboreālo un boreālo mežu zonā, neizveidojoties pietiekamam augsnes sasalumam sakņu-augsnes sasaistes nodrošināšanai (Laapas et al., 2019). Tomēr līdz šim trūkst informācijas par egles sakņu-augsnes sasaisti kūdras augsnēs un biotisko traucējumu ietekmi uz to.

1.5. Biotisko faktoru ietekme

Viens no būtiskākajiem biotiskajiem traucējumiem egļu audzēs, kura izplatībai turklāt vērojama palielināšanās, ir patogēnu izraisītie koksnes strukturālie bojājumi (Piri, 1996; Bendz-Hellgren et al., 1999; Arhipova et al., 2011; Honkaniemi et al., 2017), kam par cēloni var būt gan saimnieciskā darbība (Piri & Korhonen, 2008; Metslaid et al., 2018), gan pārnadžu izraisītie stumbra mizas bojājumi (Šņepsts et al., 2018; Burneviča et al., 2016). Piemēram, asinssarkanā sīkpiepe (*Stereum sanguinolentum*) (Roll-Hansen & Roll-Hansen, 1980; McLaughlin & Šica, 1996; Vasiliauskas et al., 1996; Čermák & Strejček, 2007), kas bieži attīstās pārnadžu izraisīto mizas bojājumu vietās, var sasniegt vertikālās izplatības ātrumu koksnē no 9,6 līdz 19,5 cm gadā un līdz 6 m augstumu no bojājuma vietas (Čermák & Strejček, 2007; Vacek et al., 2020). Šādu strauji progresējošu patogēnu attīstība kavē koku atveseļošanos pēc mehāniska bojājuma —bojājumu perifēriju nostiprināšanu ar reakcijas koksni un brūču aizaudzēšanu, un līdz ar to arī kopējo augšanu (Vacek et al., 2020), tādējādi pazeminot koku individuālo stabilitāti (*individual stability*) salīdzinājumā ar mežaudzē nebojātajiem kokiem. Savukārt egļu inficēšanās ar vienu no izplatītākajiem sakņu trupi izraisošajiem patogēniem – sakņu piepi (*Heterobasidion spp.*)–audzēm kūdras augsnēs ir vidēji 16,3% (Bruna et al., 2018), un šī patogēna izplatības ātrums egles mežaudzēs saknēs var sasniegt vidēji 24 cm gadā (Bendz-Hellgren et al., 1999). Šis ir īpaši nozīmīgs biotiskais faktors ar augstu negatīvo saimniecisko ietekmi, kas samazina ne tikai mežaudžu vēja noturību un vitalitāti (Gori et al., 2013), bet arī potenciālo egles sortimentu kvalitāti. Piemēram, jau 41 gadu vecās egles mežaudzēs ar kūdras augsnēm sakņu piepes izplatība stumbrā var pārsniegt 4 m augstumu un līdz rotācijas perioda beigām var izraisīt pilnīgu mežaudzes bojāeju (Bruna et al., 2018). Tomēr trūkst kvantitatīvu datu par saimnieciskās darbības vai pārnadžu izraisītu stumbra mizas bojājumu vietās notikušas patogēnu izplatības rezultātā radušos koksnes strukturālo bojājumu ietekmi uz egles vēja noturību. Šo ietekmi nepieciešams novērtēt, jo šāda informācija ir būtiska klimata pārmaiņu ietekmes uz saimnieciskajiem mežiem matemātiskai modelēšanai (Honkaniemi et al., 2018).

1.6. Mežaudžu vēja noturības novērtēšana

Līdz ar jau novērotā vēja bojājumu apjoma un augsnes mitruma deficīta (ilgstošu sausuma periodu) (Ruosteenoja et al., 2018) atkārtošanās biežuma palielināšanos pieaug arī dendrofāgo kukaiņu skarto egles mežaudžu apjoms gan Latvijā, gan citviet Eiropā (Jakuš et al., 2011; Marini et al., 2017). Šādu negatīvo ietekmju prevencijai ir nepieciešama informācija par vēja bojājumu izveidošanos paaugstinošajiem riska faktoriem. Šis promocijas darbs raksturo biotisko traucējumu izraisītas koksnes strukturālās integritātes samazinājuma ietekmi uz egļu audžu vēja noturību.

Vēja slodzes ietekmē, koka stumbram liecoties, var veidoties koksnes audu kompresijas deformācija—vadaudu, eglei—traheīdu, samezglošanās (Detter et al., 2015). Ir novērots, ka sākotnēji stumbra saliekšanās notiek proporcionāli liekšanas spēkam, bet brīdī, kad veidojas koksnes audu spiedes deformācija, saliekšanās palielinās disproporcionāli šim spēkam. Tādējādi tiek sasniegts koka stumbra mehāniskās noturības punkts, kas apzīmējams kā primārā lūšana (*primary failure*) (PF) (Detter et al., 2015). Koks pēc šāda bojājuma ir spējīgs atjaunot savas sākotnējās noturības līmeni, tomēr kādu laiku tā vitalitāte un stabilitāte būs pazemināta. Ja pēc primārās lūšanas ārēja spēka pielikšana turpinās, seko sekundārā lūšana (*secondary failure*) (SF), kas ir pilnīga nolūšana vai izgāšanās ar saknēm (Detter & Rust, 2013). Primārā lūšana var notikt gan stumbrā, gan saknēs. Spēcīga sakņu-augsnes sasaiste notur koka pamatni nekustīgu, primārajai lūšanai notiekot stumbrā, bet pazeminātas sakņu noturības rezultātā bojājums var rasties sakņu projekcijas aizvēja pusē (Detter et al., 2015). Atjaunošanās no primārās lūšanas bojājuma ir iespējama, taču ne vienmēr pilnīga, un tam ir nepieciešamas vairākas augšanas sezonas (Detter et al., 2019); nepilnīga atjaunošanās pēc šādas koksnes deformācijas apgrūtina koka sulas plūsmu (Detter et al., 2015). Tā rezultātā bojātie koki var tikt pakļauti fizioloģiskajam sausumam (Ieviņš, 2016). Dabisko traucējumu savstarpējo ietekmju mijiedarbībā, kad viena traucējuma novājināta audze ir uzņēmīgāka pret nākamo traucējumu, pazeminās līdz šim produktīvu mežaudžu noturība arī pret sekundārajiem biotiskajiem traucējumiem, galvenokārt dendrofāgo kukaiņu savairošanos (Jakuš et al., 2011; Marini et al., 2017), jo īpaši – pēc vētrām vai ilgstošiem sausuma periodiem, nereti izraisot plašu egles mežaudžu bojāeju, piemēram, Centrāleiropā (Nikolov et al., 2014).

Mežaudzes kopējā stabilitāte (*collective stability*) ir atkarīga no koku individuālās noturības, kas atsevišķiem mežaudzi veidojošajiem kokiem var atšķirties (Díaz-Yáñez et al., 2017). Koku individuālās vēja noturības īpašības nosaka koku savstarpējais izvietojums mežaudzē un no tā atkarīgās augšanas gaitas atšķirības (Dupont et al., 2018). Piemēram, mežaudzē tālāk no malas esošie koki visbiežāk ir ar lielāku augstuma/caurmēra attiecību (slaidāki stumbri), augstākiem vainagiem (mazāks vainaga garuma īpatsvars no koka augstuma) un vājāk attīstītu sakņu sistēmu atšķirībā no malas kokiem, kuri ir pakļauti pastāvīgai vēja iedarbībai (Šēnhofa et al., 2020). Nereti mežaudžu vēja bojājumi izveidojas tieši audžu iekšienē, kur kokiem ir zemāka mehāniskā noturība pret vēja dinamiskās slodzes laikā radīto bojājumu summu (Gardiner et al., 2013). Mežaudzēs ar zemu individuālo koku noturību ļoti svarīga ir visas audzes kopējā stabilitāte, ko var nodrošināt vienmērīgs koku izvietojums bez pārrāvumiem vainagu un sakņu sistēmu slēgumā, kad saglabājas blakus koku atbalsts, kā arī neveidojas spējas gaisa turbulences un vienmērīgi absorbējas vēja spēks (Gardiner & Quine, 2000; Mason, 2002).

Mežaudzes kopējā stabilitāte samazinās līdz ar atsevišķu koku bojāeju vai būtisku individuālās noturības samazināšanos (Snepsts et al.,. 2020). Tas var notikt dažādu apstākļu sakritību rezultātā, kas vai nu kavē augšanu, vai arī izraisa strukturālus un līdz ar to arī funkcionālus koksnes daļu bojājumus. Piemēram, mežaudzēm ar jau esošiem vēja bojājumiem ir paaugstināta līdzīgu bojājumu atkārtošanās/turpināšanās iespēja nākamajās vēja brāzmās, ja vien nav bijis pietiekami ilgs saglabājušos koku adaptācijas periods jaunajai audzes struktūrai (Detter et al., 2015). Tādējādi, izmantojot informāciju par meteoroloģisko parametru faktiskajiem un vidējiem rādītājiem un datus par mērķa un blakus esošo mežaudžu raksturojošajiem rādītājiem un meža tipu grupu, ir iespējams veikt sagaidāmajiem vēja bojājumu riskiem pielāgotus mežaudžu apsaimniekošanas pasākumus. Piemēram, mežaudzes vidusdaļas bojājumu gadījumā, kad ir izveidojušies vairāki atsevišķi atvērumi, jāplāno sanitārā vienlaidus (nevis izlases) cirte.

Individuālu koku vēja noturību ir iespējams novērtēt, pielietojot destruktīvu statiskās vilkšanas testu (*pulling test*), kurā ar vinču paraugkoku pilnībā nolauž vai izgāž ar saknēm, vienlaicīgi veicot pieliktā spēka un koka stumbra saliekuma mērījumus (Nicoll et al., 2006; Peltola, 2006). No testā iegūtajiem kvantitatīvajiem datiem primāro lūšanu (PF) fiksē kā stumbra pamatnes lieces momentu, pie kura stumbra saliekšanās kļūst disproporcionāli straujāka nekā lieces momenta palielināšanās (BBM_{PF}), bet sekundāro lūšanu (SF) – kā maksimālo lieces momentu (BBM_{SF}) (Detter et al., 2015, 2019). Vilkšanas testa laikā nenotiek pieliktās slodzes absorbēšana, kā tas būtu dabiskos apstākļos, kokam vējā svārstoties, tomēr šis tests ir līdzīgos pētījumos plaši izmantota metode mežaudzes veidojošo koku vēja noturības novērtēšanai un salīdzināšanai, analizējot iespējamos koku individuālo noturību ietekmējošos faktorus (Nicoll et al., 2006; Peltola, 2006).

1.7. Promocijas darba mērķis

Novērtēt sakņu trupes un stumbra mizas bojājumu ietekmi uz vēja bojājumu iespējamību parastās egles mežaudzēs.

1.8. Promocijas darba uzdevumi

1. Raksturot parastās egles vēja noturību saistībā ar virszemes biomasas sadalījuma un sakņu-augsnes kamola dimensiju atšķirībām mežaudzēs ar kūdras un minerālaugsnēm.
2. Raksturot koksnes strukturālo noturību ietekmējošu stumbra mizas bojājumu un sakņu trupes ietekmi uz parastās egles vēja noturību.
3. Raksturot parastās egles mežaudžu saglabāšanos aprites cikla ietvaros.

1.9. Promocijas darba tēzes

1. Stumbra mizas bojājumu sekas samazina parastās egles mehānisko stabilitāti, būtiski palielinot vēja bojājumu iespējamību.
2. *Heterobasidion spp.* izraisītās sakņu trupes negatīvā ietekme uz parastās egles sakņu-augsnes sasaisti kūdras un minerālaugsnēs būtiski neatšķiras.
3. Parastās egles mežaudžu būtiska destrukcija sākas, sasniedzot trešajai vecumklasei (41-60 gadi) atbilstošas dimensijas.

1.10. Zinātniskā novitāte

Promocijas darbā pirmo reizi Baltijas jūras reģionā analizētā parastās egles statiskās koku vilkšanas testu datu kopa ietver lielu dimensiju (DBH > 45 cm, H >30 m) kokus. Turklāt pirmo reizi šajā reģionā ir iegūti koku vilkšanas testu dati no egles mežaudzēm ar kūdras augsnēm. Sakņu trupes ietekme uz egles vēja noturību raksturojošajiem parametriem pirmo reizi hemiboreālo mežu zonā ir salīdzināta starp mežaudzēm ar kūdras un minerālaugsnēm. Tāpat pirmo reizi kvantitatīvi raksturota stumbra mizas bojājumu ietekme uz egles vēja noturību.

1.11. Promocijas darba uzbūve

Promocijas darbs sastāv no piecām publikācijām. Pirmajās divās publikācijās (I un II publikācija) ir novērtēta stumbru mizas bojājumu un sakņu trupes ietekme uz parastās egles mehānisko noturību. Egles virszemes biomasas sadalījuma atšķirības audzēs uz kūdras un minerālaugsnēm ir analizēts trešajā (III) publikācijā. Ceturtajā (IV) publikācijā ir raksturota egles audžu saglabāšanās to aprites cikla ietvaros, bet piektajā (V) publikācijā ir analizētas egles sakņu-augsnes kamolu dimensijas vējgāzēs uz kūdras un minerālaugsnēm.

1.12. Promocijas darba aprobācija (konferences)

Pētījuma rezultāti prezentēti sešos ziņojumos četrās zinātniskajās konferencēs.

1. **Krisans O.**, Baders E., Donis J., Bickovskis K., Jaunslaviete I. (2020) Long-term survival of Norway spruce in hemiboreal forests. XXth International Multidisciplinary Scientific GeoConference Surveying, Geology and Mining, Ecology and Management – SGEM 2020, 16.-25.08.2020, Albena, Bulgaria. (Stenda referāts)
2. **Krisans O.**, Samariks V., Bickovskis K., Jaunslaviete I., Zute D. (2020) Root characteristics of wind-thrown Norway spruce. XXth International Multidisciplinary Scientific GeoConference Surveying, Geology and Mining, Ecology and Management – SGEM 2020, 16.-25.08.2020, Albena, Bulgaria. (Stenda referāts)
3. **Krisans O.**, Racenis E., Rieksts-Riekstins R., Donis J., Rust S., Jansons A. (2020) Browsing damages reducing wind stability of Norway spruce (Picea abies (L.) Karst.) in hemiboreal forests, Latvia. The 9th International Wind and Trees IUFRO conference “Planning for an uncertain future: wind risk to forests and trees in a changing climate”, 21.02.-08.03.2020, Rotorua, New Zealand.
4. Jansons A., **Krisans O.**, Donis J., Rieksts-Riekstins R., Bruna L. (2020) Impact of root-rot on wind stability of Norway spruce (Picea abies (L.) Karst.) in hemiboreal forests, Latvia. The 9th International Wind and Trees IUFRO conference “Planning for an uncertain future: wind risk to forests and trees in a changing climate”, 21.02.-08.03.2020, Rotorua, New Zealand.
5. Baders E. Dubrovskis E., Snepsts G., **Krisans O.**, Kapostins R., Jansons A. (2018) Resilience Norway spruce forests: case study in Latvia. 8th edition of the International

symposium forest and sustainable development, 25-27.10.2018., Brașov, Romania. (Stenda referāts)

6. Snepsts G., **Krisans O**., Dubrovskis E., Kapostins R., Jansons A. (2018) Effect of injuries on stability of Norway spruce. LIFE+ ELMIAS Ash and Elm, and IUFRO WP 7.02.01 Root and Stem Rots Conference (LIFE-IUFRO), 26.08-01.09.2018, Uppsala and Visby, Sweden. (Stenda referāts)

2. MATERIĀLS UN METODES

2.1. Egles virszemes daļas svaigas koksnes biomasas sadalījuma un sakņu-augsnes kamola raksturojums

Egļu sakņu-augsnes kamola morfometrisko parametru mērījumi veikti vējgāzēs un koku statiskās vilkšanas testu laikā, audzēs ar kūdras un minerālaugsnēm, Meža pētīšanas stacijas Kalsnavas, Jelgavas un Šķēdes mežu novados un AS "Latvijas valsts meži" apsaimniekotajos mežos Dundagas un Ozolnieku novados (57°14'N 22°42'E, 57°34'N 22°18'E, 56°40'N 23°53'E, 56°41'N 25°50'E, 56°75'N 23°85'E). Virszemes daļas biomasas sadalījumu noteica 87 kokiem, sadalot 2 m garos nogriežņos un pēc tam atsevišķi nosverot gan stumbra nogriezni, gan attiecīgajā nogrieznī esošos (sausos un zaļos) zarus. Vējā izgāztiem 64 kokiem veica sakņu-augsnes kamola morfometrisko parametru mērījumus—sakņu dziļumu divos rādiusos no koka stumbra līdz sakņu-augsnes kamola malai 0°, 45°, 90°, 135° un 180° sektoros pa sakņu-augsnes kamola virsmu. Katrā no šiem rādiusiem sakņu-augsnes kamola biezumu mērīja 0,2 m intervālos (3.1. att.). Sakņu-augsnes kamola tilpums V (m^3) aprēķināts kā eliptiska konusa tilpums:

$$V = \left(\frac{1}{3}\right) * \pi * a * b * h \qquad (1)$$

kur:
h – sakņu-augsnes kamola vidējais dziļums (m);
a – sakņu-augsnes kamola vertikālais rādiuss (m);
b – sakņu-augsnes kamola vidējais horizontālais rādiuss (m).

Egles sakņu-augsnes kamola morfometrisko parametru mērījumus no koku statiskās vilkšanas testiem izmantoja kā kontroles datus. Kūdras augsnēm kontroles dati ir iegūti tajās pašās audzēs, kurās veikti mērījumi vējgāzēs (Kalsnava), bet minerālaugšņu dati ir no 2020. gada koku statiskās vilkšanas testiem (Jelgava, Ozolnieki). Saskaņā ar Peltola et al. (2000), koku vēja noturības raksturošanai izmantoja parametru $HDBH^2$. Strukturālo sakņu sadalījumu aprēķināja ar vispārinātu aditīvo modeli, kurā kā mainīgos izmantoja relatīvo sakņu dziļumu un relatīvo attālumu no stumbra.

Egles virszemes biomasas aprēķināšanai izmantoja lineāro modeli, kurā kā mainīgos iekļāva DBH, augstumu un svērto nogriežņu smagumu centru augstumus. Pīrsona korelācijas un galveno komponentu analīzēs pārbaudīja koku morfometrisko parametru variēšanu atkarībā no augsnes veida. Katra koka masas centra H_{mp} aprēķinā izmantoja vidējo svērto nogriežņu masas centru augstumu un masas vērtības:

$$H_{\mathrm{mp}} = \frac{\sum m \times h}{\sum m} \qquad (2)$$

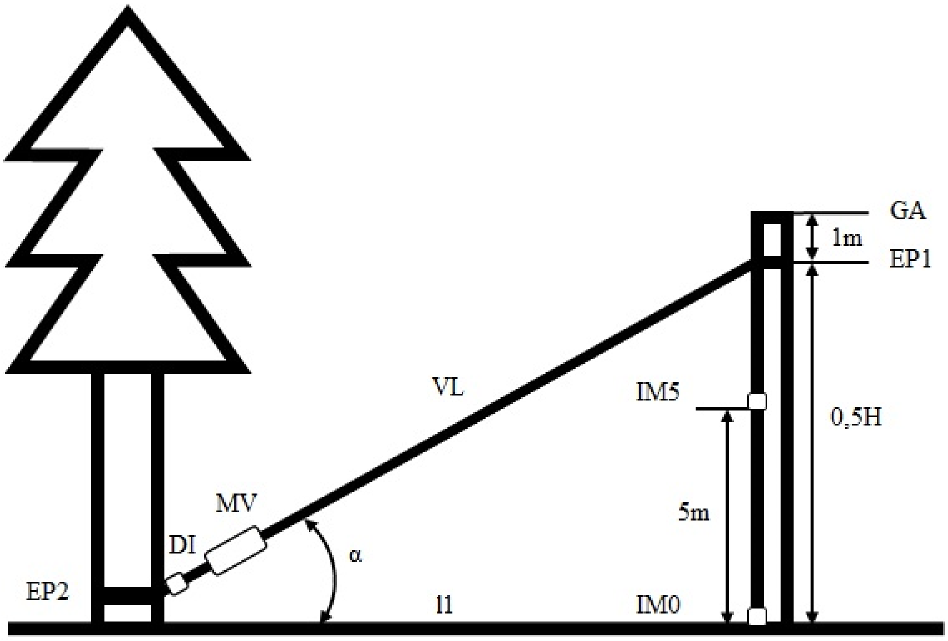
kur:
m – svērto nogriežņu masa (kg);
h – svērtā nogriežņa viduspunkta augstums (m).

Koka masas punkta relatīvais augstums ir proporcija no koka kopējā augstuma. Datu statistiskā apstrāde veikta programmā R (versija 4.0.0.) (R Development Core Team, 2019).

2.2. Koku statiskās vilkšanas testi

Lai raksturotu stumbra bojājumu un sakņu trupes ietekmi uz egles vēja noturību, veikti koku destruktīvas statiskās vilkšanas testi vairākās egļu audzēs Latvijas centrālajā daļā – Meža pētīšanas stacijas Kalsnavas mežu novadā (4 audzes) un SIA Skogssallskapet īpašumā Cēsu novadā (1 audze). Egļu tīraudzēs ar kūdras (Kp un Ks) un labi drenētām minerālaugsnēm (Dm) (Bušs, 1976) atlasīja gan bojātos, gan kontroles kokus, reprezentējot konkrēto kokaudžu DBH pakāpes (viena pakāpe 4 cm). Sakņu trupes ietekmes novērtēšanai no bojāto paraugkoku grupai paredzētajiem kokiem vispirms ievāca urbumu serdeņus, kuros laboratoriski identificēja patogēnus, un sakņu trupes paraugkopai atlasīja kokus ar *Heterobasidion spp.* klātbūtni. Savukārt kontroles grupai atlasīja kokus, kuru koksnes paraugos neattīstījās ne *Heterobasidion spp.*, ne arī citi sakņu trupi izraisoši patogēni. Mizas bojājumu ietekmes novērtēšanai bojāto koku paraugkopai atlasīja kokus ar 7 līdz 9 gadus veciem stumbra mizas bojājumiem, kas bija izvietoti no 0,8 līdz 1,5 m augstumā, bet kontroles grupai – kokus bez vizuāliem defektiem. Abiem bojājumu veidiem datu analīzē izmantoja bojājuma īpatsvaru, trupes gadījumā to aprēķinot kā attiecību starp trupējušās koksnes laukumu un celma zāģējuma virsmas laukumu, bet mizas bojājumu gadījumā – kā zudušās mizas proporciju no koka stumbra apkārtmēra platākajā bojājuma vietā.

Vilkšanas testa laikā (2.1. att.) ar dinamometru (DI) mērīja koku pretestību statiskai slodzei un leņķi (α) starp vilkšanas līniju (metāla trose ar poliestera virves pagarinājumu) (VL)un gaisa līniju starp atbalsta koku un paraugkoku (l1). Vilkšanas spēka pielikšanas punkts paraugkokam bija pusē no tā augstuma (EP1), un, lai mazinātu vēja un gravitācijas spēka ietekmi uz mērījumiem, visiem paraugkokiem nozāģēja galotni 1 m virs (GA) vilkšanas spēka pielikšanas punkta. Vilkšanu veica ar manuālu vinču (MV), kura bija stiprināta pie cita koka pamatnes (EP2) attālumā, kas pārsniedz paraugkoka augstumu, bet ne vairāk par 40 m. Testa laikā veica sinhronus mērījumu datu nolasījumus vilkšanas spēkam un vilkšanas līnijas leņķim, kā arī koka stumbra sagāzuma leņķiem, kurus mērīja ar inklinometriem pie stumbra pamatnes (IM0) un 5 m augstumā (IM5).



2.1. att. **Shematisks statiskās vilkšanas testa attēlojums**
EP1 un EP2 – vilkšanas spēka pielikšanas punkts paraugkokam un atbalsta kokam; l1 – attālums no atbalsta koka līdz paraugkokam; α – leņķis starp VL un l1; DI – dinamometrs (vilkšanas spēka un vilkšanas līnijas leņķa mērījums); MV – manuālā vinča; 0,5H – puse no paraugkoka augstuma; GA – paraugkoka nozāģēšanas augstums; IM0 un IM5 – inklinometri pie stumbra pamatnes un 5 m augstumā uz stumbra

Katram paraugkokam aprēķināts lieces moments stumbra pamatnē BBM (kNm) kā:

$$BBM = F*h_{\mathrm{EP1}}*\cos(\mathrm{median}_{\alpha}), \tag{3}$$

kur:
F – vilkšanas spēks;
h_{EP1} – vilkšanas līnijas piestiprinājuma augstums pie paraugkoka;
median_{α} – vilkšanas līnijas leņķa mediāna.

Stumbra izliekumu N_{Δ} izteica kā starpību no stumbra sagāzuma leņķu mērījumiem pie stumbra pamatnes (N_0) un 5 m augstumā ($N_{5\mathrm{m}}$):

$$N_{\Delta} = N_{5\mathrm{m}} - N_0 \tag{4}$$

N_{Δ} un BBM vērtību proporcionālā pieauguma beigu moments tika definēts kā BBM_{PF}. Savukārt pilnīga nolūšana vai izgāšanās ar saknēm pie maksimālā liekšanas spēka ir BBM_{SF}. Sakņu-augsnes kamola tilpumu V (m^3) aprēķināja kā pusi no eliptiska paraboloīda tilpuma:

$$V = \left(\frac{1}{2}\right) \cdot \pi \cdot a \cdot b \cdot h, \tag{5}$$

kur:
a un b – lielākais un mazākais izgāztās sakņu-augsnes kamola virsmas rādiuss (m),
h – maksimālais sakņu-augsnes kamola dziļums (m).

Datu statistiskā apstrāde veikta programmā R (versija 3.5.3) (R Core Team, 2018), izmantojot pakotnes "readr", "tidyverse", "DBI", "zoo", "RSQLite", "ggplot2" un "ez".

2.3. Egļu audžu saglabāšanās

Egļu audžu saglabāšanās divu Latvijas reģionu meža ainavās—Rietumlatvijā Vānē un Austrumlatvijā Dvietē raksturota, izmantojot meža inventarizācijas datus no 1975. līdz 2016. gadam. Vēsturisko meža inventarizāciju plāni no 1975., 1985. un 1999. gada tika ieskenēti un ģeoreferencēti, pielāgojot LKS-92 koordinātu sistēmai, programmas ArcGIS 10.2 vidē. Savukārt digitāli telpiskie meža inventarizācijas dati par 2011. un 2016. gadu saņemti no Valsts meža dienesta. Pamatojoties uz šīm piecu meža inventarizāciju datu kopām, izveidotas mežaudžu izmaiņu kartes 40 gadus ilgam periodam.

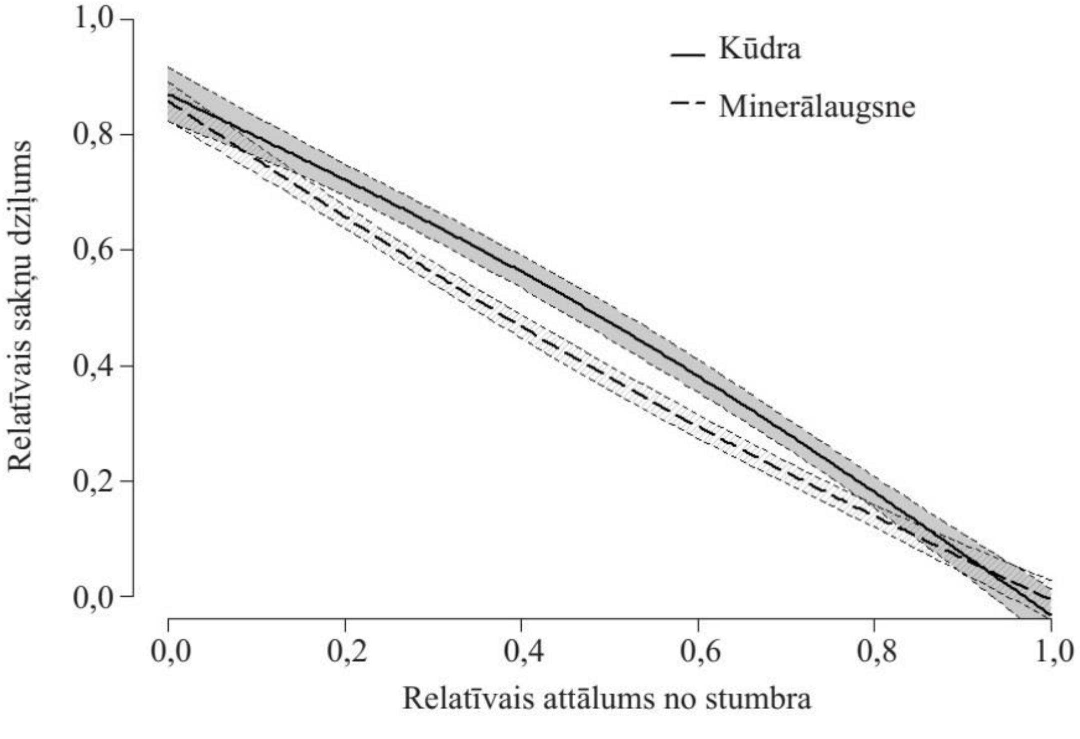
Egļu audžu dinamika analizēta, attiecīgajā inventarizācijas gadā nosakot valdošās sugas koeficientu un sadalot mežaudzes pa vecumklasēm. Analīzē tika iekļautas mežaudzes līdz ceturtajai vecumklasei, bet mežaudzes, kuras gāja bojā vai sasniedza piekto vecumklasi, vai arī tajās nomainījās valdošā suga, tika izslēgtas no turpmākās analīzes. Veicot statistisko analīzi ar lineāru jauktu efektu modeli programmas R vidē (versija 3.5.3) (R Core Team, 2018), novērtēta valdošās sugas un vecumklašu sastopamības (īpatsvara) dinamika. Ja mežaudze kā egļu audze bija saglabājusies arī nākamajā inventarizācijā, modelī mežaudzes identifikatoru izmantoja kā nejaušo efektu. Savukārt telpisko autokovarianti izmantoja, lai noskaidrotu telpiskās sakarības starp neatkarīgajiem mainīgajiem, piemēram, reģionu, vecumklasi un inventarizācijas gadu. Ar Hī-kvadrāta ($\chi 2$) testu noskaidroja egļu audžu attiecīgajā vecumklasē īpatsvaru atšķirības starp reģioniem un inventarizācijas gadiem.

3. REZULTĀTI UN DISKUSIJA

3.1. Egles saknu-augsnes kamola un virszemes biomasas sadalījuma raksturojums

Egles stabilitāti vējā nozīmīgi ietekmē tās sasaiste ar augsni un masas centrs, ko raksturo sakņu-augsnes kamola tilpums (un masa) un virszemes daļas masas sadalījums (smaguma centra augstums) (Cucchi et al., 2005; Nicoll et al., 2006).

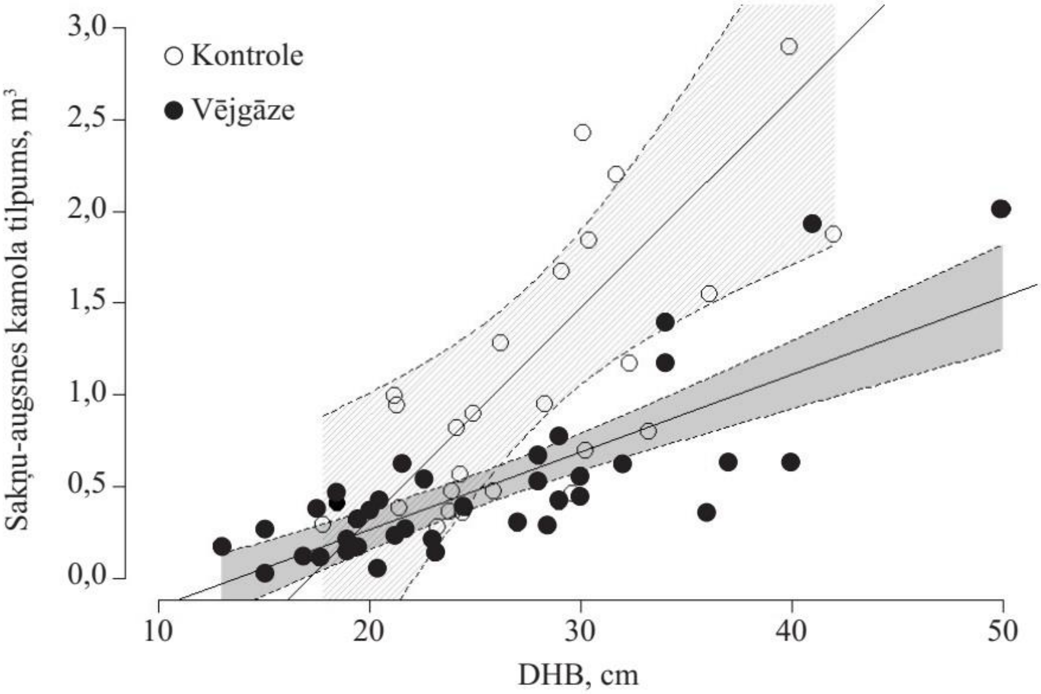
Sakņu vertikālā izplatība, kas ir viens no nozīmīgākajiem koku vēja noturību noteicošajiem faktoriem (Coutts, 1986; Dumroese et al., 2019), ir noteikta kā sakņu plātnes dziļuma standartizēts biezuma mērījumu sadalījums pa sakņu-augsnes kamola virsmas rādiusu no stumbra. Rādiusam palielinoties, samazinās kamola biezums, un iegūtā korelācija ir cieša un negatīva gan nosusinātās kūdras augsnēs, gan minerālaugsnēs ($r = –0,99$; $p < 0,001$) (3.1. att.). Vidējais sakņu dziļums pie sakņu kakla (kamola centrā) eglēm nosusinātā kūdras augsnē (Kp un Ks) bija 49,2 ± 6,6 cm (šeit un turpmāk kā izkliedes rādītājs norādīts 95% ticamības intervāls), savukārt minerālaugsnē 28,3 ± 2,3 cm. Nosusinātā kūdras augsnē augošiem kokiem lielāks sakņu dziļums saglabājās līdz 1 m attālumam no sakņu kakla, taču plātnes perifērijā tas samazinās straujāk nekā minerālaugsnēs (3.1. att.). Šādas sakņu dziļuma atšķirības norāda uz dažādu sakņu-augsnes sasaisti (Nicoll et al., 2006): gadījumos, kad tā nav tik cieša, koka stabilitātes nodrošināšanai saknes aug dziļāk (ja to pieļauj gruntsūdens līmenis) un plašāk (Ray & Nicoll, 1998; Štofko, 2010). Likumsakarīgi, ka eglēm nosusinātā kūdras augsnē sakņu-augsnes kamola tilpums bija būtiski ($p < 0,001$) lielāks nekā minerālaugsnē (3.2. un 3.3. att.); tas saskan ar pētījumu rezultātiem citās valstīs (Nicoll et al., 2006).



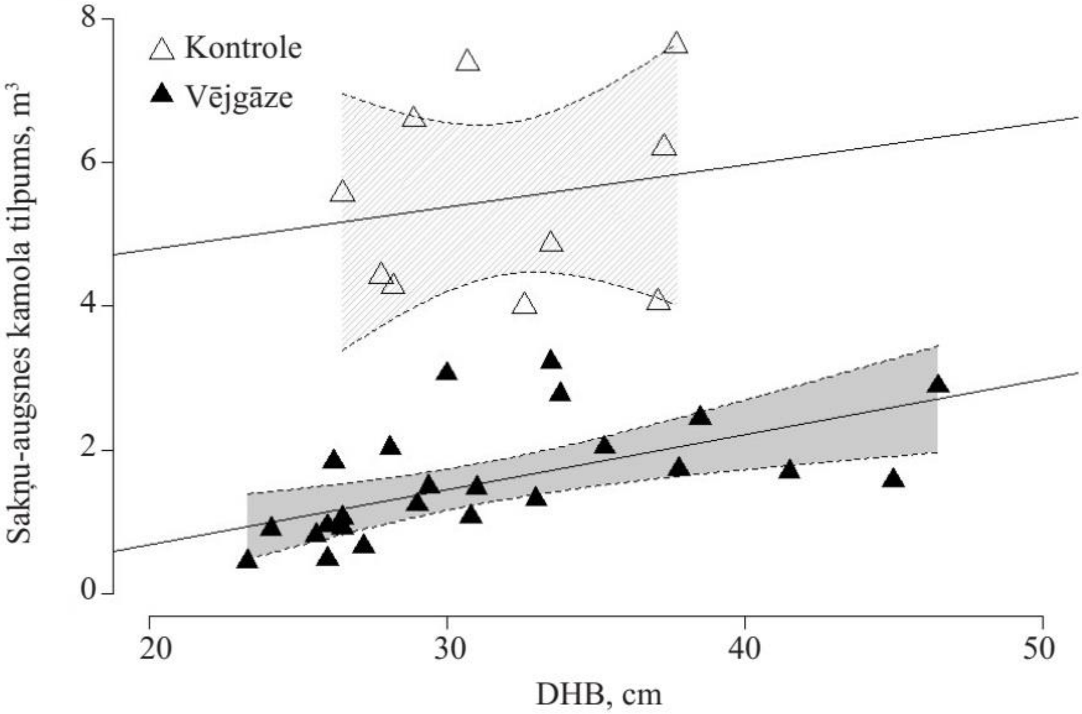
3.1. att. **Egles sakņu-augsnes kamola dziļums atkarībā no attāluma no sakņu kakla mežaudzēs ar kūdras un minerālaugsni**

Iekrāsotie laukumi atbilst 95 % ticamības intervālam

Sakņu kamola izmēra nozīmi apliecina arī fakts, ka uzmērītajām vēja izgāztajām eglēm tas bija būtiski mazāks nekā koku laušanas testos izgāztajām, turklāt izteiktāka šī atšķirība bija tieši nestabilākajās, nosusinātajās kūdras augsnēs (3.2. un 3.3. att.).



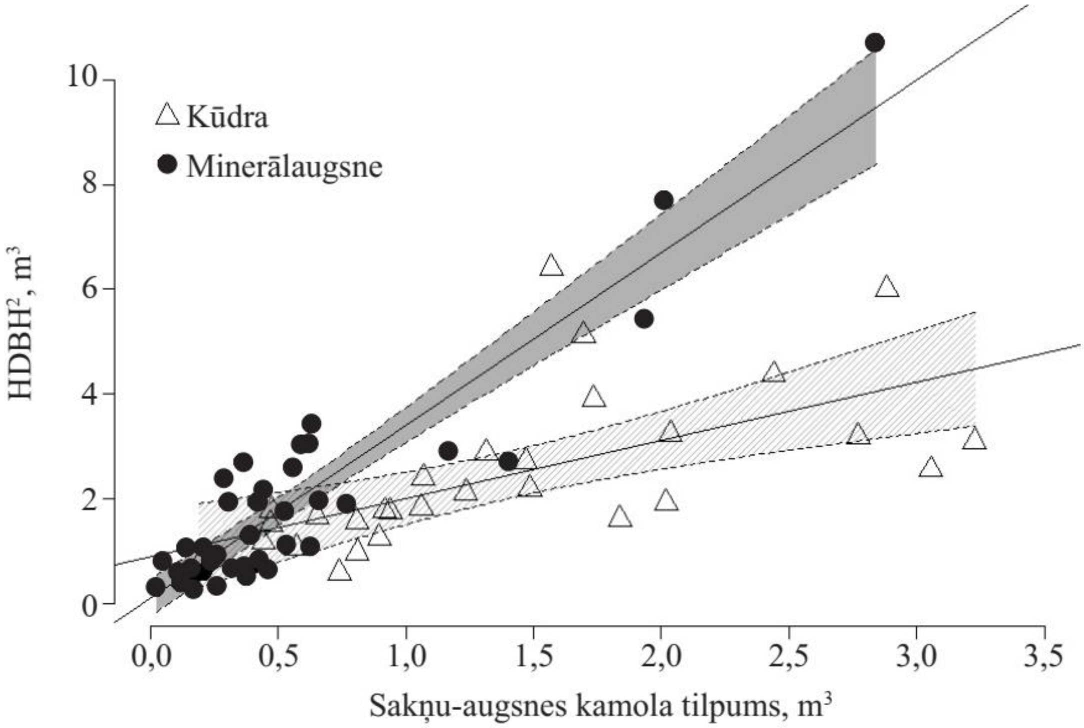
3.2. att**. Vēja izgāzto un kontroles koku sakņu-augsnes kamola tilpums minerālaugsnē**
Iekrāsotie laukumi atbilst 95 % ticamības intervālam



3.3. att. **Vēja izgāzto un kontroles koku sakņu-augsnes kamola tilpums kūdras augsnē**
Iekrāsotie laukumi atbilst 95 % ticamības intervālam

Papildus sakņu-augsnes kamola tilpumam vēja noturību nosaka arī tā masa, pazeminot kopējo koka smaguma centru un darbojoties kā atsvars. Tā atkarīga ne tikai no kamola tilpuma, bet arī augsnes mitruma un granulometriskā sastāva (Nicoll & Ray, 1996; Niccol et al., 2006). Tāpat sakņu spēju nodrošināt koka stabilitāti nosaka koka adaptācija lokālajiem apstākļiem, audzes attīstības gaita (t.sk., veiktā saimnieciskā darbība), augsnes sasalums un biotisko traucējumu ietekme (Schelhaas et al., 2003). Koka stabilitāti vētrā var nozīmīgi samazināt arī pirms tam notikusi vēja iedarbība, kas izraisījusi sakņu bojājumus. Pieaugot koka vecumam, sakņu sistēmas atjaunošanās spēja pēc šādiem bojājumiem mazinās (Puhe, 2003), un atjaunošanās laiks palielinās.

Koku vēja noturības raksturošanai var izmantot stumbra dimensijas raksturojošu parametru HDBH^2 (Peltola et al., 2000). Tas būtiski ($p < 0{,}001$) atšķīrās nosusinātās kūdras augsnēs un minerālaugsnēs augošām eglem (3.4. att.). Kopumā HDBH^2 parametra vērtības attiecība pret sakņu-augsnes kamola tilpumu minerālaugsnēs bija būtiski ($p < 0{,}001$) augstāka nekā kūdras augsnēs, t.i., minerālaugsnēs mazāks sakņu kamols uzturēja lielāku dimensiju stumbru. Palielinoties koku izmēram, atšķirības šajā attiecībā starp dažādās augsnēs augošām eglēm arī palielinājās (3.4. att.).



3.4. att. **Sakarība starp egles stumbra dimensijām (HDBH^2) un sakņu-augsnes kamola tilpumu kūdras un minerālaugsnēs**

Iekrāsotie laukumi atbilst 95 % ticamības intervālam

Koka virszemes daļas masas sadalījums dabiski mitrā stāvoklī nosaka tā smaguma centra (relatīvā masas punkta) augstumu un līdz ar to –gravitācijas spēku, kas iedarbosies uz koku pēc tam, kad vējš būs sācis to gāzt (stumbrs būs novirzījies no vertikālā stāvokļa). Zemāks relatīvais masas punkts paaugstina koka stabilitāti vējā, un otrādi (Cucchi et al., 2005; Nicoll et al., 2006). Pētījumā ietverto egļu virszemes daļas vidējā 2 m nogriežņa biomasa bija 66 ± 3,0 kg, vidējā kopējā masa 1730 ± 576 kg. Līdzīgi kā Marklund (1988) un Repola (2009) biomasu modeļos, iegūtais virszemes biomasas sadalījuma modelis (3.1. tabula) ir balstīts uz koka DBH un H, un prognozētajām svaigas stumbra koksnes masas vērtībām ir cieša korelācija ar svēršanas rezultātiem ($r = 0{,}98$) (3.2. tabula):

$$m_{ij} = \beta_2 h_{ij} + \beta_3 DBH_i^2 + \beta_4 h_{ij} DBH_i^2 + \beta_1, \qquad (6)$$

kur:

m_{ij} – 2 m nogriežņa masa (kg);
h_{ij} – nogriežņa centra augstums (m);
DBH_i – koka caurmērs (cm).

3.1. tabula

Virszemes biomasas sadalījuma modeļa parametru vērtības un standartkļūdas

Parametrs	Vērtība	Standartkļūda
β_1	0,44	0,194
β_2	- 0,163	0,201
β_3	0,083	0,001
β_4	- 0,087	0,001

Modeļa prognozēs lielākoties variēja koku pirmo—zemāko fragmentu biomasas, kas ir skaidrojams ar lielāku raukumu un masu stumbram tā bazālajā daļā.

3.2. tabula

Pīrsona korelācijas koeficienti un to p-vērtības parastās egles parametriem

Parametrs	DBH	H	Svaigas stumbra koksnes masa (kg)	Aprēķinātā stumbra biomasa (kg)
DBH	1	< 0,001	< 0,001	< 0,001
H	0,79	1	< 0,001	< 0,001
Svaigas stumbra koksnes masa (kg)	0,36	0,29	1	< 0,001
Aprēķinātā stumbra biomasa (kg)	0,39	0,32	0,98	1

Pīrsona korelācijas koeficienti parādīti zem diagonāles, bet to p-vērtības – virs diagonāles

Virszemes daļas biomasas sadalījuma datu novērtēšanā izmantotās galveno komponentu analīzes rezultāti uzrādīja 83% izskaidrojamu variāciju pirmajai (53%) un otrajai (30%) komponentei. Pirmajai komponentei izskaidrojamā variācija bija atkarīga no koka kopējā augstuma un caurmēra, stumbra un vainaga biomasas un relatīvā masas punkta augstuma. Pētījumā tika konstatēta pozitīva korelācija relatīvajam masas punkta augstumam ar koka kopējo augstumu ($r = 0{,}64$), stumbra masu ($r = 0{,}61$), DBH ($r = 0{,}55$) un zemākā dzīvā zara augstumu ($r = 0{,}57$). Tomēr augstāka korelācija relatīvajam masas punkta augstumam bija ar dzīvo zaru biomasu ($r = 0{,}77$). Šis rezultāts norāda, ka stumbra un vainaga dimensijām, no kurām ir atkarīgs relatīvais masas punkta augstums, ir nozīmīga ietekme uz egles vēja noturību. Savukārt otrajai komponentei izskaidrojamā variācija bija atkarīga no augsnes veida ($p < 0{,}008$), un tai bija pozitīva korelācija ar relatīvo masas punkta augstumu, zemākā dzīvā zara augstumu, bet negatīva – ar vainaga relatīvo augstumu, kurš variēja starp 34% un 44% no koka kopējā augstuma.

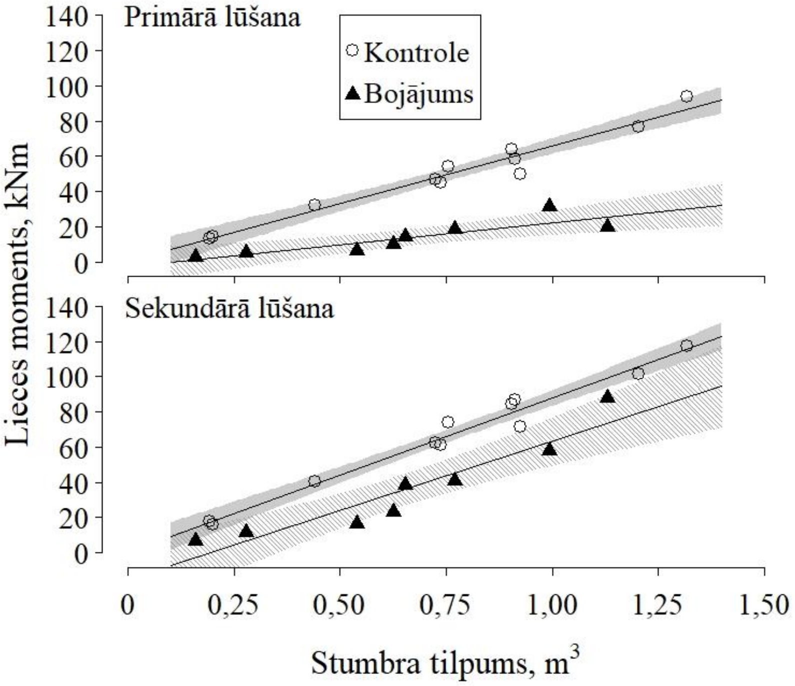
Rezultāti liecina, ka egles virszemes biomasa un sakņu-augsnes kamola morfometriskie parametri mežaudzēs ar kūdras augsnēm būtiski atšķiras no mežaudzēm ar minerālaugsnēm. Mežaudzēs ar kūdras augsnēm egļu vainagiem ir relatīvi mazāks garuma īpatsvars (no koka kopējā augstuma) nekā minerālaugsnēs, tādējādi kūdras augsnēs eglēm ir lielāks relatīvais masas punkta augstums. Savukārt, eglēm minerālaugsnēs konstatētā būtiski straujākā $HDBH^2$ vērtību palielināšanās attiecībā pret sakņu-augsnes kamola tilpumu saistīta ar augstāku vēja noturību.

3.2. Koku statiskās vilkšanas testi

Stumbra mizas bojājumi, visbiežāk briežu dzimtas pārnadžu radīti, un sakņu trupe ir uzskatāmi par nozīmīgākajiem biotiskajiem traucējumiem egles mežaudzēs, kas spēj izraisīt būtiskus koksnes strukturālos bojājumus (Wagener, 1963; Shibata & Torazawa, 2008; Honkaniemi et al., 2017; Cukor et al., 2019). Tāpēc ir nepieciešama informācija par šo biotisko faktoru ietekmi uz egles vēja noturību, kā arī tās integrācija vēja bojājumu prognozēšanas algoritmos. Koku noturības pārbaudi veica, pielietojot statiskās vilkšanas testu (Peltola, 2006).

Kokiem ar abu biotisko aģentu izraisītiem bojājumiem bija būtiski zemākas gan PF, gan SF vērtības nekā kontroles (nebojātiem) kokiem visās mežaudzēs gan kūdras, gan minerālaugsnēs (3.5. un 3.6. att.), un veselo koku lieces momentu vērtības ir salīdzināmas ar parastās egles vilkšanas testu pētījumos iegūtajām vērtībām citviet Eiropā (Lundström et al., 2007; Peltola et al., 2010; Jillich et al., 2013). Mizas bojājumiem nozīmīga ietekme bija uz augsnes-sakņu sasaisti, nevis stumbra koksnes mehānisko izturību, pretēji sākotnēji gaidītajam. Pēc SF sasniegšanas testētie koki visbiežāk izgāzās ar saknēm, nevis lūza—tas arī ir izplatītākais parastās egles mežaudžu vēja bojājuma veids (Gardiner et al., 2013).

Vidējā mizas bojājuma proporcija no stumbra apkārtmēra bija 28,1 ± 7,3%, bet trupējušās koksnes proporcija no celma virsmas laukuma—50,3 ± 26,5%. Lai arī testēto koku noturība primāri bija atkarīga no stumbra tilpuma, tomēr bojājumu ietekmē, neatkarīgi no to apjoma, abas testētās BBM robežvērtības (BBM$_{PF}$ un BBM$_{SF}$) bija būtiski zemākas.

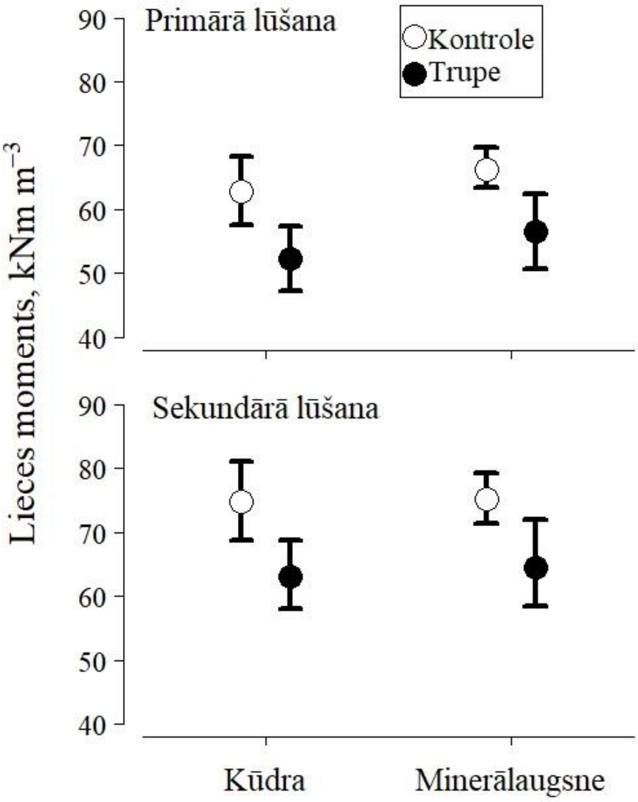


3.5. att. **Parastās egles stumbra pamatnes lieces momenti pie primārās un sekundārās lūšanas atkarībā no stumbra tilpuma un mizas bojājumiem**
Iekrāsotie laukumi atbilst 95 % ticamības intervālam

Noturība pret PF palielinājās proporcionāli stumbra tilpumam, un veseliem kokiem šī palielināšanās bija daudz straujāka (t.i., sakarību starp BBM$_{PF}$ un stumbra tilpumu aprakstošās taisnes slīpums lielāks) nekā bojātiem (3.5. att.). Tomēr relatīvais BBM$_{PF}$ samazinājums koka stumbra mizas bojājuma ietekmē dažādu dimensiju kokiem bija nemainīgs: 61%. Savukārt bojāto koku BBM$_{SF}$ bija vidēji par 16 kNm m^{-3} zemāks nekā kontroles kokiem. Šādas atšķirības starp BBM$_{PF}$ un BBM$_{SF}$ norāda, ka nozīmīgāka praktiskā stumbra mizas bojājuma ietekme ir uz primāro lūšanu, ko mežaudzē vizuāli nevar konstatēt. Lai arī koka dimensiju palielināšanās paaugstina koku noturību, tomēr mežaudzēs ar tādiem lielu dimensiju kokiem, kuriem ir stumbra mizas bojājumi, arī relatīvi mazās vēja slodzēs var veidoties bojājumi, kas būtiski samazina koku mehānisko stabilitāti un pretestības spējas citiem ārējas vides faktoriem.

Mizas bojājumi, kavējot koka sulas vadītspēju, izraisa nozīmīgus fizioloģisko procesu traucējumus (Cukor et al., 2019), kuru mazināšanai koks izmanto resursus, kas citkārt būtu nodrošinājuši tā augšanu (Vasiliauskas, 2001). Tādējādi vielu transporta sistēmas apgrūtinājuma apstākļos augšanas enerģija tiek ieguldīta augstuma pieauguma veidošanā, lai nodrošinātu koka konkurētspēju, turpretī sakņu attīstība, pastāvot pietiekamai mežaudzes kopējai stabilitātei, tiek kavēta (Szoradova et al., 2013; Honkaniemi et al., 2017). Koka fizioloģiskos procesus un arī sakņu attīstību kavē patogēnu invāzija mizas bojājumu brūcēs (Szoradova et al., 2013; Burneviča et al., 2016; Honkaniemi et al., 2017; Cukor et al., 2019). Stumbru šķērsgriezumos mizas bojājumu vietās trupējusi koksne netika konstatēta, tomēr dažādu patogēnu sugu izplatības īpatnību dēļ (Deflorio et al., 2008; Burneviča et al., 2016) kokiem ar mizas bojājumiem pastāv iespēja, ka augsnes-sakņu sasaiste var samazināties patogēnu darbības ietekmē (Vasiliauskas, 1998; Honkaniemi et al., 2017).

Otra analizētā biotiskā faktora – sakņu trupi izraisošo patogēnu – klātbūtne būtiski samazināja gan BBM_{PF}, gan BBM_{SF} neatkarīgi no augsnes veida un mitruma, kā arī sakņu-augsnes kamola tilpuma, norādot, ka egles noturība ir atkarīga no laterālo sakņu mehāniskajām īpašībām (3.6. att.). Kokiem ar sakņu trupi BBM_{PF} un BBM_{SF} samazinājums bija attiecīgi 25,4% un 24,1%. Jāatzīmē, ka sakņu trupes ietekmes uz koku noturību novērtēšanai izvēlētajiem paraugkokiem, kuriem pirms vilkšanas testiem tika apstiprināta *Heterobasidion spp.* klātbūtne, konstatēti arī citi patogēni, visbiežāk *Armillaria spp.* un *Resinicium bicolor*.



3.6. att. **Parastās egles stumbra pamatnes lieces momenti pie primārās un sekundārās lūšanas atkarībā no augsnes veida un sakņu trupes klātbūtnes**

Abu biotisko faktoru—stumbra mizas bojājumu ($p < 0{,}001$) un sakņu trupes ($p < 0{,}05$) klātbūtnē būtiski samazinājās egļu vēja noturība, ko apliecina zemākas BBM_{PF} un BBM_{SF} vērtības. Pazeminâts BBM_{PF} nozīmē paaugstinātu koksnes audu deformācijas risku spiedē (Detter et al., 2015), bet BBM_{SF}—maksimālās noturības samazinājumu. Koksnes audu deformācijā var izveidoties strukturāli traucējumi vielu transporta sistēmā, izraisot augšanas samazināšanos vai fizioloģiskā sausuma izveidošanos vēja bojājuma rezultātā (Seidl & Blennow, 2012). Šādi koksnes bojājumi saknēs ne tikai samazina to ūdens uzņemšanas un transportēšanas spējas, bet arī paaugstina koka invadēšanās risku ar sakņu trupi izraisošajiem patogēniem. Tā kā vēja bojātajiem kokiem palielinās biotisko aģentu izraisīto bojājumu risks, un vēja radīto mehānisko bojājumu iespējamība ir augstāka kokiem ar jau esošiem biotisko aģentu izraisītiem bojājumiem (Gardiner et al., 2013; Seidl et al., 2017), saskaņā ar Honkaniemi et al. (2017) egļu mežaudzes nākotnē var tikt pakļautas cikliskai šo procesu negatīvajai ietekmei.

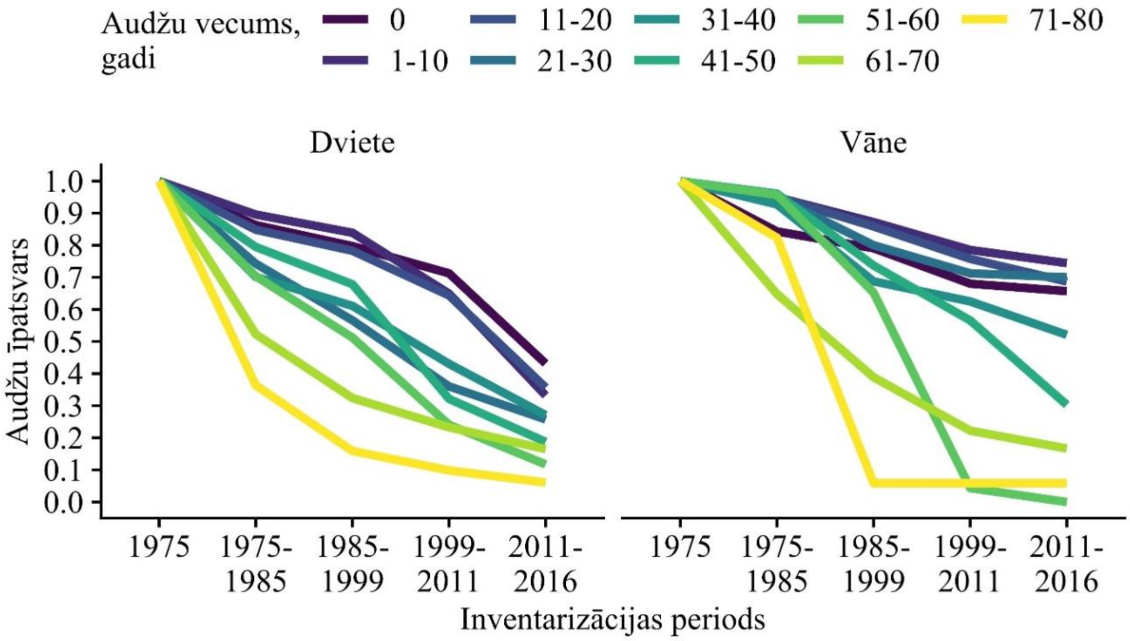
Ņemot vērā stipra vēja (pēc Boforta skalas 13,9 – 17,1 m s^{-1} (Barua, 2005)) un vētru atkārtošanās biežuma palielināšanās prognozes (Mölter et al., 2016), egles stumbra mizas bojājumi un sakņu trupe ir uzskatāmi par nozīmīgiem egļu audžu vēja bojājumu risku paaugstinošiem faktoriem. To negatīvo ietekmi uz egles audžu vēja noturību ir iespējams mazināt, īstenojot atbilstošus meža apsaimniekošanas pasākumus (Gardiner et al., 2013). Piemēram, stādījumu ierīkošana ar sākotnēji zemu biezumu vai savlaicīga augstas intensitātes audzes sastāva kopšana bez mehanizētas krājas kopšanas ciršu veikšanas mazinātu gan koku sakņu sākotnējos kontaktus, gan mehānisku sakņu bojājumu iespējamību, paaugstinot egļu audžu noturību pret sakņu trupi izraisošo patogēnu izplatību (Stenlid & Redfern, 1998). Arī stumbra mizas bojājumu iespējamība mazinātos, gan izvairoties no mehanizētas kopšanas ciršu veikšanas, gan samazinoties lielo pārnadžu izraisītiem stumbra mizas apgrauzumiem, kas zemāka biezuma stādījumos tiek novēroti retāk (Baders et al., 2017; Katrevičs et al., 2018).

Savlaicīga bojāto koku identificēšana un izvākšana no jaunaudzēm un vidēja vecuma audzēm var nodrošināt izveidotā atvēruma malas kokiem pietiekamu laiku, lai pielāgotos sagaidāmajai vēja ietekmei (Šēnhofa et al., 2020). Turklāt laiks, kad egļu mežaudzes ir pakļautas nozīmīgam vēja bojājumu riskam, var tikt samazināts, saīsinot to aprites ciklu (Donis et al., 2020; Samariks et al., 2020), t.i., veicot mērķtiecīgu meža apsaimniekošanu, kas orientēta uz galveno cirti pēc mērķa caurmēra. Savukārt, pēc vēja iedarbības savlaicīgi identificēta nepieciešamība veikt mežaudzes nomaiņu var novērst papildus zaudējumus koku turpmāka kvalitātes zuduma un paaugstinātas sekundāro bojājumu varbūtības dēļ.

3.3. Egļu mežaudžu sastāva saglabāšanās

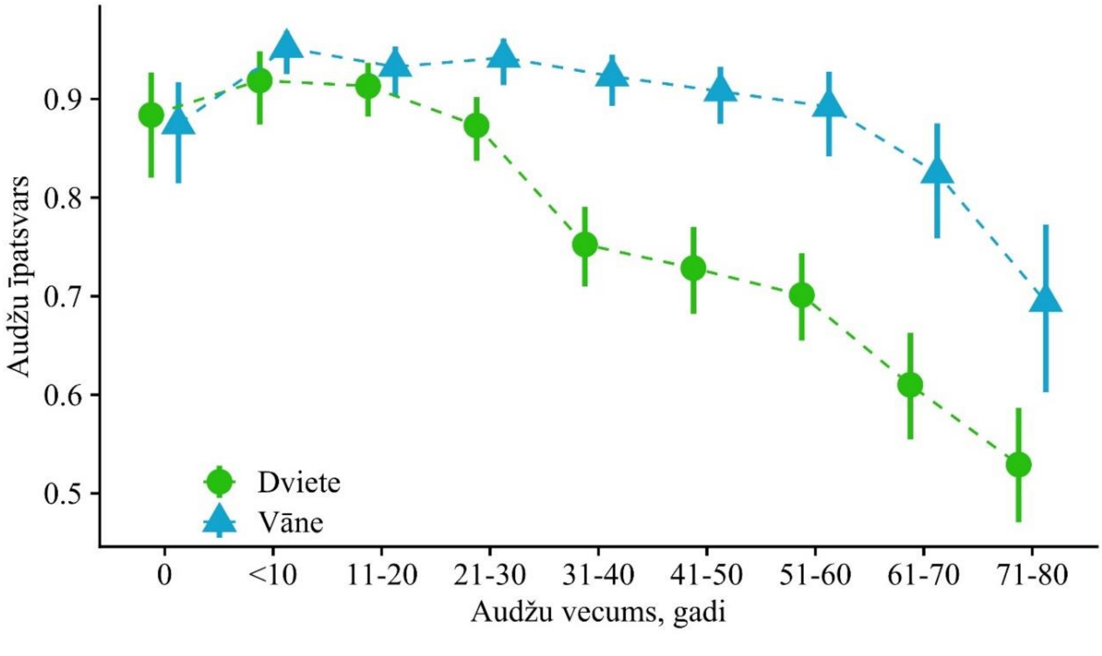
Egles audžu attīstībai un klimatam (t.sk., vēja klimatam) novērojamas reģionālas atšķirības pat salīdzinoši nelielā teritorijā, kāda ir Latvija (Zeltiņš et al., 2019). Tādēļ egles audžu ilgtermiņa saglabāšanās raksturošanai izvēlēti meža masīvi Latvijas austrumu un rietumu daļā, attiecīgi Dviete un Vāne.

Reģionam bija būtiska ietekme uz egles audžu saglabāšanos: Dvietē to audžu īpatsvars, kas pārgāja nākamajā vecumklasē, salīdzinot 1975. gada un 1985. gada inventarizācijas datus, bija 76,5%, kamēr Vānē tas bija 93,1%. Nav zināms precīzs iemesls, kāpēc egļu audžu platības samazinājās, neļaujot izdarīt precīzus secinājumus. Dvietē vecāko vecumklašu mežaudžu nesaglabāšanās līdz nākamajai inventarizācijai periodā no 1975. līdz 1985. gadam ir saistāma ar vēja izraisītiem bojājumiem periodā līdz 1983. gadam (stipra vēja gadījumi Latvijā, 1.1. att.), jo īpaši 1967. gadā, kad nozīmīgākie postījumi izveidojās Latvijas dienvidu daļā (Bengtsson & Nilsson, 2007; Hanewinkel et al., 2008, 2011; LVĢMC, 2017). Nereti stiprā vējā saglabājušās mežaudzes turpmākajos gados degradējas sekundāro biotisko faktoru izraisītu bojājumu ietekmē (Deschênes et al., 2019), visbiežāk mizgraužu savairošanās rezultātā (Nikolov et al., 2014). Tāpat vētrā izdzīvojušajiem, bet tās ietekmētajiem kokiem var būt nozīmīgi sakņu bojājumi, kuru dēļ tie nākamajos gados neiztur arī mazāk stipru vēju iedarbību. Savukārt, 2016. gada inventarizācijā fiksētā trešās vecumklases mežaudžu zemā saglabāšanās varētu zināmā mērā būt skaidrojama ar kaitēkļu—bruņuts (*Physokermes piceae* Schrank.) savairošanos 2010. gadā (VMD dati) (Bāders et al., 2018) (3.7. att.). Visā 40 gadu novērojumu periodā egļu audžu sastāva saglabāšanās starp inventarizācijām augstāka bija Vānē nekā Dvietē ($p < 0,001$).



3.7. att. **Nākamajā vecuma desmitgadē pārgājušo egles mežaudžu īpatsvars pēc sākotnējā vecuma 1975. gadā**

Konstatēts, ka egles audžu saglabāšanos būtiski (p<0,01) ietekmē to vecums: abos reģionos augstākā saglabāšanās bija pirmās vecumklases (0 līdz 20 gadi) audzēm (3.7. att.). Straujš mežaudžu saglabāšanās kritums abos reģionos (3.8. att.) novērots, sākot ar trešo vecumklasi (41 līdz 60 gadi), lai gan Dvietē nozīmīgs samazinājums sākās jau otrajā vecumklasē.



3.8. att. **Vidējais saglabājušos egles mežaudžu īpatsvars pa vecuma desmitgadēm abos reģionos**

Līdzīga audžu saglabāšanās izmaiņu tendence ir novērota arī citos pētījumos, īpaši, dažādu bojājumu—gan vēja (Peltola et al., 1999; Zeng et al., 2007), gan biotisko faktoru (Piri, 1996; Arhipova et al., 2011; Bāders et al., 2018;) ietekmē. Egļu mežaudžu vēja noturības samazināšanās ir sagaidāma, sasniedzot tādas dimensijas, kādas parasti augstāko bonitāšu egles audzēs ir, sākot ar pāreju no otrās uz trešo vecumklasi. Noturības samazināšanos veicina šajā vecumā sagaidāmā stumbra mizas bojājumu un/vai sakņu trupes sastopamības palielināšanās un ar to saistītā stumbra un sakņu koksnes destrukcija. Turklāt augstas biezības audzēs, kurās veikta novēlota un/vai pārlieku intensīva retināšana, vēja noturība samazinās vēl straujāk.

Kopumā konstatētās faktiskās egles audžu saglabāšanās izmaiņu tendences saskan ar modeļu prognozētajām, norādot, ka audžu monetārās un citu ekosistēmas pakalpojumu vērtības saglabāšanai nozīmīga mērķtiecīga to apsaimniekošana, orientējoties uz mērķa caurmēra sasniegšanu ātrāk nekā 80 gados (Katrevičs et al., 2018), jo īpaši – meža tipos ar auglīgām nosusinātām kūdras augsnēm, kur ir paaugstināts vēja bojājumu risks (Samariks et al., 2020).

SECINĀJUMI

1. Parastās egles mehānisko stabilitāti būtiski pazemina stumbra mizas bojājumi, kuri analizētajām eglēm bija vidēji 28±7,3% no stumbra apkārtmēra (no 16% līdz 40,8%). Slodze, pie kuras notiek primārā lūšana, palielinās proporcionāli stumbra tilpumam (paraugkopa no 0,16 līdz 1,32 m^3), un veseliem kokiem šī palielināšanās ir straujāka. Koku ar stumbra bojājumiem lieces momenta pie primārās lūšanas relatīvais samazinājums dažādu dimensiju kokiem, salīdzinot ar nebojātiem, bija nemainīgs: 61%. Bojāto koku lieces moments pie sekundārās lūšanas bija būtiski mazāks nekā nebojāto, neatkarīgi no to dimensijām starpībai sasniedzot 16 $kNm \cdot m^{-3}$.

2. Sakņu trupe (paraugkopā trupējušās koksnes proporcija no celma virsmas laukuma bija no 4 % līdz 94,8 %, vidēji 50±26,5%,) izraisa statistiski būtisku un nozīmīgu parastās egles stabilitātes samazinājumu neatkarīgi no augsnes veida un mitruma, un sakņu-augsnes kamola tilpuma. Tas liecina, ka parastās egles noturība ir atkarīga no laterālo sakņu mehāniskajām īpašībām. Sakņu trupes bojāto koku lieces momenta pie primārās un sekundārās lūšanas relatīvais samazinājums, salīdzinot ar nebojātu koku vērtību, ir attiecīgi vidēji 25,4% un 24,1%.

3. Sakņu-augsnes kamola tilpumam ir būtiska loma koku vēja noturības nodrošināšanā: vienu un to pašu dimensiju vēja izgāztajām eglēm tas bija būtiski mazāks, nekā koku statiskās vilkšanas testos izgāztajām, turklāt izteiktāka šī atšķirība bija tieši nestabilākajās, nosusinātajās kūdras augsnēs. Adaptējoties vēja slodzei, audzēs ar nosusinātām kūdras augsnēm egles sakņu kamola tilpums ir lielāks nekā tādu pašu dimensiju kokiem meža tipos ar minerālaugsnēm, un šīs atšķirības galvenokārt nosaka laterālo sakņu garums.

4. Parastās egles zemāku noturību mežos ar nosusinātām kūdras augsnēm, salīdzinājumā ar minerālaugsnēm, būtiski ietekmē paaugstināts masas centrs.

5. Parastās egles mežaudžu saglabāšanās būtiski samazinās, sasniedzot trešo vecumklasi (41-60 gadi). Mežkopības pasākumu kompleksu egles audzēs nepieciešams adaptēt klimata pārmaiņām, paaugstinot to saglabāšanos līdz galvenās cirtes parametru sasniegšanas brīdim.

REKOMENDĀCIJAS

1. Rekomendējams izmantot zemāku stādīšanas biezumu un/vai augstas intensitātes jaunaudžu kopšanu, saīsinot parastās egles vienvecuma mežaudžu aprites ciklu un laiku, kad audze pakļauta nozīmīgam vēja bojājumu riskam, tādējādi mazinot šī abiotiskā faktora izraisīto bojājumu varbūtību. Īpaši nozīmīga šāda pieeja ir meža tipos ar nosusinātu kūdras augsni. Rekomendētie pasākumi mazinās arī sakņu trupes risku un koksnes destrukciju tādu patogēnu ietekmē, kas var iekļūt stumbrā pa mizas bojājumu vietām, tādējādi papildus veicinot audžu noturību. Tāpat bojājumu risku mazinās koku ar stumbra mizas bojājumiem savlaicīga izvākšana no audzes, nodrošinot izveidotā atvēruma malas kokiem laiku pielāgoties vēja ietekmei. Rekomendējams realizēt meža aizsardzības pasākumus, kas vērsti uz sakņu trupes un briežu dzimtas dzīvnieku nodarīto postījumu ierobežošanu, jo tas vienlaikus mazinās arī vēja bojājumu risku.

2. Turpmākie pētījumi kompleksas vēja ietekmes uz mežaudzēm modelēšanas sistēmas izstrādei veicami ar mērķi kvantificēt sekundāro bojājumu risku vēja skartās audzēs.

PATEICĪBAS

Paldies par atbalstu un palīdzību promocijas darba izstrādē darba zinātniskajam vadītājam Ārim Jansonam un konsultantam Jānim Donim. Īpaši pateicos kolēģiem Robertam Matisonam, Endijam Bāderam, Valteram Samarikam, Didzim Elfertam, Steffen Rust par līdzdalību un palīdzību zinātnisko rakstu sagatavošanā, Unai Neimanei un Renātei Saleniecei par valodas lietojuma koriģēšanu un Tomam Bricim par konsultācijām meteoroloģijā. Izsaku pateicību pārējiem LVMI “Silava” kolēģiem par palīdzību lauka darbu metodikas izstrādē un aprobācijā. Paldies ģimenei un, jo īpaši, manai līgavai.

1. INTRODUCTION

During the last decades, future silvicultural importance of Norway spruce (further in text – spruce) has gradually decreased along with the decline of its habitats as a result of climate change (Yousefpour et al., 2010; Hanewinkel et al., 2013; Cermák et al., 2019). Suitable growing conditions for spruce in Europe are projected to remain in northern part – in both boreal and hemiboreal forest zones (Hickler et al., 2012; Suvanto et al., 2016; Kapeller et al., 2017; Marini et al., 2017). However, in these regions as well, forest damages increase in both frequency and severity under natural disturbances caused by both abiotic and biotic agents, especially in old-growth stands (Jakuš et al., 2011; Marini et al., 2017). Yet, considering the notable both economic and ecological (carbon sequestration) (Ķēniņa et al., 2018) importance of spruce due to its high growth productivity (Pretzsch et al., 2014), spruce will remain to be of high silvicultural importance in Latvia if silvicultural practices will be adapted in terms of prevention and mitigation of negative effects of natural disturbances.

1.1. Frequency of severe winds

Wind is the most important natural disturbance in both European and Latvian forests (Gardiner et al., 2013), where strong winds originate from both North Atlantic extra-tropical cyclones (further in text – cyclones) and thunderstorms (EEA, 2017; Taszarek et al., 2019). Although, during both events the mean wind speed (m s^{-1}) per 10 minutes can reach the threshold to be qualified as a severe gale—20.8 m s^{-1} according to the Beaufort scale (Barua, 2005). Also, frequently forest damages occur during moderate gales—13.9 – 17.1 m s^{-1} (Barua, 2005) as gusts may exceed the mean wind speed for up to 10 m s^{-1} (Sheridan, 2011). During thunderstorms, severe and intensive downwards wind bursts known as squalls may be formed; however, thunderstorms are local, thus potential forest damages are difficult to be forecasted (Schoen & Ashley, 2011). Although, territories affected by thunderstorms rarely exceed several km^2, the effect on forest stands can be devastating (Nagel et al., 2007, 2017). The season of thunderstorms is relatively short compared with autumn—winter cyclones; however, the frequency and severity are expected to increase in future (Rädler et al., 2019).

Most severe wind damage to forest stands in both Europe and Latvia occur during autumn—winter cyclones, which can affect large areas, up to several thousand square km^2, bringing along heavy precipitation (Stewart, 1985; Gardiner et al., 2013; Gregow et al., 2017). Most important are cyclones of North Atlantic origin, which heavily affects North-West parts in Europe while moving inwards to the mainland their force decreases (Dravniece, 2007). Since 1871, daily maximum wind speed and mean annual number of gale days have an upwards trend (Donat et al., 2011; Gardiner et al., 2013). Especially since 1950, more than 130 events with 10 minute mean wind speed reaching 20.8 m s^{-1} (Barua, 2005; Donat et al., 2011; Gregow et al., 2017). In most cases autumn-winter cyclones affect British Isles, North Sea coastal areas and Fennoscandia; however, cyclone tracks are frequently observed to turn more into central areas of Europe, as well as Baltic states (Gardiner et al., 2013). During last 60 years, in Latvia the period between severe wind events has not been longer than 10 years (Fig. 1.1.) (LVĢMC, 2020).

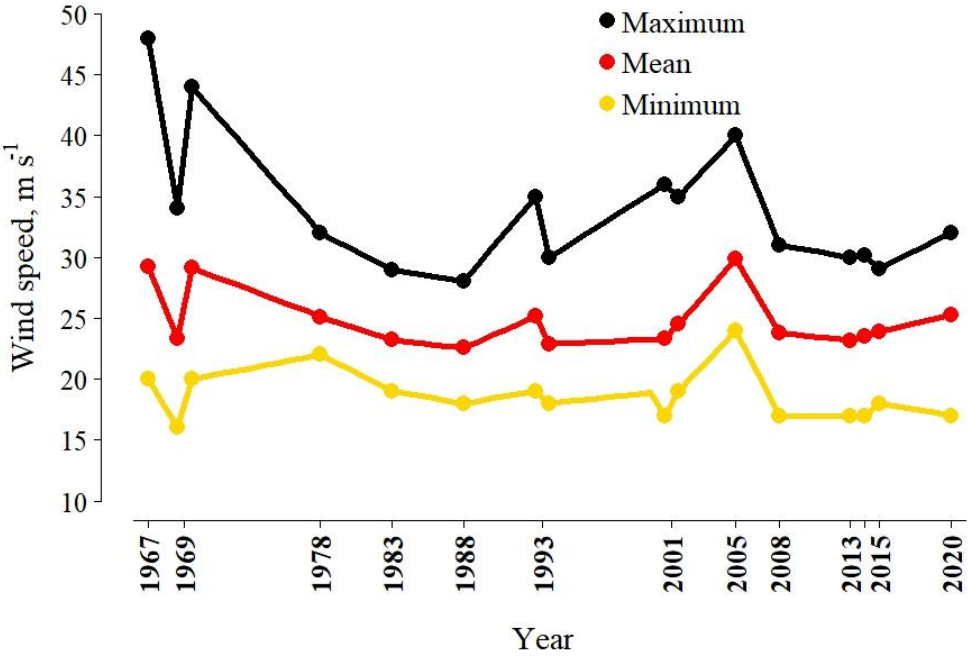


Fig. 1.1. **Most severe wind events in Latvia** (LVĢMC, 2020)
Lines represents the minimum (yellow), the mean (red) and the maximum (black) wind speed of recorded wind gusts during each strong breeze event (LVĢMC, 2020)

1.2. Wind induced damages in forest stands

During autumn-winter cyclone activity, large scale forest damages can occur across Europe, damaging growing stock up to tens of millions of m^3 within one event (Gardiner et al., 2013). In Europe, the amount of damaged wood has increased along with the increase of total volume of standing stock since World War II (UNECE, 2011). Current standing stock volume is estimated to be highest since the Early Middle Ages (UNECE, 2011; Nabuurs et al., 2013; EEA, 2017) and large proportion of European forests consist of old-growth forest stands that are highly susceptible to natural disturbances (Nabuurs et al., 2013). In the last 20 years, in Europe more than 89 thousand reports have been recorded about forest stand damages resulting in up to 1 million ha of affected areas in total. More than 340 million m^3 of damaged wood have been estimated after 6 cyclones during that period (Forzieri et al., 2020). Also in Latvia the amount of damaged forest stands has increased along with proportion of old-growth forests (National Forest Inventory (NMM), 2019). During last 11 years, in Latvia estimated increase of spruce standing stock has reached 16 million m^3 and spruce stand area has increased for about 54 thousand ha (NMM, 2019). In turn, damages caused by wind and ungulates in spruce stands have increased by area as well, 61 and 75 thousand ha, respectively (NMM, 2019; Šņepsts et al., 2018).

The critical wind load for any forest stand corresponding to certain critical wind speed can be estimated as maximum bending moment at the base of the stem causing irreversible damage either as stem fracture or uprooting—secondary failure (Detter et al., 2019). Wind load has no static characteristics. It is formed by series of gusts caused by turbulent movement of air, thus dynamic loading is created (Sheridan, 2011). Therefore, trees appear to fail under cumulative damage caused by dynamic wind loading, thus critical wind speed appears to be lower – wind speed in gusts 25 m s^{-1} is reported to initiate tree failure (Spatz & Speck, 2000; Cullen, 2002; James et al., 2006). Forest stand critical wind speed is determined by various factors, such as orography of landscape, canopy surface of stands, soil conditions, morphometry of trees within target stand and neighbouring stands, silvicultural legacy as well as the presence of biotic disturbances (Fig. 1.2.).

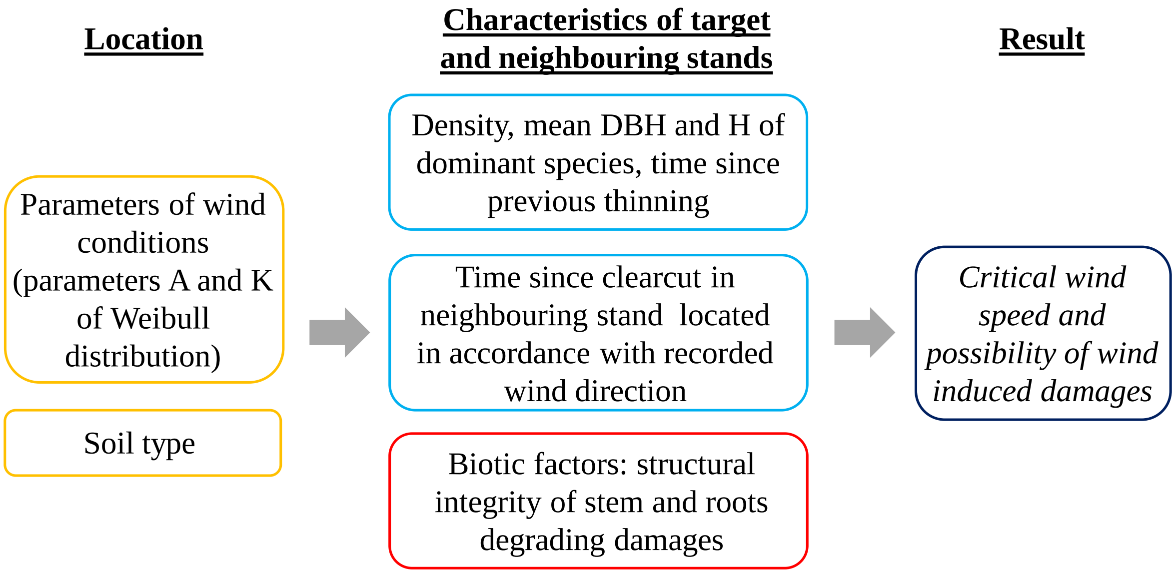


Fig. 1.2. **Conceptual scheme of estimation of forest stand wind resistance** (ERAF, 2019)

1.3. Estimation of potential wind induced damages of forest stands

Magnitude and spatial distribution of potential wind induced forest stand damages can be estimated by analysis of records and forecasts of weather parameters (wind speed in gusts, depth of soil frost, soil moisture, snow or icing load on tree canopies, etc.), information about forest type (soil) and characteristics of target and neighbouring stands. Thus, potential damages can be prevented or mitigated by implementation of planning levels, such as operational, tactical and strategical. Operational planning involves application of records of weather parameters and information about characteristics (soil types and morphometry of trees) of target and neighbouring stands in determining damaged areas, thus, planning of salvage logging can be placed. The level of tactical planning allows current silvicultural practices to be adjusted according to the scale and magnitude of expected wind damage by applying long-term means of weather parameters and information about characteristics (soil types and morphometry of trees) of target and neighbouring stands. Information used in both planning levels supplemented with data from tree growth models allow the planning of wind resilient future forest landscape, thus, the level of strategic planning can be created (ERAF, 2019).

1.4. Factors affecting forest stand wind stability

The characterisation wind resistance of uneven-aged mixed stands is very complex and no appropriate modelling tool available for this purposes. In even-aged stands, parameters, such as dominant species, mean height and diameter, stand density as well as the time period since the last thinning are most important in determining the wind resistance (Donis et al., 2018). These factors can have the effect on forest stand wind resistance either directly or through interactions. For example, higher stand density increase the height/diameter ratio and root competition, thus the stability of individual trees decreases (Gardiner et al., 2013). Most part of spruce stand in Latvia (88.8%, NMM, 2019) represents highest groups bonity (Ia, I, II). During second and third age class, mean height of trees in such stands may reach the threshold that subjects stands to high wind damage risk (Peltola et al., 2010). The mean tree diameter in spruce stands (21.5 cm) corresponds to the begging of the third age class (21.9 cm, NMM, 2019)

Information about distribution of above-ground biomass and dimensions of root plate are considered to characterize the site effect of mechanical stability of spruce (Cucchi et al., 2005;

Nicoll et al., 2006). Assessment of tree mechanical stability in forest stands required a model that predicts distribution of fresh above-ground biomass to be developed as most of currently available models calculate dry biomass (Marklund, 1988); Repola, 2009; Lībiete et al. 2017; Kenina et al. 2018). The distribution of above-ground biomass determines the effect of gravity on critical wind speed as reduced height of mass point increases wind damage risk (Gardiner et al., 2013). In different soil conditions parameters, such as above-ground biomass and dimensions of root-soil plate differs (Nicoll et al., 2006); however, present information is insufficient in comparing the effect on wind resistance in forest stands on peat and mineral soils (Nicoll et al. 2006; Štofko & Kodrík, 2008).

Tree wind resistance largely depends on root-soil anchorage, which is determined by soil conditions (Grime, 2001). Tree rooting adapts to soil mechanical properties by developing a stabilizing root projection under frequent movement caused by wind (Coutts, 1986; Dumroese et al., 2019). Root-soil anchorage is higher in dry mineral soils formed by dense parent material, such as moraine or clay compared with loose parent material soils, such as sand or gravel, especially peat (Štofko, 2010). Although, root projections tend to be larger due to frequent movement (Coutts, 1986; Dumroese et al., 2019). In Baltic Sea region, forest stands situated on peat soils are widely distributed, where spruce stands are highly productive. Thus, evaluation of wind resistance of such stands has high economic and ecological importance (Päivänen & Hånell, 2012; Pretzsch et al., 2014). In Latvia, the most productive spruce stands on peat soils are distributed in such forest types as *Myrtillosa turf.mel.* and *Oxalidosa tuf. Mel.* (Bušs, 1976) and according to data from the National Forest Inventory, within the time period from 2011 until 2018, total area and standing stock of such forest types has increased for 1.78 thousand ha and 0.86 million m^3, respectively (NMM, 2019).

Root-soil anchorage decreases along with the increase of soil moisture, thus promoting root sliding when tree stem swings under wind loading (Mickovski, 2002). During autumn-winter cyclone activity, mostly no soil frost appears to be formed, which intensifies wind induced forest damage together with precipitation, as it was observed during 3 most devastating events in Latvia during last 60 years – in 1967, 1969 and 2005 (LVĢMC, 2020). In future, expected warmer winters in boreal and hemiboreal forest zones are considered to shorten soil-frost period subjecting forest stands to wind damage under insufficient root-soil anchorage during autumn-winter cyclones (Laapas et al., 2019). However, there is still a lack of information about the root-soil anchorage and the effect of biotic disturbances on spruce wind resistance, especially on peat soils.

1.5. The effect of biotic factors

Pathogens are one of the most common biotic disturbances in spruce stands creating structural damages in wood (Piri, 1996; Bendz-Hellgren et al., 1999; Arhipova et al., 2011; Honkaniemi et al., 2017). Severity of pathogen invasion can be intensified by mechanical tree damage as a result of silvicultural activities (Piri & Korhonen, 2008; Metslaid et al., 2018) and stem bark damage (bark-stripping) by large ungulates (Šņepsts et al., 2018; Burneviča et al., 2016). However, the effects of such factors on spruce wind resistance are insufficiently quantified.

Bark-stripping is usually followed by invasion of *Stereum sanguinolentum* (Roll-Hansen & Roll-Hansen, 1980; McLaughlin & Šica, 1996; Vasiliauskas et al., 1996; Čermák & Strejček, 2007; Šņepsts et al., 2018), with speed of axial spreading from 9.6 to 19.5 cm per year reaching up to 6 m from the wound (Čermák & Strejček, 2007; Vacek et al., 2020). Development of such fast progressing pathogens hinders tree recovery from mechanical damage as formation of reaction wood at the edge of wound is slowed (Vacek et al., 2020). Thus, individual stability can be lowered in comparison with undamaged trees within the same stand.

In Latvia, infestation with one of the most common root rot pathogens *Heterobasidion spp.* for spruce on peat soils is 16.3 % on average (Bruna et al., 2018) and the annually mean speed of spreading in roots of forest stands can reach up to 24 cm (Bendz-Hellgren et al., 1999). This pathogen has very high negative economic impact on spruce stands by causing both decline and reduction of wind resistance (Gori et al., 2013). For example, in 41-year-old spruce stands on peat soils, vertical distribution of *Heterobasidion spp.* can reach up to 4 m, thus a significant decline of the whole stand could occur by the end of 80-year rotation period (Bruna et al., 2018). Therefore, evaluation of the effect of root rot on individual tree stability is important in terms of improving the modelling of the effects of climate change on commercial forests (Honkaniemi et al., 2018).

1.6. Evaluation of wind resistance of forest stands

Observation in both Europe and Latvia indicates that the outbreak risk of dendrophagous pests significantly increases along with the increase of proportion of wind damaged forest stands and prolongation of drought periods (Jakuš et al., 2011; Marini et al., 2017; Ruosteenoja et al., 2018). Therefore, information about factors that intensify wind damage is important in prevention of such negative effects. This thesis characterizes the effect of structural wood damage caused by biotic factors on wind resistance of spruce stands.

During the stem bending by wind loading, wood fibre deformation by compression cause a kinking of tracheids of spruce (Detter et al., 2015). Initial stem bending occurs proportionally with the increase of force until the start of wood fibre kinking under the compression deformation. From that point, stem bending increases disproportionally faster than the applied force and, thus, primary failure (PF) has occurred (Detter et al., 2015). Primary failure may occur in both roots and stem and recovery of strength at a pre-damage level may not be sufficient. Trees with primary failure are more likely subjected to secondary failure (SF), such as stem fracture or uprooting (Detter & Rust, 2013). Sufficient root-soil anchorage prevents movement of roots, thus primary failure occurs in stem; however, reduced root-soil anchorage allows root sliding in soil, which may result in structural damage of roots (Detter et al., 2015).

Tree hydraulic conductance is hindered under wood structural deformation by reaching primary failure (Detter et al., 2015, 2019), thus damaged trees are subjected to physiological drought after severe wind events (Ieviņš, 2016). Forest stands weakened by certain disturbances have increased susceptibility towards secondary biotic disturbances that follow, such as outbreaks of dendrophagous pests during post-storm seasons accompanied with drought (Jakuš et al., 2011; Marini et al., 2017) as observed in Central Europe (Nikolov et al., 2014).

Collective stability of forest stands depends on individual tree stability which might differ (Díaz-Yáñez et al., 2017) due to differences in tree location within a stand which determines their tree growth productivity (Dupont et al., 2018). Wind induced damages are frequently observed in central areas of forest stands (Gardiner et al., 2013). Trees within a stand are considered to have higher susceptibility towards wind damage as they tend to be slenderer than edge trees having higher located canopy and thus a mass point (Šēnhofa et al., 2020). Collective stability can be increased by providing an even spatial distribution of individuals (spacing) avoiding gaps in both canopy cover and in rooting distribution. Also, even canopy surface of stand minimizes development of turbulent air motion above the stand, thus reducing energy of local wind gusts (Gardiner & Quine, 2000; Mason, 2002).

Decline of individual trees decreases the collective stability of whole stand (Snepsts et al., 2020). Hindered growth by competition or structurally damaged trees are considered as weak spots within stands. Therefore, stands with damaged trees during previous severe wind events are subjected to increased wind damage risk in following wind gusts as survived trees have insufficiently adapted to a changed structure of the stand (Detter et al., 2015). Nevertheless, eventual wind induced damages can be prevented or mitigated by application of data of weather parameters and information about characteristics of target and neighbouring stands. For example, harvesting should be considered in case of several damaged canopy trees within the stand.

The stability of forest stands can be evaluated by application of static tree pulling tests during which trees are destructively winched till tree fracture or uprooting with simultaneous tilt and force measurements (Nicoll et al., 2006; Peltola, 2006). For example, obtained data are used to calculate primary failure as the basal bending moment (BBM_{PF}) at which deflection of stem starts to increase disproportionally faster than the applied pulling force. Secondary failure (BBM_{SF}) is characterized as maximum bending moment (Detter et al., 2015, 2019). During such tests, absorption of applied force, which would happen during natural motion when tree swings in wind, is not taking place as pulling is static, however, such method is widely used in similar researches with scope of estimation of tree resistance against wind load (Nicoll et al., 2006; Peltola, 2006).

1.7. The aim of the thesis

To assess the effect of root rot and bark-stripping on possibility of wind induced damages in Norway spruce stands.

1.8. Thesis objectives

1. To characterize the possibility of wind induced damages in Norway spruce stands on peat and mineral soils in accordance with distribution of above-ground biomass and root plate dimensions.
2. To characterize the effect of structural strength of wood affecting factors, such as root rot and bark-stripping on the possibility of wind induced damages in Norway spruce stands.
3. To characterize the survival of Norway spruce stands within the rotation period.

1.9. Thesis

1. The effect of bark-stripping reduces the mechanical stability on Norway spruce, thus notably increasing wind damage susceptibility.
2. The effect of root rot caused by *Heterobasidion spp*. on the root-soil anchorage do not differ significantly among peat and mineral soils.
3. Significant destruction of Norway spruce stands starts by reaching dimensions corresponding to third age class (41-60 years).

1.10. Scientific novelty

For the first time in the Baltic Sea region the static tree pulling test has been applied to assess the mechanical stability of large dimension (DBH > 45 cm, H >30 m) Norway spruce individuals. Also, for the first time in the region and whole hemiboreal and boreal forest zones such data have been obtained from Norway spruce stands on peat soils, where effect of root rot on Norway spruce stability has been assessed. Furthermore, for the first time the effect of bark-stripping on the root-soil anchorage of Norway spruce has been tested by application of static tree pilling tests, thus the obtained quantitative information facilitates modelling of the effect of biotic factors on the possibility of wind induced damages in Norway spruce stands.

1.11. Thesis structure

The doctoral thesis consists of five research articles. The effect of bark-stripping and root-rot on the mechanical stability of spruce has been estimated in first two publications (I and II). Distribution of above-ground biomass in accordance with soil type has been estimated in third research article (III). In fourth (IV) publication, description of Norway spruce survival in two forested landscapes has been given, and root-plate dimensions of windthrown Norway spruce situated on both peat and mineral soils has been characteristized in fifth (V) publication.

1.12. Approbation of research results (conferences)

The research results have been reported in six presentations within four scientific conferences.

1. **Krisans O**., Baders E., Donis J., Bickovskis K., Jaunslaviete I. (2020) Long-term survival of Norway spruce in hemiboreal forests. XXth International Multidisciplinary Scientific GeoConference Surveying, Geology and Mining, Ecology and Management – SGEM 2020, 16.-25.08.2020, Albena, Bulgaria. (Poster)
2. **Krisans O**., Samariks V., Bickovskis K., Jaunslaviete I., Zute D. (2020) Root characteristics of wind-thrown Norway spruce. XXth International Multidisciplinary Scientific GeoConference Surveying, Geology and Mining, Ecology and Management – SGEM 2020, 16.-25.08.2020, Albena, Bulgaria. (Poster)
3. **Krisans O**., Racenis E., Rieksts-Riekstins R., Donis J., Rust S., Jansons A. (2020) Browsing damages reducing wind stability of Norway spruce (Picea abies (L.) Karst.) in hemiboreal forests, Latvia. The 9th International Wind and Trees IUFRO conference “Planning for an uncertain future: wind risk to forests and trees in a changing climate”, 21.02.-08.03.2020, Rotorua, New Zealand.
4. Jansons A., **Krisans O**., Donis J., Rieksts-Riekstins R., Bruna L. (2020) Impact of root-rot on wind stability of Norway spruce (Picea abies (L.) Karst.) in hemiboreal forests, Latvia. The 9th International Wind and Trees IUFRO conference “Planning for an uncertain future: wind risk to forests and trees in a changing climate”, 21.02.-08.03.2020, Rotorua, New Zealand.
5. Baders E. Dubrovskis E., Snepsts G., **Krisans O**., Kapostins R., Jansons A. (2018) Resilience Norway spruce forests: case study in Latvia. 8th edition of the International symposium forest and sustainable development, 25-27.10.2018., Brașov, Romania. (Poster)
6. Snepsts G., **Krisans O**., Dubrovskis E., Kapostins R., Jansons A. (2018) Effect of injuries on stability of Norway spruce. LIFE+ ELMIAS Ash and Elm, and IUFRO WP 7.02.01 Root and Stem Rots Conference (LIFE-IUFRO), 26.08-01.09.2018, Uppsala and Visby, Sweden. (Poster)

2. MATERIAL AND METHODS

2.1. Characteristics of above-ground biomass and root plate dimensions of Norway spruce

Measurements are carried out in stands with both peat and mineral soils located in North-West, central and eastern parts on Latvia (57°14'N 22°42'E, 57°34'N 22°18'E, 56°40'N 23°53'E, 56°41'N 25°50'E, 56°75'N 23°85'E). Above-ground biomass was determined for 87 trees by weighing stem after cutting into 2 m long sections separated from branches. Dimensions, such as rooting depth along radii (in 0°, 45°, 90°, 135° and 180° sectors) from the stem to the edge of root plate of 64 windthrown trees were measured. In each of these radii, root plate thickness was measured at every 0.2 m (Fig. 3.1.). The volume V (m^3) of root plate was calculated using elliptic cone volume equation:

$$V = \left(\frac{1}{3}\right) * \pi * a * b * h, \tag{1}$$

where:
h – mean height of root-plate centre (depth);
a – vertical radius of the root-plate;
b – mean horizontal radius of the root-plate.

As control, data from static pulling tests were selected from investigations conducted in commercial Norway spruce stands with similar characteristics as the wind-thrown stands. Control data from trees situated on drained peat soils were obtained from studying the effect of root-rot on mechanical stability (56°41'N 25°50'E). For mineral soils, root-plate dimension data from pulling tests carried out in summer 2020 in central part of Latvia (56°40'N 23°53'E) are used. The approach of tree height multiplied by DBH squared ($HDBH^2$) was used to estimate the susceptibility of trees towards the tipping as shown by Peltola et al., (2000). In the generalized additive model, the structural root depth distribution was calculated using relative root depth and relative distance from the stem were as predictors.

Calculation of above-ground biomass was done by using linear model where DBH, H and mass point of weighed 2 m sections. Pearson correlation and Principal Component Analysis was used to test the variation of tree morphometric parameters in accordance to soil type. The height of mass point (H_{mp}) of each tree was calculated using height and weight values of mass centres of weighed 2 m sections.

$$H_{\mathrm{mp}} = \frac{\sum m * h}{\sum m}, \tag{2}$$

where:
m – a mass (kg) of weighed 2 m sections;
h – the middle point of the H of tree (m).

Height of the relative mass point is a proportion of total H. Statistical analysis was done using program R (version 4.0.0.) (R Development Core Team, 2019).

2.2. Static tree pulling tests

Static tree puling tests were applied in order to characterize the effect of both root rot and bark-stripping on the mechanical stability of spruce. Study was carried out in stands located in central part of Latvia – 4 in The Forest Research Station and 1 in Skogssallskapet Ltd. owned forests. All were spruce monocultures situated on peat (*Oxalidosa tuf. Mel* and *Myrtillosa turf.mel*) and drained mineral (*Hylocomiosa*) soils. In those stands, both damaged and control trees were selected representing DBH classes (each class is 4 cm step) of each stand. The presence of fungal pathogens was tested in the laboratory from increment cores extracted below the root collar from the opposite sides of stem. Trees with the presence of fungal pathogens were selected as sample trees. The presence of *Heterobasidion spp.* in the samples was confirmed by observing its characteristic asexual sporulation (conidiophores). Based on these results, in each stand tree pulling tests were performed within the same season. To characterize the effect of bark-stripping on spruce mechanical stability, trees with 7-9 years old wounds (located on stems at the height of 0.8 to 1.5 m from ground) were selected. Trees with no visual damages were selected for control. The scale of the damage was quantified by measuring the proportion of damaged wood on the circumference of the stem. For root rot, the proportion of decayed wood was measured from the cross-section of stump and was used to quantify the scale of the effect of fungal pathogen.

During the pulling test, dynamometer (DI Fig. 2.1.) was used to measure both tree resistance against static loading and the angle (α) between pulling line (VL) and horizontal sight line between anchoring and sample tree (l1). To minimize the effect of both gravity and own mass, all tested trees were de-topped prior the test at the height of 1 m above the half of the total height (GA). On the sample tree, the pulling line was anchored 1 m bellow the topping (EP1) to prevent the slip-over of the anchoring sling. Pulling was done using manual winch (MV) with steel cable prolonged with polyester rope. Winch was anchored at the base of tree located opposite in the distance ~40 m (EP2). During the pulling, measurements of pulling force were recorded simultaneously with stem deflection on the root plate (IM0) and at the height of 5 m (IM5).

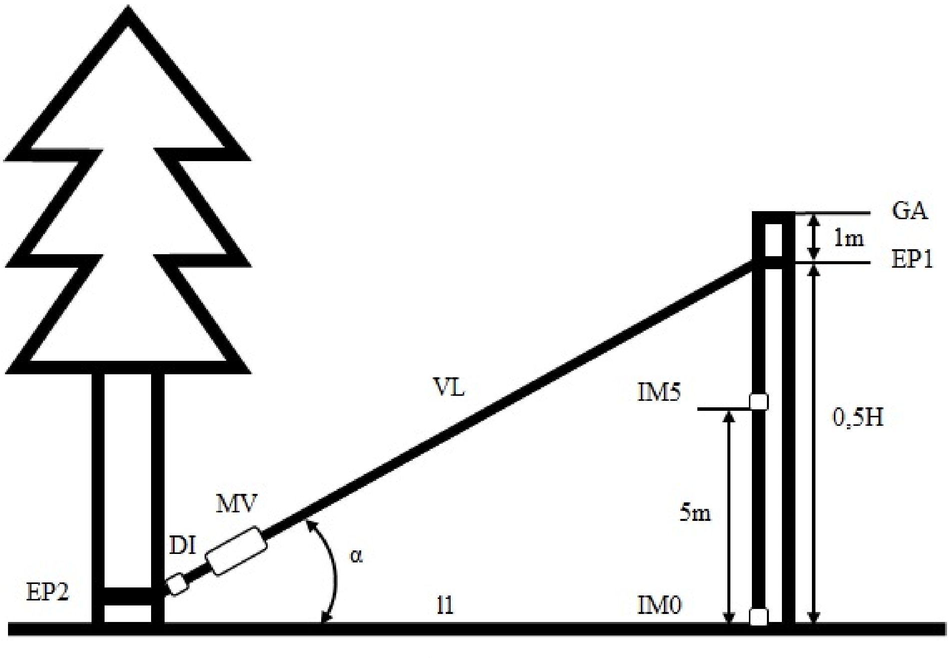


Fig. 2.1. **Scheme of static tree pulling test**

EP1 and EP2 – anchoring of pulling line on the sample tree and anchoring tree, respectively; l1 – distance from sample tree to anchoring tree; α – angle between VL and l1; DI – dynamometer; MV – manual winch; 0.5H – half height of sample tree; GA – topping height; IM0 and IM5 – inclinometers on the root plate and on the height of 5 m

For each tree, basal bending moment BBM (kNm) was calculated as

$$BBM = F * h_{\mathrm{AP1}} * \cos(\mathrm{median}_{\alpha}), \quad (3)$$

where:
F – a pulling force;
h_{AP1} – the anchoring height of the pulling line on the sample tree;
median_α – median of the angle between the pulling line and ground.

Stem deflection (N_Δ,) was expressed as the difference between readings of inclinometers done on the root plate (N_0) and on the stem at the height of 5 m (N_{5m}):

$$N_\Delta = N_{5m} - N_0 \tag{4}$$

The BBM and the end of proportional increase of N_Δ and BBM was defined as BBM_{PF}, while tree failure at the highest value of BBM was defined as BBM_{SF}. The volume of root plate V (m^3) was calculated as the volume of an elliptical paraboloid as follows:

$$V = \left(\frac{1}{2}\right) \cdot \pi \cdot a \cdot b \cdot h, \tag{5}$$

where:
a and b – largest and smallest radii (m) of root plate, respectively;
h – maximum depth of root ball (m).

The data were analysed using "readr", "tidyverse", "DBI", "zoo”, "RSQLite", "ggplot2” and “ez” packages in program R (version 3.5.3) (R Core Team, 2018).

2.3. Survival of spruce stands

Survival of spruce stands is characterized in two forest landscapes in Latvia – West (Vāne) and East (Dviete) part, using data obtained from forest inventories carried out between 1975 and 2016. Maps of historical inventories were scanned and adjusted to coordinate system of LKS-92 by georeferencing using program ArcGIS 10.2. Furthermore, digitalised spatial data forest inventories from 2011 and 2016 were obtained from the State Forest Service. Maps revealing changes of forest stand composition throughout last 40 years were prepared based on information from those five forest inventories in Vāne and Dveite, respectively.

Dynamics of spruce stands were analysed by determining both the age class (20-year step) and coefficient of dominant species in according year of inventory, respectively. Stands above 4th age class were excluded from the analysis as the age of spruce rotation period was 80 years, thus harvesting might be the limiting factor of survival of such stands. In program R (version 3.5.3.) (R Core Team, 2018), linear mixed-effect model was used to test the effect of variables, such as coefficient of dominant species and age on the dynamics of proportion of dominant species and age classes. The identifiers of stands that has transitioned into next age class were used as random effects in the model. However, spatial autocovariant was used to assess spatial interactions among independent variables, such as region, age class and the year of inventory. Chi-square ($\chi 2$) test was applied to test proportional differences of age classes between regions and inventories.

3. RESULTS AND DISCUSSION

3.1. Characteristics of distribution of above-ground biomass and dimensions of root plate of spruce

Spruce stability is largely affected by soil-root anchorage and the height of mass centre and these parameters can be characterized by root plate volume and the distribution of above-ground biomass (Cucchi et al., 2005; Nicoll et al., 2006).

Vertical rooting is considered as one of the most important factors affecting tree mechanical stability (Coutts, 1986; Dumroese et al., 2019). In this study, vertical rooting is detected as standardized measurements of root plate thickness along radius from stem to the edge of root plate. Thickness of root plate decreased along with the increase of distance from stem by the radius having strong and significant negative correlations ($r = -0.99$, $p < 0.001$) in both peat and mineral soils (Fig. 3.1.).

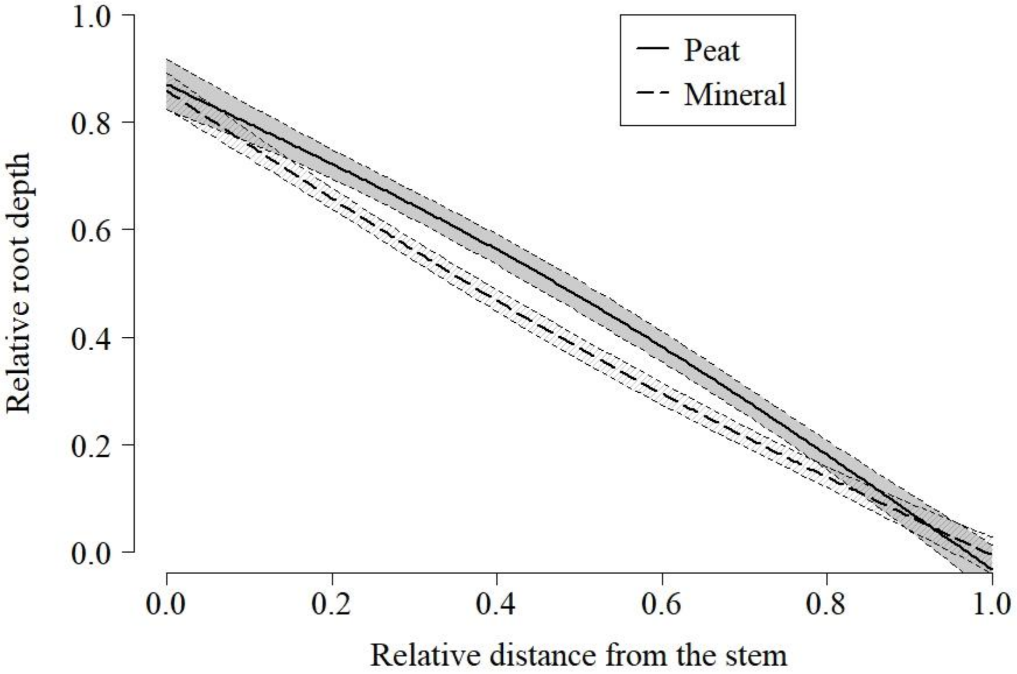


Fig. 3.1. **Relative structural root-plate depth distribution at measurement points of relative distance from the stem in peat and mineral soils**
Grey area denotes 95% confidence interval

Mean thickness of root plate right below the stem (centre) was 49.2 ± 6.6 cm (95% confidence interval) in peat and 28.3 ± 2.3 cm in mineral soils, respectively. Within first meter, root plates were thicker in peat soils, and towards the edge a decrease of thickens appears more pronounced in comparison with mineral soils (Fig. 3.1.). Thus, showing differences in root-soil anchorage (Nicoll et al., 2006) as spruce stability depends on horizontally developed lateral roots due to insufficient vertical rooting. For example, in the case of high depth of groundwater table (Ray & Nicoll, 1998; Štofko, 2010).

In accordance with Nicoll et al. (2006), root-plate volume was lower for trees growing on mineral soil (0.50 ± 0.14 m^3), while trees on drained peat soils tend to have larger values (1.5 ± 0.3 m^3), and this difference was statistically significant ($p < 0.001$). Also, mean root-plate volume of control trees was significantly higher compared with uprooted trees (Fig. 3.2., Fig. 3.3.)—1.3±0.5 m^3 and 5.5±1.0 m^3 in mineral and drained peat soils, respectively.

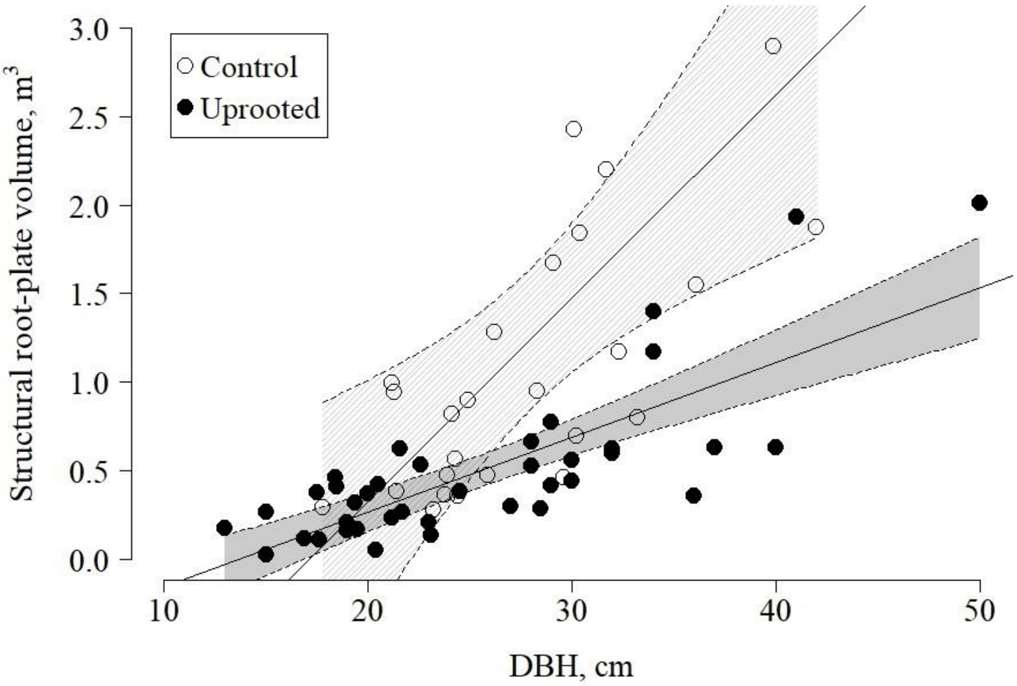


Fig. 3.2. **Root-plate volume against diameter at breast height of windthrown and control trees in mineral soil**

Grey area denotes 95% confidence interval

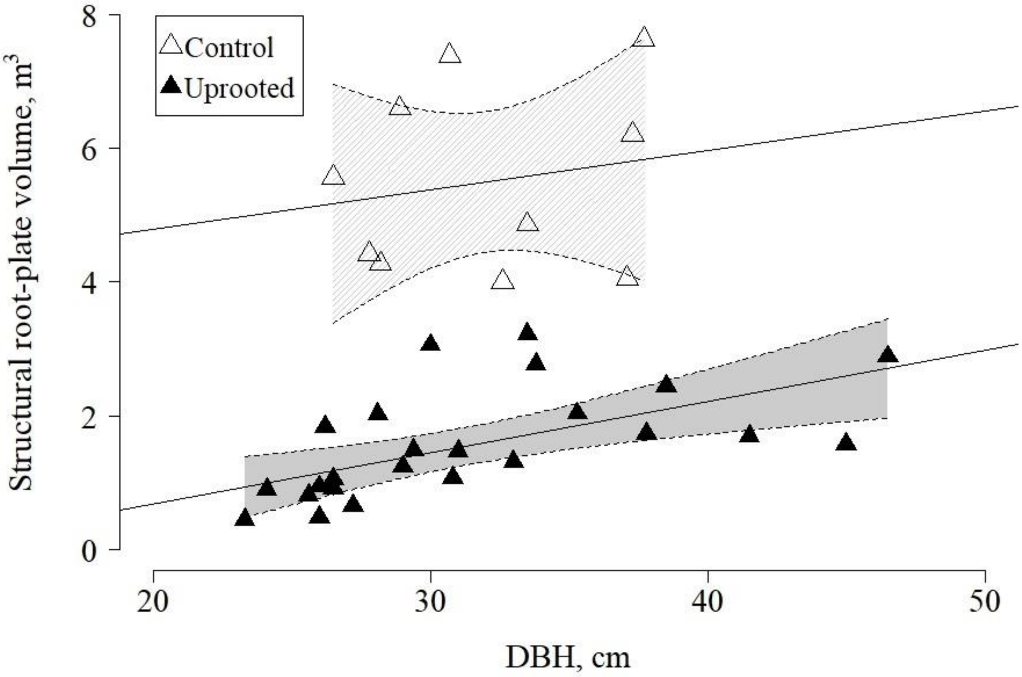


Fig. 3.3. **Root-plate volume against diameter at breast height of windthrown and control trees in peat soil**

Grey area denotes 95% confidence interval

Additionally to root-plate volume, wind resistance is increases by higher root-plate mass as the height of mass point of tree reduces by heavier root-plate, which is affected by the soil moisture and soil mechanical properties (Nicoll & Ray, 1996; Niccol et al., 2006). Also, tree adaptation to local growing conditions determines the ability of roots to maintain the wind resistance in accordance with silvicultural management history of the stand and natural disturbances (Schelhaas et al., 2003). By the tree growth, the capacity of recovery of root system reduces, thus increasing risk of failure (Puhe, 2003).

Differences in spruce wind resistance between soil types might be shown as differences in root plate volume, which was lower in mineral soils (Nicoll et al., 2006). However, as the importance of DBH in determining root-plate volume was indicated, a HDBH^2 was calculated. This parameter, which is known to describe tree wind resistance to uprooting in mineral soils (Peltola et al., 2000), showed significant differences ($p < 0.001$) between soil types. Although, mean values of HDBH^2 for mineral soil were lower in comparison to drained peat soils, by the increase of root-plate volume, the estimated values of HDBH^2 increased more rapidly in mineral soils (Fig. 3.4.), indicating better anchoring of smaller root-plates for larger trees in mineral soil, or, to state otherwise – need for proportionally larger soil-root plate to sustain larger trees in drained peat soil. .

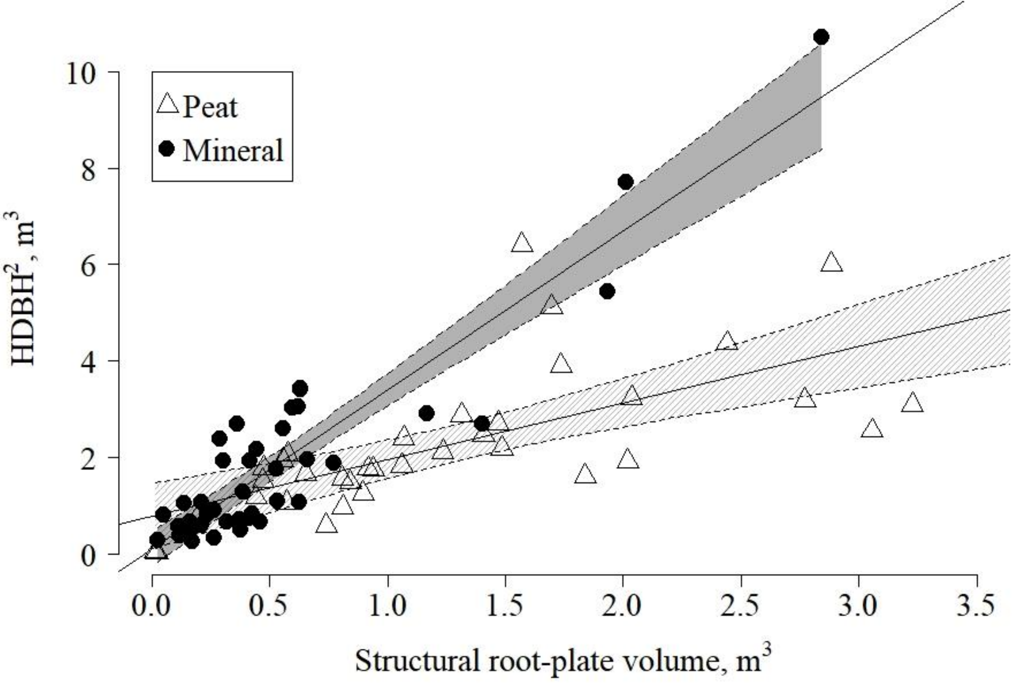


Fig. 3.4. **Relationship between stem dimensions (HDBH^2) and root-plate volume in peat and mineral soils**

Grey area denotes 95% confidence interval

The distribution of above-ground biomass of fresh wood determines the height of mass point, which is affects tree stability as lower this point is, larger load is required for failure (Cucchi et al., 2005; Nicoll et al., 2006). The mean total weighted above-ground biomass was 1730 ± 576 kg and mean value for weighted 2-m section was 66.36 ± 2.97 kg. Values obtained by model of fresh above-ground biomass distribution (table 3.1.) has tight and significant correlation with results of weighing ($r = 0.98$, $p < 0.001$) (table 3.2.). However, predicted values varied for stem base due to lower slenderness compared with other part of stem. In accordance with Marklund (1988) and Repola (2009), obtained model is based on DBH and H:

$$m_{ij} = \beta_2 h_{ij} + \beta_3 DBH_i^2 + \beta_4 h_{ij} DBH_i^2 + \beta_1, \tag{6}$$

where:

m_{ij} – mass of stem fragment (kg);

h_{ij} – height of stem fragment (m);

DBH_i – stem diameter at breast height (cm).

Table 3.1.

Values of above-ground biomass distribution model

Parameter	Value	Standart error
β_1	0.44	0.194
β_2	- 0.163	0.201
β_3	0.083	0.001
β_4	- 0.087	0.001

Table 3.2.

Pairwise Pearson`s correlation coefficients and p-values among variables of Norway spruce

Parameter	DBH	H	Stem fresh weight (kg)	Estimated biomass (kg)
DBH	1	< 0.001	< 0.001	< 0.001
H	0.79	1	< 0.001	< 0.001
Stem fresh weight (kg)	0.36	0.29	1	< 0.001
Estimated biomass (kg)	0.39	0.32	0.98	1

Evaluation of distribution of above-ground biomass was done by Principal Component Analysis, which showed 83% of explained variations for both first (53%) and second (30%) component. Explained variation of first component was dependent on H and DBH, biomass of both stem and canopy, and relative height of mass point. The relative height of mass point was identified as wind resistance determining factor having positive correlations with H ($r = 0.64$, $p < 0.001$), mass of stem ($r = 0.61$, $p < 0.001$), DBH ($r = 0.55$, $p < 0.001$) and height of lowest living branch ($r = 0.57$, $p < 0.001$). However, relative height of mass point had higher correlations with biomass of canopy ($r = 0.77$, $p < 0.001$). Thus, relative height of mass point, which is stem and canopy dimension dependent has significant effect on wind resistance of spruce. Reduction of this height increases wind resistance significantly (Cucchi et al. 2005; Nicoll et al. 2006). However, explained variation of second component was soil type dependent ($p < 0.008$) having positive correlation with relative height of mass point and the height of lowest living branch, while negative correlation was observed with relative height of canopy, which varied between 34% and 44% from H.

Results suggest that morphometric parameters of stem and root plate of spruce varies significantly between soil types, such as peat and mineral. In stands with peat soils, canopies have smaller both mass and height proportion from H, thus spruce in such growing conditions tend to have higher located mass point. Therefore, reduction of root plate thickness, which determines lower root-soil anchorage in combination with difference in dimensions of above-ground parts, explains differences in wind resistance of spruce stands on peat and mineral soils.

3.2. Static tree pulling tests

Root rot and bark-stripping are considered the most common biotic disturbances in spruce stands causing significant structural damages of wood (Wagener 1963; Shibata & Torazawa, 2008; Honkaniemi et al., 2017; Cukor et al., 2019). Therefore, assessment of such effect can provide significant information that could be used in improvement of wind damage predicting algorithms. Damaged spruce individuals were tested applying static tree puling test (Peltola, 2006).

The presence of either type of biotic damage reduced both BBM$_{PF}$ and BBM$_{SF}$ significantly regardless the proportion of damage – proportion of removed bark from stem circumference (mean 28.1 ± 7.3%) and the proportion of decayed wood from the area of stump cross-section (mean 50.3 ± 26.5%). Primarily, main factor determining tree stability was stem volume; however, both biotic agents significantly reduced both PF and SF in comparison with control trees in the same stands and soil types (Fig. 3.5. and 3.6.). Obtained values are comparable with results from similar studies elsewhere in Europe (Lundström et al., 2007; Peltola et al., 2010; Jillich et al., 2013). Contrary to expectations, bark-stripping reduced root-soil anchorage, not the mechanical strength of stem wood. After reaching SF, tested trees uprooted rather than fractured in stem. However, the influencing factors affecting failure type was not possible to be analysed as limited number of the trees fractured. Uprooting is the most common tree failure type in spruce stands (Gardiner et al., 2013).

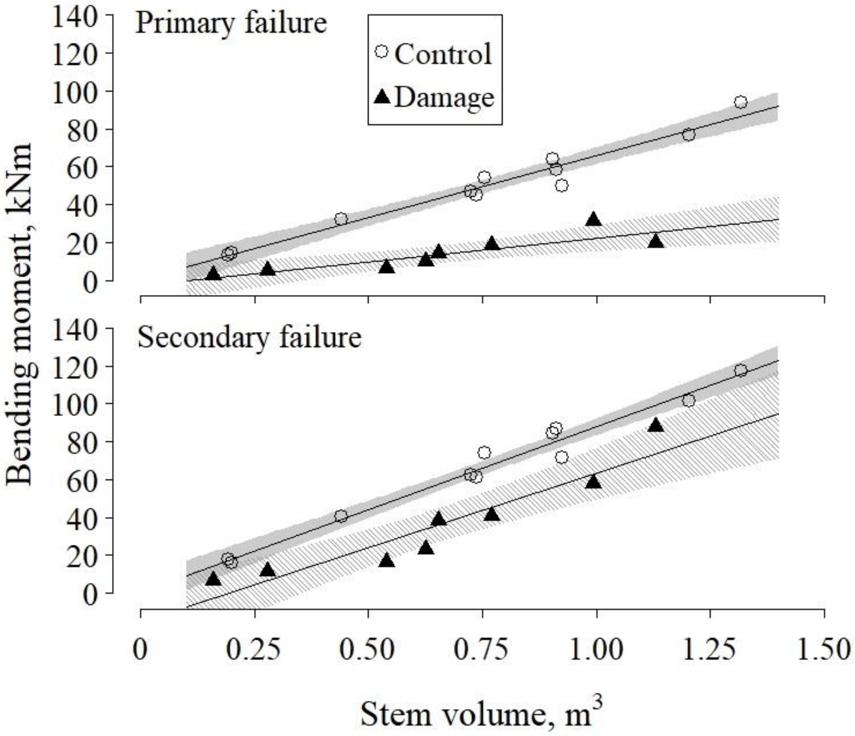


Fig. 3.5. **Basal bending moment of the Norway spruce stem at the primary and secondary failure according to stem wood volume and presence of bark-stripping wound**
Grey area denotes 95% confidence interval

By the presence of bark-stripping BBM$_{PF}$ was reduced proportionally (value differences between undamaged and damaged trees as proportion from value of undamaged trees) regardless to tree size as 61 % less load was required to reach PF. However, mean reduction of BBM$_{SF}$ was 16 kNm·m^{-3} (Fig. 3.5.). Bark-stripping disrupts conductive tissues altering sap flow pattern, thus causing risk of physiological drought (Cukor et al., 2019) and loss of energy of growing (Vasiliauskas, 2001). Under disturbed tree hydraulic conductance, energy from growing purposes is allocated for heeling. Therefore, it could be speculated that damaged trees do not locate enough carbon into root system, thus they become more susceptible to uprooting (Szoradova et al., 2013; Honkaniemi et al., 2017). Physiological processes of trees can be altered by pathogen invasion through stem wounds as well (Szoradova et al., 2013; Burneviča et al., 2016; Honkaniemi et al., 2017; Cukor et al., 2019). In stem cross-sections taken at the widest parts of wounds, decayed wood was not found; however, trees with such bark damage are under the risk of invasion of root pathogens (Deflorio et al., 2008; Burnevičа et al., 2016), thus root-soil anchorage could be reduced under the presence pathogens in roots (Vasiliauskas, 1998; Honkaniemi et al., 2017).

The presence of root rot causing pathogens reduced both BBM_{PF} and BBM_{SF} significantly regardless to soil type and moisture, as well as root plate volume, suggesting spruce mechanical stability to be dependent on mechanical properties of lateral roots (Fig. 3.6.). Mean reduction of both BBM_{PF} and BBM_{SF} was 25.4% and 24.1%, respectively. It should be noted that the selection of sample trees to test the effect of root rot on spruce stability was done for trees with confirmed presence of *Heterobasidion spp.*; however, often other root rot pathogens, such as *Armillaria spp.* and *Resinicium bicolor* were also detected in the same trees.

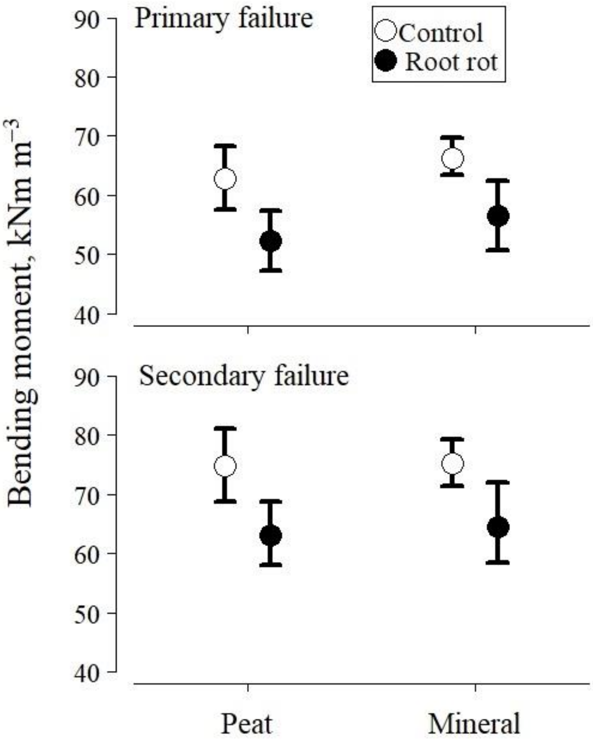


Fig. 3.6. **Basal bending moment of the Norway spruce at the primary and secondary failure according to stem wood volume and root rot in peat and mineral soils**

The presence of both biotic factors significantly reduced resistance against static loading of spruce, which is shown by lower values of both BBM_{PF} and BBM_{SF}. Reduction against BBM_{PF} leads to increased risk of wood fiber kinking under compression loading, while decrease of resistance against BBM_{SF} means lowered threshold of maximum resistance (Detter et al., 2015). Wood fiber kinking disrupts water conductive system of the tree leading to reduction in vitality and growth. Also, after such damage in roots, not only a physiological drought can follow but invasion risk of root rot pathogens increases (Seidl & Blennow, 2012). As Honkaniemi et al., (2017) showed, trees that are affected by biotic disturbances have increased risk to suffer wind induced damages and initially healthy trees that have survived strong wind event have an increased risk of damages caused by secondary biotic agents (Seidl et al., 2017). Under expected circumstances with increased frequency and severity of strong wind events in the future (Mölter et al., 2016), bark-stripping and root rot caused wood structural damages are considered to be significant factors affecting survival of spruce stands.

Expected negative effects could be prevented or mitigated by implementation of appropriate silvicultural practices, such as establishment of plantations with low initial spacing or timely high intensity thinning without mechanized approaches. Thus, minimizing of both root contacts and damages are expected to decrease the risk of pathogen invasion (Stenlid &

Redfern, 1998). Intensified game management, lower stand densities and avoidance of mechanized commercial thinnings would reduce distribution of stem bark damages in spruce stands (Baders et al., 2017; Katrevičs et al., 2018).

Identification and removal of damaged trees from young and middle-aged stands can provide sufficient adaptation time to develop mechanical stability of remaining trees at the edges of newly formed openings. Moreover, shortened rotation period could reduce the period of time when spruce stands are subjected to notable risk of wind induced damage (Donis et al., 2020; Samariks et al., 2020). However, in case of necessity a replacement of stands right after significant disturbances might reduce the risk of further degradation of affected stand.

3.3. Survival of spruce stands

Regional differences are pronounced in survival of spruce stands also in the relatively small territory such is Latvia (Zeltiņš et al., 2019). Thus, both analysed regions (Dviete in the East and Vāne in the West) were selected to characterize these differences.

In Dviete, the proportion of stands successfully transitioned between inventories from 1975 to 1985 was 76.5% while in Vāne it reached 93.1%. However, the cause of reduction of spruce stands is unknown. In Dviete, failed transitioning of older stands between inventories from 1975 to 1985 could be explained by wind induced damages in the period until 1983 (Fig. 1.1.), especially in 1967 when the most severe wind storm damages were observed in southern part on Latvia (Bengtsson & Nilsson, 2007; Hanewinkel et al., 2008, 2011; LVĢMC, 2017). Occasionally, storm-survived stands decline during the following years after the damage under the damage of secondary biotic agents, such as dendrophagous pests (Nikolov et al., 2014; Deschênes et al., 2019). According to data obtained from State Forest Service, observed decline on stands of third age class in the inventory of 2016 might be intensified by outbreak of spruce bud scale (*Physokermes piceae* Schrank.) in 2010 (Bāders et al., 2018) (Fig. 3.7.). During whole observation period, higher spruce stand survival between inventories was observed in Vāne ($p < 0,001$). In both regions, higher survival was observed for first age class (0-20 years) (Fig. 3.7.). However, the start of rapid decrease of survival (Fig. 3.8.) was observed for stands in the third age class (41-60 years), and in Dviete such trend started in second age class (21-40 years).

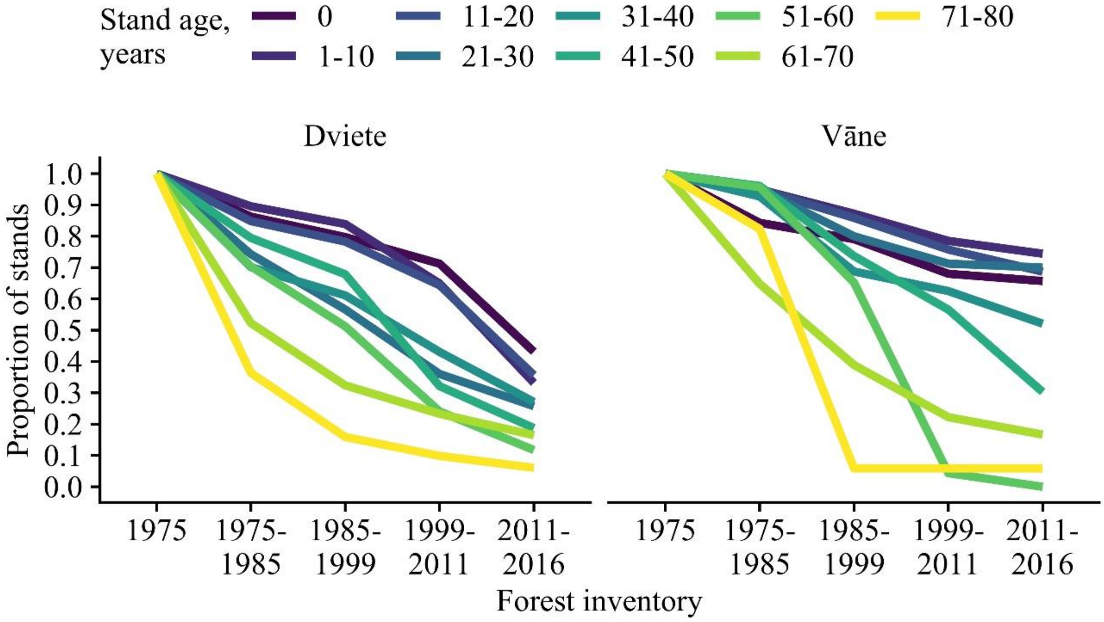


Fig. 3.7. **The proportion of successfully transitioned Norway spruce stands in both landscapes by the initial age in 1975**

Increase of susceptibility to damages in spruce stands is expected when transitioning into third age class, especially with the presence of bark-stripping and root rot in spruce stands. In our study, stand age was the most important factor that affected transition of stands into next age class ($p < 0.001$) as proportion of survived stands decreased by the increase of age. Similar trend has been observed in other studies where intensity of both biotic (Piri, 1996; Arhipova et al., 2011; Bāders et al., 2018) and wind (Peltola et al., 1999; Zeng et al., 2007) damage increased by stand age. The reduction of wind resistance of spruce stands is expected to decrease by reaching dimensions corresponding to most productive bonity (Ia, I, II)—typically in third age class. Also, risk of bark-stripping or invasion of root-rot increases in such age class, especially in dense stands with delayed or high intensity thinning.

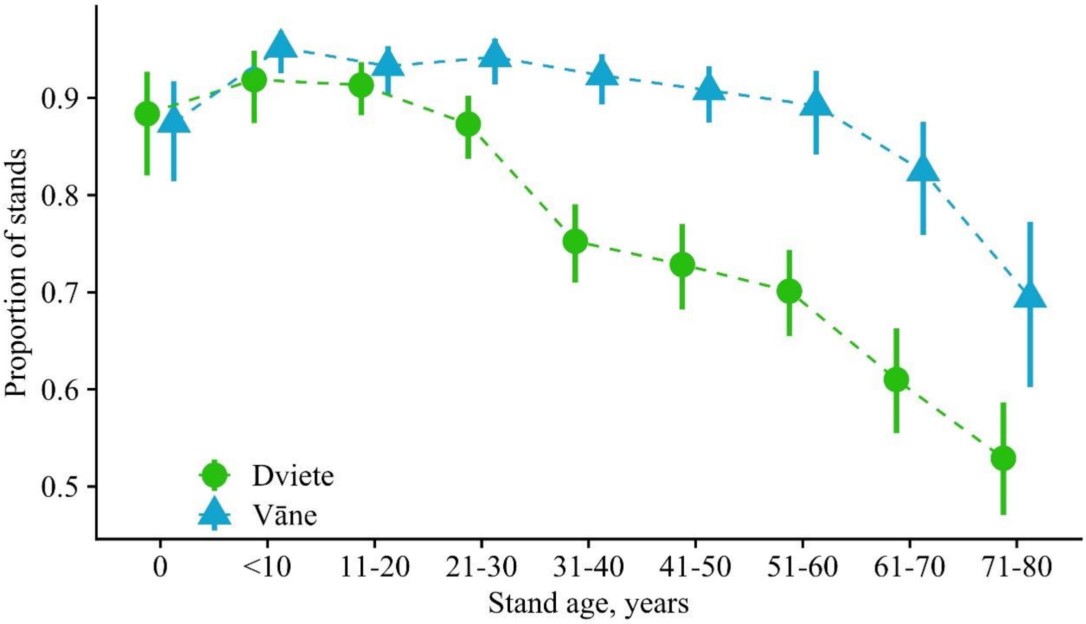


Fig. 3.8. **Mean proportion of survival of Norway spruce stands by age groups in both regions**

Observed tendencies in survival of spruce stands corresponds to model predictions, suggesting the importance of appropriate management in increasing spruce stand wind resistance. Results of economic evaluation of wind damage on spruce stands indicate to stand age as notable factor that increases risk of wind damage, thus shortened rotation period (50-60 years) is considered as appropriate solution in avoidance of notable decline of spruce stands (Katrevičs et al., 2018), especially with fertile soils, such as peat (Donis et al., 2020; Samariks et al., 2020). Therefore, forest owners should be allowed to implement most suitable management solutions, such as felling accordingly to target DBH, thus both potential economic and ecological losses could be reduced.

CONCLUSIONS

1. Mechanical stability of Norway spruce is significantly reduced by the consequences of bark-stripping wounds (from 16 to 40.8 % from stem circumference). Loading resistance was tightly linked to stem volume (from 0.16 to 1.32 m^3): basal bending moment at primary failure increased gradually with tree size for damaged trees and sharply for undamaged. Relative reduction (in comparison to undamaged trees) of basal bending moment at primary failure remained constant regardless of tree size: 61%. The mean reduction of loading necessary for secondary failure was 16 $kNm \cdot m^{-3}$ regardless to tree size.

2. The presence of root rot (from 4 to 94.8 % of stump surface) reduced mechanical stability of Norway spruce regardless of soil type and moisture, and root-soil plate volume. Thus indicating the dependence of spruce stability from mechanical properties of lateral roots. Mean relative reduction of basal bending moment at primary and secondary failure due to presence of root-rot in comparison to values of healthy trees, was 25.4% and 24.1%, respectively.

3. Root-plate volume has a crucial role in ensuring tree mechanical stability: it was significantly smaller for wind-thrown trees than for the ones uprooted in the static pulling tests; this difference was more pronounced in less stable, drained peat soil. In this soil adaptation to wind loading requires development of larger root-soil plate, primarily linked to longer lateral roots, than in freely drained mineral soil.

4. Norway spruce growing on drained peat soils have higher mass point, causing lower mechanical stability, than on mineral soil.

5. The survival of Norway spruce stands significantly decreases from the third age class (41-60 years). The silvicultural practices in Norway spruce stands needs to be adapted to climate change, increasing the survival of trees till they reach the target dimension for final harvest.

RECOMENDATIONS

1. To reduce probability of wind damages, lower initial density of planted stands and/or higher intensity of pre-commercial thinning is recommended, with increases the radial growth and shortens the period, when trees reach the target diameter for final harvest. Especially important this approach is in stands on drained peat soil. In this way also the time when stands are subjected to significant wind damage risk is reduced, thus minimizing the probability of such disturbance. Recommended approach will also minimizes the risk of root rot and decay of wood caused by pathogens entering the tree via bark-stripping wounds, thus further improving wind resistance of the stands. Timely removal of tree with bark-stripping wounds from the stands is recommended to provide sufficient adaptation period to develop mechanical stability of remaining trees. Implementation of protection measures against bark striping and root rot will also minimize the wind damage risk in Norway spruce stands.

2. Further research is required for development of models considering whole spectrum of wind effects on Norway spruce stands, including quantification of changes in probability of secondary abiotic and biotic damages.

ACKNOWLEDGEMENTS

I thank my supervisor Āris Jansons and consultant Jānis Donis for support and assistance in the conceptualization and development of the dissertation. Special thanks to my colleagues Roberts Matisons, Endijs Bāders, Valters Samariks, Didzis Elferts, and Steffen Rust for their involvement in preparing scientific articles. I thank Una Neimane and Renāte Saleniece for correcting the use of language, and Toms Bricis for consultancy about meteorology. Additionally, I would like to thank to many other colleagues of LVMI "Silava" for their help in developing and approbating the fieldwork methodology. My family, especially my bride, deserves most of gratitude.

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Article

Effect of Bark-Stripping on Mechanical Stability of Norway Spruce

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Received: 28 February 2020; Accepted: 20 March 2020; Published: 21 March 2020

Abstract: The increasing effects of storms are considered the main abiotic disturbance affecting forest ecosystems. Bark-stripping damage from the growing ungulate populations, in turn, are among the main biotic risks, which might burden the stability of trees and stands. Therefore, the aim of our study is to estimate the effect of cervid bark-stripping on the mechanical stability of Norway spruce using a static tree-pulling test. For the test, eight damaged and 11 undamaged canopy trees were selected from a 40-year old stand (plantation with 1 × 3 m spacing) growing on mineral mesotrophic soil. The selected trees were bark-stripped 7–9 years prior to the experiment. Uprooting was the most frequent type of failure; only two trees broke at the stem. For the damaged trees, the resistance to pulling was significantly reduced (p-value < 0.001). Stem volume and presence of bark-stripping were the best linear predictors of the basal bending moment at the primary failure (irreversible deformation of wood structure) and secondary failure (collapse of the tree). A significant (p-value < 0.001) interaction between stem–wood volume and presence of bark-stripping was observed for primary failure, indicating a size-dependent reduction of stability of the damaged trees. Such interaction lacked significance (p-value = 0.43) for the secondary failure (mostly uprooting), indicating a decrease in stability irrespectively of tree size. Somewhat surprisingly, the decrease in the overall mechanical stability of the bark-stripped trees appeared not to be related to a direct reduction of the strength of the stems, but rather to physiological effects such as altered allocation of carbon, increased drought stress because of interfered hydraulic conductance of wood, or secondary infestation. The reduced stability also suggests that bark-stripped trees can act as the weak spots decreasing the collective stability of stands in the long term, thus increasing the susceptibility to storms.

Keywords: *Picea abies*; cervids; pulling test; wildlife damage; uprooting; wind damage

1. Introduction

In European forests, storms are the main abiotic disturbance [1], which have caused more than half of the losses in standing stock during the last 50 years [1,2]. The impact of storms is expected to further increase due to climatic change [3]. In Northern Europe, increasing damage of storms is related to unfrozen soil conditions under warming winters, hence the mechanical stability of individual trees is essential for the sustainability of stands [4]. Furthermore, the impact of storms is intensified by the accompanying legacy effects, such as pest outbreaks and predisposal to pathogens as the trees are weakened [1,2]. Accordingly, storms are projected to further intensify the negative effects of climate changes on Norway spruce (*Picea abies* L. Karst), which is already associated with lower mechanical stability against wind, particularly in pure stands [5–7].

European forests suffer increasing damage caused by the growing cervid populations [8]. Middle-aged (stem exclusion phase; cf. Oliver and Larson [9]) Norway spruce stands are frequently subjected to bark-stripping [10,11], as bark can make more than 10% out of the red deer diet [12]. Bark-stripping damage intensifies with an increasing proportion of spruce in stands and with increasing stand density [13], which subjects pure stands to increased risk [6]. Stem breakage of Norway spruces damaged by moose at the wound height has been observed by Randveer and Heikkilä [14], linking the wildlife damage with the stand stability and susceptibility to wind damage [4]. The interactions between the biotic and abiotic agents can also amplify their individual influence [1]. For example, bark-stripping results in the loss of timber value because of the removal of phloem, while the uncovering of xylem interferes with the physiological processes, thus reducing increment and weakening trees [15], as well as providing a gateway for infections [16].

The effects of storms on stands are shaped by collective and individual stability of trees, which depend on stand density, openings in the canopy, which are the starting points for wind damage, and mechanical resistance of the individuals [2,17,18]. Injuries to the stem can cause a loss of mechanical strength of the tree, resulting in weakened parts in the canopy of a stand, thus decreasing the collective stability [2,18]. Additionally, stripped bark acts as a gateway for pathogens [16,19]; hence, stem rot has been found on 60%–100% of damaged trees [15,16,18]. Rot-infected trees are more prone to stem breakage due to increased susceptibility to wind damage [6], causing negative effects on the stability and growth of a stand. However, the empirical data on the effect of bark-stripping on the wind stability of individual trees, which are needed for a deeper understanding and more precise modelling of the expected effects of wind in the future, are still lacking [1,18,20].

The aim of the study is to evaluate the effect of bark-stripping on the mechanical stability of middle-aged Norway spruce growing in a pure stand. We hypothesise that bark-stripping reduces the mechanical stability of trees, causing stem breakage (snapping) at the wound.

2. Materials and Methods

2.1. Study Site and Sample Trees

A 40-year-old monoculture (planting density 3 × 1 m) of Norway spruce established in lowland conditions (113 m above sea level) on oligotrophic well-drained soil in the central part of Latvia (56°42′ N; 25°53′ E) was studied. Such selection was made because dense Norway spruce stands are common in the eastern Baltics. The studied stand is located in a national forest research station, hence information on bark-stripping and sanitary conditions were available.

The area of the stand was 0.89 ha, and it was exposed to a clear-cut on the south and southwest sides, and to mature Norway spruce stands on the other sides. No management has been done except weed control after the establishment. The climate at the site location is temperate. The 30-year mean annual precipitation is 600 mm and the mean monthly temperature ranges from −7 to 16.9 °C in January and July, respectively. Westerlies are the dominant winds with a mean annual velocity of 3 ms^{-1}. The strongest winds mostly occur during winter. Five storms stronger than 22 ms^{-1} have occurred over the last 18 years [21].

In the studied stand, eight canopy trees with stripped bark on the stems and 11 undamaged trees, representing the diameter distribution of the plantation, were selected for the destructive static pulling tests. The selected trees appeared visually healthy (apart from bark-stripping wounds). Additional criteria for the selection of the damaged trees were the exposure of the wounds to the north and northeast direction. Trees on the edges of the stand were avoided. The undamaged trees had slightly larger stem diameter at breast height (DBH), height and stem volume (Table 1). More details on each tree are shown in the supplementary material (Table S1). Bark-stripping wounds on the damaged tree stems were at a height of 80–150 cm above the ground. The age of the wounds, as determined from stem discs collected after the pulling test, was 7–9 years. The shapes of the bark-stripping wounds were transferred to transparent film, and, later in the laboratory, measured using a planimeter (Planix 10S, Tamaya, Japan). The area of the damage ranged from 603 to 2375 cm^2. Bark-stripped trees did not have any other visual damage. Presence of wood rot was evaluated on stem discs.

Table 1. Statistics of the studied dataset. Mean values ± 95% confidence intervals are shown.

	Undamaged	**Bark-Stripped**
Number of trees	11	8
Stem circumference (cm)	86.0 ± 13.7	82.2 ± 17.3
Damage circumference (cm)	-	22.5 ± 6.2
Damage proportion (%)	-	28.1 ± 7.3
DBH (cm)	27.3 ± 4.3	25.8 ± 5.1
Tree height (m)	24.3 ± 2.6	23.1 ± 3.3
Stem volume (m^3)	0.76 ± 0.24	0.64 ± 0.27
Pulling direction (cosine)	0.33 ± 0.46	0.83 ± 0.23

2.2. *Static Pulling Tests*

Destructive static pulling tests [22] were used to assess the effect of bark-stripping on the stability of Norway spruce. The pulling line was anchored at 50% of the height of each sample tree (Figure 1). Before the pulling, trees were topped 1 m above the anchorage point to prevent the influence of wind and canopy weight on the measurements.

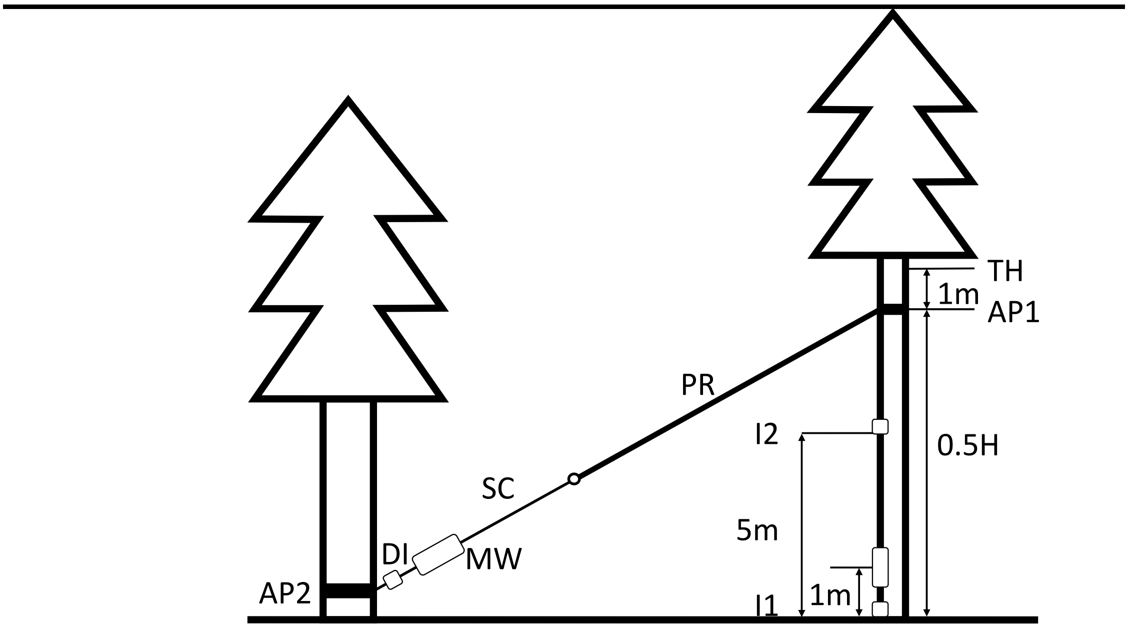

Figure 1. Schematic depiction of the static destructive pulling test setup. AP: anchorage point, DI: dynamometer (includes inclinometer for rope angle), I: inclinometer, MW: manual winch, TH: topping height; SC: steel cable; PR: polyester rope.

The trees were pulled using a manual winch (working load limit 32 kN) and steel cable (diameter 16 mm) anchored at the ground level. The pulling cable was extended with a static polyester rope (Tenex Tec 16; Samson Rope Technologies Inc., Ferndale, WA, USA). Damaged trees were pulled in the direction of the wound. Measurements were done with the TreeQinetic System (Argus electronic GmbH, Rostock, Germany). A dynamometer, recording pulling force and rope angle was placed between the winch and the rope (Figure 1). The inclination of the root plate and the curvature of the stem were measured with two inclinometers at the base and at the height of 5 m.

2.3. Data Processing and Analysis

For each tree, the bending moment at the base of the stem (BBM, in kNm), was calculated as follows:

$$BBM = F \times h_{\text{anchor}} \times \cos\,(\text{median}_{\alpha\ \text{rope}}), \tag{1}$$

where F is the pulling force, h_{anchor} is the height of the anchor point of the sample tree, and $\text{median}_{\alpha\ \text{rope}}$ is the median of the rope angle. The difference between two simultaneous inclinometer measurements ($N_{5\text{m}}$ at the height of 5 m; N_{base} at the base, 0 m) was used to characterise the curvature of the stem N_{Δ}:

$$N_{\Delta} = N_{5\text{m}} - N_{\text{base}} \tag{2}$$

The primary failure of the stem occurs when the structure of wood starts to change due to stress caused by the external force. At that point, the wood fibers start to buckle, while the damage might not be visually detectable. The limit of proportionality between N_{Δ} and BBM was considered as the point when the primary failure occurs [23]. This point was determined by graphical inspection. The secondary failure was considered to occur when the maximum BBM was reached, after which tree collapse (either uprooted or its stem broke) followed.

Linear models were used to assess the main tree-level variables affecting primary and secondary failure. The full model was fit to describe both individual and interacting effects of the studied factors on the BBM at primary and secondary failure (Table 2). As the study had a limited scope, a restricted number of factors were analyzed together according to the arbitrary selection principle. The tested predictors were tree dimensions (DBH, height, and stem volume), presence and size of bark-stripping, and presence of wood rot. Pulling direction (cosine) was tested as a proxy for the effects of dominant winds. Model performance was assessed using diagnostic plots. If models had similar performance, they were compared using ANOVA; if no statistical difference between the models was estimated, the simplest was used. Stem–wood volume was calculated using local functions by Liepa [24]. The data were processed in R Software (version 3.5.3) using packages: "readr", "tidyverse", "DBI", "zoo", "RSQLite", "ggplot2" [25].

Table 2. Regression between tree stability parameters and stem volume and cervid damage for the damaged trees.

Parameter	*F*-Value	*p*-Value
Primary failure		
Stem volume	268.9	<0.001
Presence of bark-stripping wound	159.3	<0.001
Stem volume by presence of bark-stripping interaction	28.9	<0.001
R^2	0.96	
Model overall significance, *p*-value	<0.001	
Secondary failure		
Stem volume	294.5	<0.001
Presence of bark-stripping wound	38.0	<0.001
Stem volume by presence of bark-stripping interaction	0.6441	0.43
R^2	0.95	
Model overall significance, *p*-value	<0.001	

3. Results

Uprooting was the most frequent type of failure, as only two of the 19 trees studied had stem breakage (one bark-stripped and one undamaged tree). However, the limited sample size of the fractured trees prevented statistical analysis of factors influencing failure type. Both broken trees had similar DBH and height. The breakage on the bark-stripped tree occurred a few meters above the bark-stripping wound. Wood decay was not observed on the stem disc at the wound. The undamaged broken tree showed notably higher BBM at the primary and secondary failure compared to the uprooted ones; therefore, it was excluded from further analysis as an outlier.

The best performing models describing primary and secondary failure contained the same two predictors: stem–wood volume and presence of a bark-stripping wound, which were strictly significant (p-value < 0.001; Table 2). The interaction between the predictors, however, was significant (p-value < 0.001) only in case of primary failure. Nevertheless, both models showed a good fit ($R^2 \geq 0.95$), and their residuals were independent and followed the normal distribution. The BBM at primary and secondary failure showed a clear linear dependency on the stem–wood volume (Figure 2). The presence of bark-stripping wounds on stems significantly (Table 2) reduced the BBM necessary for tree failure to occur (Figure 2). The effect of bark-stripping was particularly pronounced for the occurrence of primary failure. With the increasing size of the trees, the effect of bark-stripping became larger. On average, the damaged trees required 61% less load to fail (Figure 2A). The presence of bark-stripping wounds had a tree-size-independent effect on the resistance of trees to secondary failure, reducing the BBM by ca. 16 kNm per m^3, indicating higher susceptibility of the smaller trees.

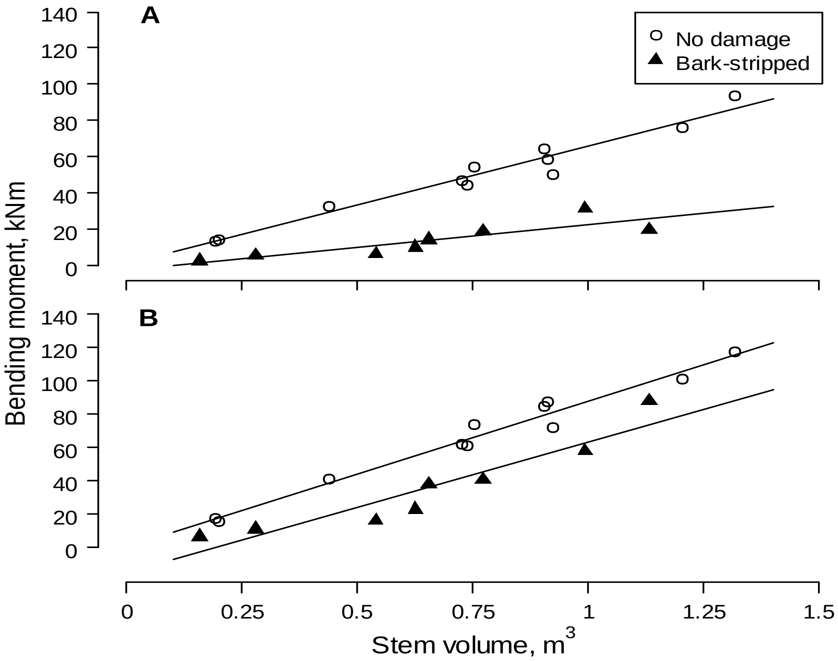

Figure 2. Bending moment of the Norway spruce stem at the primary failure (**A**) and secondary failure (**B**) according to stem–wood volume and presence of bark-stripping wound.

4. Discussion

Beyond the general rule that bark-stripping enables fungal infection [18] and wood decay reduces the mechanical strength of trees [26], little is known about the quantitative effects of ungulate bark-stripping on the stability of individual trees [27,28]. Because this type of damage is widespread in commercial forests, models for storm risk assessment might benefit from more comprehensive information.

To quantify the effect of bark-stripping on tree stability, damaged and undamaged Norway spruce trees were pulled to failure. Contrary to expectations, most trees with wounds did not snap but were uprooted, which is the most frequent wind damage for shallow-rooted species such as the Norway spruce [2]. However, the presence of bark-stripping reduced bending moments at primary and secondary failures significantly (Figure 2; Table 2), confirming our initial hypothesis at least in part. The critical bending moments were comparable to the results found for Norway spruce in other parts of Europe [4,29,30].

Bark-stripping wounds reduced not only stem strength but also anchorage. Bark-stripping disrupts conductive tissues of trees, causing physiological stress [18], and triggers the allocation of resources to healing [15]. Both effects reduce growth in the long term. Under such conditions, we speculate that trees invest less carbon into the root system, thus reducing anchorage and facilitating uprooting [28,31]. Bark-stripping also acts as a gateway for pathogens [16,18,32], which can reduce the growth and vigour of trees, reducing the mechanical stability of trees [28]. One of the most common Norway spruce pathogens, *Heterobasidion annosum*, has been related to increased uprooting and stem breakage [28,33]. Although wood rot was not detected on the stem discs at the wound, the spread of pathogens in the stem can differ by species [16,34]; hence, fungal infection still might have had affected roots of the bark-stripped trees, although not visible higher in the stem.

The marked increase in susceptibility of the bark-stripped trees to primary failure (Figure 2A), which disrupts conductivity of wood facilitating physiological drought and weakening of trees [23], suggested that the studied damage by wildlife might enhance the negative legacy effects of storms, such as increased susceptibility to pests [1,2]. The legacy effects of bark-stripping are decreased mechanical stability of trees and increased susceptibility of stands to wind damage [18]. Weaker resistance of the bark-stripped trees (Figure 2) implies that they reach primary failure at considerably slower wind speeds, facilitating storm legacy effects, which in turn are increasing susceptibility to wind damage, thus resulting in a negative feedback loop and drawing negative perspectives to Norway spruce stands in the eastern Baltic region. In addition, the primary failure creates irreversible damage to the wood fibers (even if not visually detectable) [23], reducing the quality and value of timber [28,35]. Furthermore, the negative effect of bark-stripping on tree stability (Figure 2; Table 2) suggests that damaged trees, as the triggering points, might reduce the collective stability of stands to wind loads [2,17,18]. The growing frequency of stand-replacing storms [2,3,36] in combination with intensifying cervid damage [10,20] are expected to cause increasing calamities to Norway spruce in Northern Europe.

5. Conclusions

Under the growing influence of storms, bark-stripping damages caused by growing cervid populations will intensify the direct and legacy effects of storms on Norway spruce. Considering the long-term and short-term effects and risks allocated to bark-stripping on trees and stand, the damaged trees are to be harvested soon after the damage, while the legacy effects have not caused more extensive damage, although the harvesting of the damaged trees should be carried out when the risk of storms is the lowest, allowing stands to restore collective stability. In this sense, prevention of wildlife damage could notably improve the sustainability of Norway spruce stands against wind damage.

Supplementary Materials: The following are available online at http://www.mdpi.com/1999-4907/11/3/357/s1.

Author Contributions: Conceptualization, O.K. and A.J.; methodology, O.K., R.M., S.R.; formal analysis, D.E., R.M., data curation, R.K., R.M.; writing—original draft preparation, R.S., O.K.; writing—review and editing, R.M., S.R.; project administration, A.J. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by ERDF grant number 1.1.1.1/16/A/260.

Acknowledgments: This study was funded by the European Regional Development Fund project development of decision support tool for prognosis of storm damages in forest stands on peat soils (No. 1.1.1.1/16/A/260).

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

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Presence of Root Rot Reduces Stability of Norway Spruce (*Picea abies*): Results of Static Pulling Tests in Latvia

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Received: 9 March 2020; Accepted: 6 April 2020; Published: 8 April 2020

Abstract: Storms are the main abiotic disturbance in European forests, effects of which are expected to intensify in the future, hence the importance of forest stand stability is increasing. The predisposition of Norway spruce to wind damage appears to be enhanced by pathogens such as *Heterobasidion spp.*, which reduce stability of individual trees. However, detailed information about the effects of the root rot on the stability of individual trees across diverse soil types is still lacking. The aim of the study was to assess the effect of root rot on the individual tree stability of Norway spruce growing on drained peat and mineral soils. In total, 77 Norway spruce trees (age 50–80 years) growing in four stands were tested under static loading. The presence of *Heterobasidion spp.* had a significant negative effect on the bending moment at primary and secondary failure of the tested trees irrespectively of soil type. This suggests increased legacy effects (e.g., susceptibility to pathogens and pests due to fractured roots and altered water uptake) of storms. Damaged trees act as weak spots increasing the susceptibility of stands to wind damage, thus forming a negative feedback loop and contributing to an ongoing decline in vitality of Norway spruce stands following storms in the study region in the future. Accordingly, the results support the importance of timely identification of the decayed trees, lowering stand density and/or shortening rotation period as the measures to counteract the increasing effects of storms on Norway spruce stands.

Keywords: natural disturbances; resistance; uprooting; wind damage; disturbance interactions; spruce forest management

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1. Introduction

The increasing frequency of storms causes growing losses of both economic and ecological (e.g., carbon sequestration) value in European forests [1], which is expected to intensify in the future [2,3]. The susceptibility of forests to wind damage is amplified by the presence of additional disturbance agents, such as pathogens (e.g., *Heterobasidion spp.*), thus increasing the vulnerability of a forest stand [4]. Moreover, in the future, northern forests are expected to become more susceptible to wind impact during extra-tropical cyclones in the autumn-winter period, as well as in summer thunderstorms [5,6]. Under such conditions, management measures improving the mechanical stability of forest stands are becoming crucial [7,8].

The collective stability of forest stands is largely attributed to individual tree stability because the collapse of weakened individual trees initiates further damage in the stand via the domino effect [2,9].

The stability of an individual tree is determined by the species, stand properties, and tree health conditions, as well as aerial tree characteristics and root anchorage [2,9]. The size of soil-root plate is considered as the factor determining individual stability of a tree, which might be reduced by root rot [10]. High stand density is known to affect individual tree stability because competing trees invest in stem growth rather than root development [11,12]. Furthermore, denser stands are more susceptible to the spread of pathogens, which affect roots and, consequently, also stems [13]. Accordingly, forest management measures aimed at increasing the individual stability of the trees have been considered a major measure to reduce the consequences of storms [14–16].

Norway spruce (*Picea abies* L.) is economically important in Northern Europe; hence, efforts are aimed at maintaining its productivity [17]. A rather large proportion of highly productive stands of Norway spruce are growing on fertile, drained peat soils in Northern Europe [18]. The species is prone to wind damage due to shallow rooting and its relatively dense crown [19–21]. Among the pathogens of Norway spruce, root rot caused by *Heterobasidion spp.* is the most common, causing severe economic losses due to a decrease in stem quality [22]. In stands growing on mineral soils, the effect of root rot on the mechanical stability of conifers, such as Norway spruce, has been investigated using winching tests [23–26], suggesting the reduction of root anchorage due to root rot by up to 33%. However, no studies on this aspect exist in stands on peat soils. Soil is a significant factor, affecting tree wind stability [23], thus, it is important to assess the impact of root rot on the stability of Norway spruce growing on diverse soils. The aim of the study is to assess the effect of root rot caused by *Heterobasidion spp.* on the individual tree stability of Norway spruce growing on peat and mineral soils. We hypothesise that the reduction of the soil-root anchorage by *Heterobasidion spp.* is stronger in peat soils than in mineral soils due to the reduction of soil-root plate.

2. Materials and Methods

2.1. Study Site and Sample Trees

The study was conducted in the summer seasons of 2018 to 2019 in Norway spruce stands situated on mineral and peat soils in the central part of Latvia (Table 1). Mature Norway spruce dominated forest stands with deep drained peat and fine dry sandy soils were selected for the study. Evenly distributed within stands, dominant trees without visual damage were selected for sampling. Prior information on the presence of *Heterobasidion spp.* in the stands was collected during previous research (unpublished data). Additionally, the presence of fungal pathogens in sample trees' wood was tested in the laboratory from increment cores extracted below the root collar from the opposite sides of stem. The presence of *Heterobasidion spp.* in the samples was confirmed by observing its characteristic asexual sporulation (conidiophores). Based on these results, in each stand infected (root rot group) and not infected sample trees (control group) were selected and pulled to failure within the same season. Additionally, *Armillaria spp.* was found in 70% of trees of the root rot group.

Table 1. Sample size, soil type, species composition, and DBH (diameter at breast height) of the pulled Norway spruce (*Picea abies* L.) trees in tested stands.

Stand	*N*	Soil Type	Tree Species (%)	Min DBH (cm)	Max DBH (cm)	Mean DBH (cm)
1	20	Fine sand	Norway spruce (80), birch (10), Scots pine (10)	18.3	40	29
2	17	Fine sand	Norway spruce (100)	27	43.6	32.9
3	20	Peat	Norway spruce (70), birch (20), black alder (10)	21.7	46	32.2
4	20	Peat	Norway spruce (100)	23.7	44.2	34.7

2.2. Pulling Tests

Trees were pulled with a hand winch (working load limit 32 kN) to determine the maximum force needed for failure, either uprooting or stem fracture. The winch was anchored at the base of a second tree with a polyester roundsling (working load limit of 40 kN) at a distance that exceeded the sample tree height. The pulling line consisted of a 20-m-long (16 mm diameter) steel cable, which was extended using a static polyester rope (Tenex Tec 16; diameter 16 mm; working load limit 77 kN; Samson Rope Technologies Inc, Ferndale, USA). On the sample tree, the pulling line was anchored at the half of the height. To minimise the potential underestimation of the pulling force caused by the effects of wind and the canopy weight above the anchoring point of the sample tree, the sample trees were topped 1 m above the anchor point and pruned prior the test.

TreeQinetic System instruments (Argus electronic GmbH, Rostock, Germany) were used for the simultaneous measurements of the pulling force, stem inclination, and wood fibre deformation. A dynamometer was used for measuring the pulling force, and the angle of the pulling line was placed between the winch and the polyester roundsling. The stem inclination was measured at two heights (at the root collar and at 5 m) using inclinometers placed on the same side of the stem perpendicularly to the pulling direction. The wood fiber deformation of the stem was measured using a strain gauge on the compression side (facing the winch) at the height of 1 m from the root collar. This measurement was done from the beginning of the pulling test until the root collar inclination of 0.25° as bending moment at this threshold correlates well with anchorage [27,28].

2.3. Soil and Root Measurements

The soil water content was measured for each tree after the pulling test using an ML3 ThetaKit (Delta-T Devices Ltd., United Kingdom). For the uprooted trees, the largest (half of the width) and smallest (height) radius of the soil-root plate were measured from the centre of the stem to point where roots were damaged. The soil-root plate depth was measured from ground surface to depth of roots with diameter larger than 1 cm. The cross-sections of stumps, as well as the decay, were transferred to transparent films, and measured using a planimeter (Planix 10S; Tamaya, Japan) in the laboratory. The cross-section area of wood decay ranged from 75.7 to 1512.8 cm^2.

2.4. Data Analysis

The basal bending moment (BBM) was calculated as follows:

$$BBM = F \cdot h_{\text{anchor}} \cdot cos(median_{\alpha\ \text{rope}}) \tag{1}$$

where F is the pulling force, h_{anchor} is the height of the anchor point on the sample tree, and $median_{\alpha\ \text{rope}}$ is the median of the rope angle. The stem curvature was expressed as the difference in the stem inclination measured at different heights (at the height of 5 m and at the base) as follows:

$$N_{\Delta} = N_{5\text{m}} - N_{\text{base}} \tag{2}$$

During the static pulling, the stem curvature (N_{Δ},) and BBM increase proportionally until the point of irreversible wood fibre kinking on the compression side of the stem [29,30]. This point characterises the primary failure (BBM_{prim}) after which N_{Δ} increases faster than BBM. Secondary failure (BBM_{sec}) occurs at the maximum loading as tree collapses.

The modulus of elasticity (MOE) was calculated according to a previous study [31]:

$$MOE = \frac{\text{BBM} \cdot y}{I \cdot e} \tag{3}$$

where BBM is the bending moment at the height of 1 m above the root collar, y is the radius of the stem section to the centre of the strain gauge, I is the area moment of inertia of the section, and e is the strain. The volume of the soil-root plate was calculated as the volume of an elliptical paraboloid as follows:

$$V = \left(\frac{1}{2}\right) \cdot \pi \cdot a \cdot b \cdot h \tag{4}$$

where a and b are the largest and smallest radii of the soil-root plate and h is the depth of the soil-root plate.

Considering the split-site study design, the effects of soil type (nested within site), root rot, and their interaction on force (BBM) necessary for the primary and secondary failures to occur were tested using the fractional analysis of variance (ANOVA) [32]. As trees of different size were analysed, BBM was expressed per tree size; tree height, DBH, stem volume, root rot cross-sectional area, soil-root plate volume, and tree height multiplied by the second power of DBH were tested as proxies for the tree size; stem volume was identified as the best performing one. Presence and cross-section area of decay on stump were tested as proxies for the root rot, among which presence (binomial variable) showed the best performance. The best performing proxies were selected according to the arbitrary principle considering residual variance as a criterion. Due to limited scope of the study, the total number of factors analysed was kept to a minimum. The statistical analysis was conducted in R software (v. 3.5.3) [33], using packages "tidyverse" [34] and "ez" [35]. The stem wood volume was calculated according to the local equation [36].

3. Results and Discussion

Uprooting was the most common type of failure as only nine out of 77 had stem fracture. The stem fracture occurred similarly in all groups according to root rot and soil types. Fractured trees tended to be smaller and were in dryer soil conditions (Table 2). However, a statistical analysis to describe the influencing factors for the failure type was not possible due to the limited number of the fractured trees.

Table 2. Mean values and standard deviations of diameter at breast height (DBH), soil-root plate volume (V_{srp}), soil moisture (SM), bending moment at primary (BBM_{prim}) and secondary (BBM_{sec}) failure, and modulus of elasticity (MOE) for all tested trees.

Variable	**Root Rot**				**Control**			
	Soil		**Failure**		**Soil**		**Failure**	
	Peat	**Fine Sand**	**Uproot**	**Fracture**	**Peat**	**Fine Sand**	**Uproot**	**Fracture**
DBH (cm)	33 ± 6.3	29.2 ± 7	31.6 ± 6.5	28.4 ± 9	32 ± 4.8	30.5 ± 7.2	32.1 ± 5.4	21.5 ± 3.5
V_{srp} (m^3)	3.92 ± 2.04	3.1 ± 2.02	3.51 ± 2.01	-	4.12 ± 1.04	3.9 ± 1.59	4.03 ± 1.25	-
SM (%)	64.6 ± 20	39.5 ± 21.3	55.9 ± 23.3	31.7 ± 17.8	67.5 ± 17.4	38.2 ± 21.9	55.4 ± 23.1	37 ± 38.2
BBM_{prim} (kNm)	56.8 ± 25.2	46.9 ± 26.7	53.5 ± 27.1	42.9 ± 18.9	60.1 ± 21.4	63.3 ± 26.9	64.2 ± 22.8	29.55 ± 5.8
BBM_{sec} (kNm)	67.9 ± 29.6	53.2 ± 30	62.4 ± 31.4	50.8 ± 23.8	72 ± 25.9	71.3 ± 29.1	74.4 ± 26.1	38.7 ± 11.5
MOE (GPa)	38.4 ± 19.9	30 ± 15.4	34.8 ± 18.1	32.8 ± 20.8	28.2 ± 9	29.1 ± 9.6	28.1 ± 9.3	34.2 ± 2.7

The presence of root rot had explicit negative effect on mechanical stability of Norway spruce, significantly reducing BBM both at the primary and secondary failures ($p < 0.05$; Table 3, Figure 1) on peat, as well as mineral soils. This indicated explicit increase in vulnerability to wind damage of root rot affected Norway spruce stands. The mean BBM (Table 3) in our study were lower than observed in an earlier study [37] implying regional differences in Norway spruce wind stability. The other terms tested, i.e., soil type and plot were not significant for BBM_{prim} and BBM_{sec} (Table 3).

Table 3. Results of the fractional analysis of variance between bending moment at primary (BBM_{prim}) and secondary (BBM_{sec}) failure, soil type, the presence of root rot, and the interaction between soil type and the presence of root rot.

BBM_{prim} (kNm)	***F*-Value**	**Ges ***	***p*-Value**
Soil	0.15	0.07	0.73
Root rot	224.83	0.34	<0.01
Soil: root rot	0.36	<0.001	0.60
BBM_{sec} (kNm)	*F*-Value	Ges *	*p*-Value
Soil	0.01	0.004	0.92
Root rot	39.69	0.44	0.02
Soil: root rot	0.05	0.001	0.83

* Generalized Eta-Squared [32].

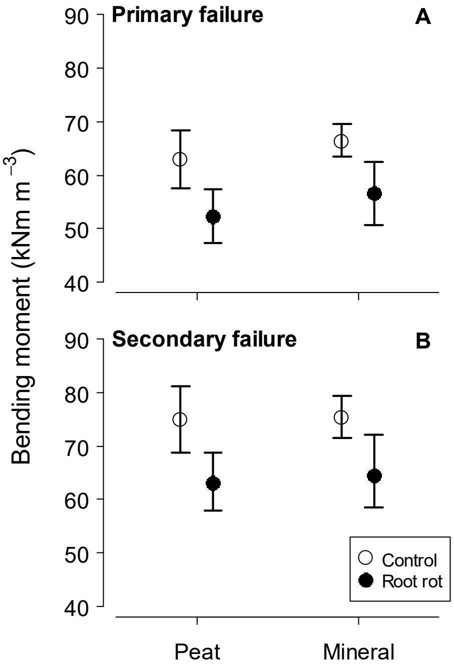

Figure 1. Basal bending moment (BBM) of the Norway spruce at the primary failure (**A**) and at secondary failure (**B**) according to stem wood volume and root rot.

The hypothesis of the study was confirmed partly, as the soil-root anchorage was reduced by the presence of *Heterobasidion spp.* while the volume of the soil-root plate did not appear as the primary factor affecting changes in tree stability in relation to a slowly decomposing pathogen. This pathogen develops wood decay in roots and stem base [13]. This suggests that the uprooting of the affected trees was facilitated by the reduction of the mechanical strength of the lateral roots regardless of soil type.

The presence of root rot appeared to be a better proxy for the effect of root rot on tree stability than the area of rot on stem (according to the arbitrary selection principle), thus implying facilitated detection of the "weak" trees within a stand. As the trees affected and unaffected by root rot were tested simultaneously within each stand, the effect of the seasonal differences in the soil moisture [38] on our results was minimal. This is important as the linkage between increased soil moisture and tree stability is explained by reduced bearing capacity of soil [39–41]. Alternatively, considering Norway spruce as a water demanding species, the effect of soil moisture on root anchorage might be indirect via faster growth under moister soil conditions, hence wood strength has been decreased due to lower wood density [42].

Primary failure is the irreversible deformation of wood fibres as tangential sideways kinking occurs in the compression zone under loading [29]. Such damage affects tree hydraulics [43], triggering physiological drought stress [29,30], consequently subjecting storm-surviving trees to consecutive disturbances, such as pests or pathogens [2,3]. Thus, the reduced force needed to cause primary failure in moister soils could cause a potential underestimation of the negative legacy effect of storms. Reduced hydraulic conductivity caused by primary failure in stems might also contribute to pervasive growth reduction observed in Norway spruce forests after storms [44]. An additional storm legacy effect is caused by fracturing the roots, as it reduces the water uptake and facilitates the spread of root rot. A faster spread of root rot reduces the tree wind stability; thus, a negative feedback loop progressively decreases the sustainability of spruce stands in Northern Europe [45].

The cumulative probability of wind effects on Norway spruce stands could be reduced by the application of silvicultural measures, such as early identification and removal of infected trees, gradual lowering of the stand density, or shortening the length of the rotation period [2]. Also, the spread of *Heterobasidion spp.* could be slowed by reduced root contact in stands with lower density [13]. However, the decrease of stand density might facilitate effects of other disturbances, such as bark-stripping [46] and pests [3] that might increase the susceptibility to wind damage. Accordingly, a regional evaluation of silvicultural measures is necessary.

4. Conclusions

Under the increasing frequency of storms and related disturbances in the future, the reduction of mechanical stability will increase the cumulative probability of wind damage in Norway spruce stands across different soil types. Considering the importance of Norway spruce in Northern Europe, silvicultural measures, such as gradual lowering of the stand density or shortening the length of the rotation period, will become essential to ensure the long-term vitality and to decrease the vulnerability of Norway spruce stands to wind damage. Considering regional differences in mechanical strength, local evaluations of tree stability are necessary.

Author Contributions: Conceptualization, O.K. and A.J.; methodology, O.K., R.M., S.R.; formal analysis, D.E., data curation, L.K., N.B., L.B.; writing—original draft preparation, O.K.; writing—review and editing, R.M., S.R., A.J.; project administration, A.J. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by European Regional Development Fund grant number 1.1.1.1/16/A/260.

Acknowledgments: This study was funded by the European Regional Development Fund project Development of decision support tool for prognosis of storm damages in forest stands on peat soils (No. 1.1.1.1/16/A/260).

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

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III

PUBLIKĀCIJA / *PUBLICATION*

Model of Above-ground Biomass Distribution of Norway Spruce (*Picea abies* L. (Karst.))

Oskars Krišāns, Valters Samariks, Roberts Matisons, and Āris Jansons *

Climate change with more frequent extreme weather events and prolonged winter periods with un-frozen, wet soil is causing frequent wind damage events in forests. Trees with higher mass point and heavier weight are more prone to wind damage; however, limited information exists on distribution of biomass under naturally moist conditions. Such information is essential to improve models of wind damage prediction. Therefore, the aim of the present study was to assess the biomass distribution and the parameters important for wind-load of Norway spruce (*Picea abies* (L.) Karst.). Samples were collected in the year 2019 from 87 trees growing on two different sites, corresponding to freely drained mineral and peaty mineral soils at the age of 55 and 88 years, respectively. Tree diameters at breast height, height, and height of first living branch were measured. Tree stems were pruned and cut into 2-m-long fragments and weighed (fresh weight) afterwards. A biomass distribution model was developed to estimate fresh weight of the stem of Norway spruce using easy measurable tree variables. Relative height of the mass point and height of living branches were higher in peaty mineral soil than on freely drained mineral soil, which was an indicator for higher windthrow risks.

Keywords: Fresh weight; Gales; Mass point height; Storm; Wind load; Windthrow

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INTRODUCTION

Future climate change scenarios predict an increase in mean air temperature and extreme weather events (wind (storm) intensity and frequency) (IPCC 2019). Yet another effect of climate change is winter with long periods of un-frozen, wet soil, and thus difficult logging conditions (Peltola *et al.* 2010). Therefore, wind damage to trees is considered to be a major problem in the future, with the potential to result in notable economic losses (Von Gadow and Hui 2001). This is a concern especially for Norway spruce (*Picea abies* (L.) Karst.) because of the shallow root system and increased susceptibility to various hazards such as storms, droughts, insects, or diseases (Greiss *et al.* 2012; Caudullo *et al.* 2016).

Diverse biomass estimation models have been developed (Classon *et al.* 2001; Lehtonen *et al.* 2004; Wirth *et al.* 2004; Zianis *et al.* 2005; Mikšys *et al.* 2007; Pajtik *et al.* 2008; Repola 2009; Socha 2012) based on easily measurable tree variables. Most of the developed tree biomass models were expressed as dry weight for prediction of outcome of sawn good, calorific value of energy wood, although the models of biomass for possible wind damage should be expressed as fresh weight. Therefore, complex dynamic wind-load prediction models (Moore and Maguire 2007; Sellier *et al.* 2008; Pivato *et al.* 2014), and several static wind damage prediction models (HWIND, GALES, and FOREOLE) have been developed (Peltola *et al.* 1999; Gardiner *et al.* 2000; Ancelin *et al.* 2004). Only the

FOREOLE model used the approach that trees were divided into successive (1 to 2 m long) fragments for assessment of biomass distribution (Ancelin *et al.* 2004). Accuracy of all the models can be improved by adding empirical data where their availability is limited. The tree wind resistance depends on its root system, mechanical strength of the stem, and biomass (amount and distribution) (Peltola *et al.* 1999; Cucchi *et al.* 2005; Scott and Mitchell 2005). Therefore, the tree height of the mass point (centre of mass) may be used as proxy to estimate the risks of windthrow (Cucchi *et al.* 2005; Nicoll *et al.* 2006).

The aim of present study was to assess the biomass distribution and parameters important for wind-load of Norway spruce (*Picea abies* (L.) Karst.).

EXPERIMENTAL

Materials

The study was conducted in trial sites located in Kalsnava, in the eastern part of Latvia (56°41 N, 25°50 E and 56°41 N, 25°52 E). The sites were situated on a flat relief, where the elevation was approximately 100 to 120 m.a.s.l (Spalvins *et al.* 2012). Materials were collected in Norway spruce stands growing on different soil types, corresponding to *Myrtillosa melior* forest type with freely drained mineral soil (A1) and typically with shallow root system, and *Myrtillosa turf melior* type with peaty mineral soil (C1), and root depth < 40 cm (Bušs 1976; Pyatt 1982, 2001; Kennedy 2002).

In total, 87 first layer trees were randomly selected: 47 trees from the diameter at breast height (DBH) that ranged from 25.8 to 40.6 cm from A1 at the age of 55 years old, and 40 trees (DBH ranged from 23.8 to 44.3 cm) from C1, that were 88 years old, were sampled in winter 2019. Tree height ranged from 23 to 28.9 m in A1 and 24.2 to 31.1 m in C1. Cutting was done as close as possible to the root collar. The DBH, tree height (H), and height of the lowest living branch (H_{lb}) were measured for each tree. Tree stems were pruned, cut into 2-m-long fragments, weighed (fresh weight), and diameter measured in the middle point of each fragment. Total branch weight of a tree was measured after all the small branches from the stem were removed, however, only living branches were weighed excluding dead and dry branches.

Methods

Data analysis

All biomass prediction variables corresponded to normal distribution. A linear mix effects model was used to apply the model for Norway spruce biomass prediction based on the DBH, H, height of the fragments middle point, or the combination of these parameters. Pearson’s correlation analysis was introduced to assess the relationship between tree biomass and model prognosis, and relationships between measured variables. Principle component analysis was employed to examine the effect of soil type on tree variables and to discover the relationship between the studied samples.

Each tree’s height of mass point (H_{mp}) was calculated with the average weighed value of height of the middle point and the mass of each part of the tree (tree fragments) as,

$$H_{\mathrm{mp}} = \frac{\sum m \times h}{\sum h} \tag{1}$$

where m is the mass of part of the tree (kg) and h is the height of middle point of part of the tree (m).

The relative height of mass point (rel. H_{mp}) is a proportion of the total tree height. All steps of the data analysis were completed using the statistical software R 3.6.1. (R Core Team 2019, Vienna, Austria).

RESULTS AND DISCUSSIONS

Biomass Distribution Model

The model was based on DBH and H, which are commonly used as independent variables in biomass models of Marklund (1988) and Repola (2009). The mean total above-ground biomass (95% confidence interval, CI) of Norway spruce was 66.36 ± 2.97 kg. All analysed variables were statistically significant ($p < 0.001$); however the strength of the correlations differed (Table 1). A high correlation between the stem fresh weight (stem weight with water and bark, but without needles and branches) and modelled weight prognosis (estimated fresh weight with water and bark, but without branches) ($r = 0.98$) indicated nearly the same variation and high model accuracy. Moreover, high correlation ($r = 0.79$) between the tree dimensions (DBH and H) exhibited similar variation pattern; therefore, the use of these variables can provide an estimation of tree above-ground biomass.

Table 1. Pairwise Pearson's Correlation Coefficients (Below Diagonal) and Significance (p-values – Above Diagonal) Among Variables of Norway Spruce

Variable	DBH	H	Stem Fresh Weight (kg)	Estimated Biomass (kg)
DBH	1	< 0.001	< 0.001	< 0.001
H	0.79	1	< 0.001	< 0.001
Stem Fresh Weight (kg)	0.36	0.29	1	< 0.001
Estimated Biomass (kg)	0.39	0.32	0.98	1

Models of biomass distribution predicted stem fragment fresh weight and compared the predictions with an actual stem fragment weight (Fig. 1). In general, the developed model showed a good fit to the stem weight data, as shown by the coefficient of determination ($R^2 = 0.95$).

Most of the models predicted dry wood biomass (Marklund 1988; Repola 2009), but the authors' model was a prediction of fresh stem wood biomass, as it was necessary for the assessment of the wind load effect. Model prognosis varied most with a prediction of first stem fragment weight (Fig. 1), which can be explained that the lower and thicker parts of the stem (which was primarily the first fragment) were the heaviest and their weight varied the most. A majority of the biomass models underestimate the actual tree biomass, and their predictions are lower than the real weight (Lībiete *et al.* 2017; Kenina *et al.* 2018). However, the authors' model overestimated the prognosis, as indicated by mean estimated biomass (84.66 ± 4.03 kg, 95% confidence interval). Results differ because most dry wood biomass models (belowground or aboveground) predict stem weight when trees have dried and lost a majority of stored stem water (Marklund 1988; Repola 2009; Lībiete *et al.* 2017; Kenina *et al.* 2018), while prediction of stem fresh weight biomass includes additional weight of water in the stem (amount of water varies noticeably).

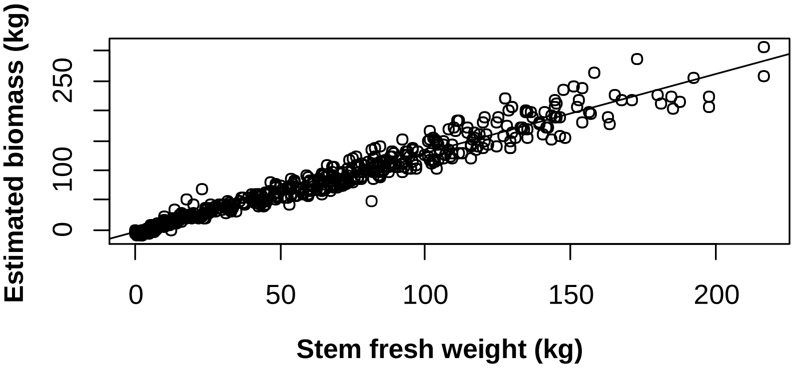

Fig. 1. Biomass distribution prognosis (kg) of Norway spruce against stem fresh weight (kg)

Component comparison

Principle component analysis (PCA) determined that approximately 83% of explainable variances were located in the first and second components (Fig. 2A), with proportions of 53.2% and 30.4%, respectively.

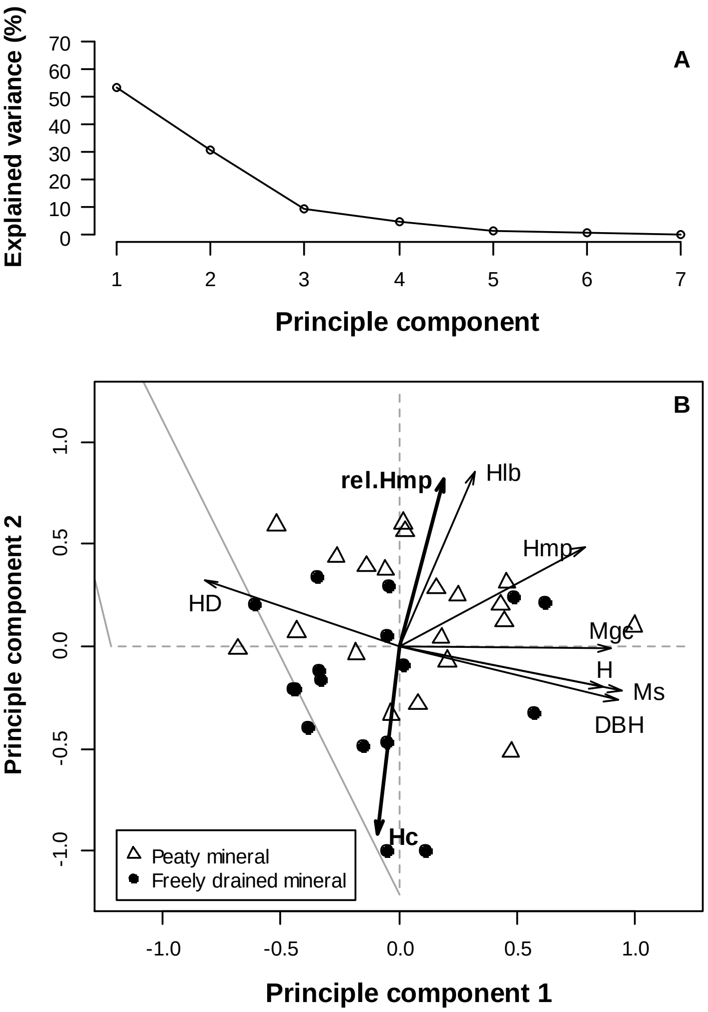

Fig. 2. Explained variance (%) of principle component (A); distribution and correlation between the studied trees in the vector space (B), where DBH: diameter at breast height; M_s: mass of stem, M_{gc}: mass of green crown; H: height, H_{lb}: height of the lowest living branch; H_{mp}: mass point height; rel. H_{mp}: relative mass point height; HD: slenderness ratio; H_c: relative canopy height

The PCA between the first two components was used to explain the effect of soil type on Norway spruce variables. The first component was associated with tree variables: H, DBH, mass of stem fresh weight (M_s), mass of green canopy (M_{gc}), H_{mp}, and slenderness ratio (HD). The second component was related to canopy parameters: rel. H_{mp}, H_{lb}, and relative height of crown (H_c) (Fig. 2B). Moreover, the second component had a statistically significant relationship with soil type.

More than 53.2% of explainable variations of first component were not affected by soil type; however, there was a strong correlation with H, DBH, M_s, and M_{gc} (Fig. 2B). Stem mass was tightly correlated with DBH (r = 0.95), H (r = 0.85), and M_{lb} (r = 0.83), which indicated a significance of effects of DBH ($p < 0.01$) and H ($p < 0.01$) on stem biomass variation, where the increase in these variables directly increased stem weight. Further, stem mass was used to assess tree's height of the mass point, and this parameter is dependent on various tree variables, such as height, DBH, and tree weight, of which H_{mp} was generally determined. Therefore, if tree height and diameter increases, then the height of a mass point also increases in most cases, and the correlation (r = 0.64) between these variables indicated that H_{mp} and height of tree had similar pattern of variation. Height of mass point was significantly and tightly correlated (r = 0.77) with the M_{gc}, and it had a moderate correlation with most of the analysed variables, such as M_s (r = 0.61), DBH (r = 0.55), H (r = 0.64), and H_{lb} (r = 0.57). In the analysis, H_{mp} was used to describe tree resistance to wind-load.

If the mass point height was located lower, then the resistance was greater and *vice versa* (Cucchi *et al.* 2005; Nicoll *et al.* 2006). Correlation between H_{mp} with all the above-mentioned variables indicated that properties of stem and crown might influence the potential susceptibility to wind damage, as it directly affects height of the mass point. However, biomass distribution might differ between trees because of the stem and crown architecture (Jansons *et al.* 2014). Slenderness ratio had a tight inverse correlation with DBH (r = -0.91), which indicates that with an increase in stem diameter tree HD ratio decreases, resulting in possibly higher resistance for wind load on a tree level (Mickovski *et al.* 2005). Taller and narrower trees with HD value over 1 are more susceptible to windthrow (Rudnicki *et al.* 2004) and have higher probability of being uprooted or snapped.

Another 30.4% of explainable variances of the second component were affected by soil type ($p < 0.008$), and they were positively correlated with rel. H_{mp}, H_{lb}, and negatively with H_c (Fig. 2B). Relative height of the mass point is from 34% to 44% of the whole tree height. For spruce with a relatively smaller canopy size, the whole tree mass point height was located higher ($p < 0.001$), resulting in unevenly balanced weight.

The tree's canopy serves as a 'sail' to catch larger wind loads and with a taller tree stem (the lever arm), the probability of wind damages increases (Gardiner *et al.* 2008; Schindler *et al*. 2012). Therefore, they were less resistant to wind-load damages (resulting in either stem breakage or windthrow) as less wind force is needed because of the vertical force applied due to gravity, including the crown and stem weight (Peltola *et al.* 1999). Results indicated that tree canopy on peaty mineral soils might be smaller in comparison to those growing on freely drained mineral soils. Additionally, trees growing on peaty mineral soils had poorer anchorage than on any other soil, similar results have been reported by Nicoll (2006). Thus, spruce growing on peaty soil need lower critical wind speed at which the damages occur.

CONCLUSIONS

1. A biomass distribution model was successfully applied using easy measurable variables for prediction of stem fresh weight. Biomass model was a useful tool for the above-ground biomass estimation for Norway spruce.
2. Principle component analysis revealed 83.7% of explainable variances in the first two components of which 53.2% of explainable variances were affected by height, diameter at breast height, stem and canopy weight, and height of the mass point. Trees with relatively higher stem mass and mass point height located lower will have a higher chance to survive extreme wind loads (storms).
3. Other 30.4% of variance were affected by soil type, indicating that spruce on peaty mineral soil had relatively smaller canopy; thus rel. H_{mp} was located higher, which resulted in less resistant to wind load. Accordingly, the relative height of the mass point was a significant variable for determination of wind damage risks. Trees growing on peaty soil had a higher wind damage risk than tree growing on fresh mineral soil.

ACKNOWLEDGMENTS

This study was funded by the European Regional Development Fund Project "Development of Decision Support Tool for Prognosis of Storm Damages in Forest Stands on Peat Soils" (No. 1.1.1.1/16/A/260).

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Article submitted: February 4, 2020; Peer review completed: April 11, 2020; Revised version received and accepted: April 16, 2020; Published: April 20, 2020.
DOI: 10.15376/biores.15.2.4314-4322

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

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Received: 29 May 2020; Accepted: 7 July 2020; Published: 9 July 2020

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

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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.

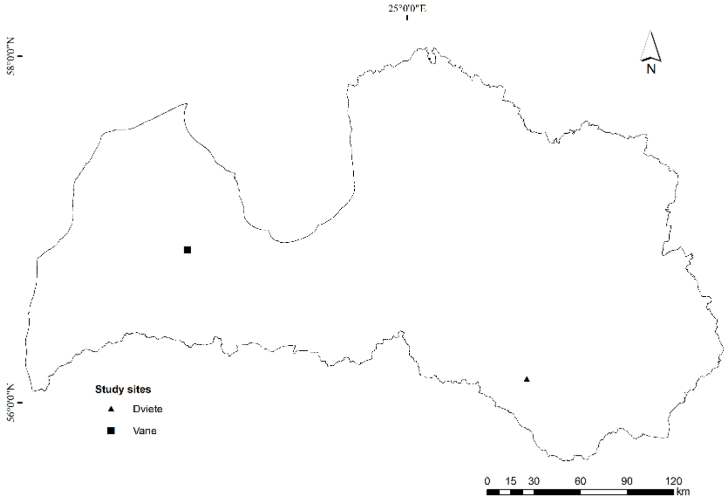

Figure 1. Location of the two study sites in Latvia.

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.

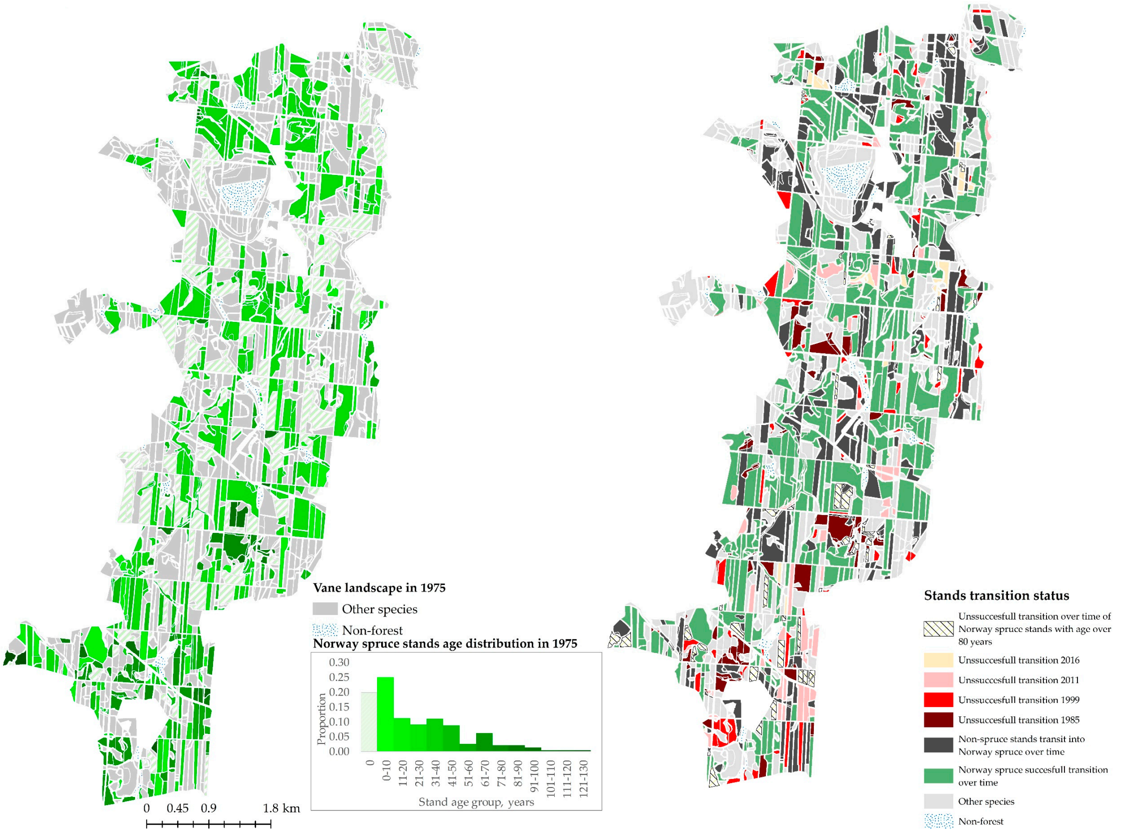

Figure 2. Norway spruce stands dynamics in Vane over 40 years (1975–2016).

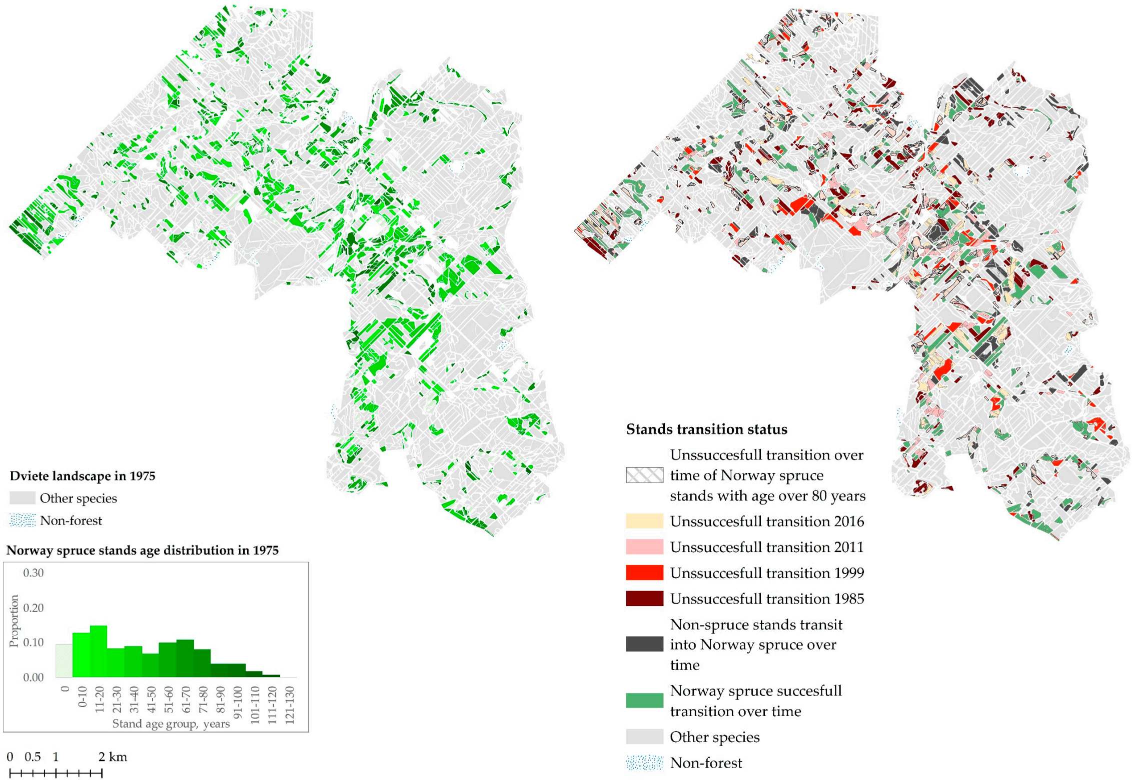

Figure 3. Norway spruce stand dynamics in Dviete over 40 years (1975–2016).

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.

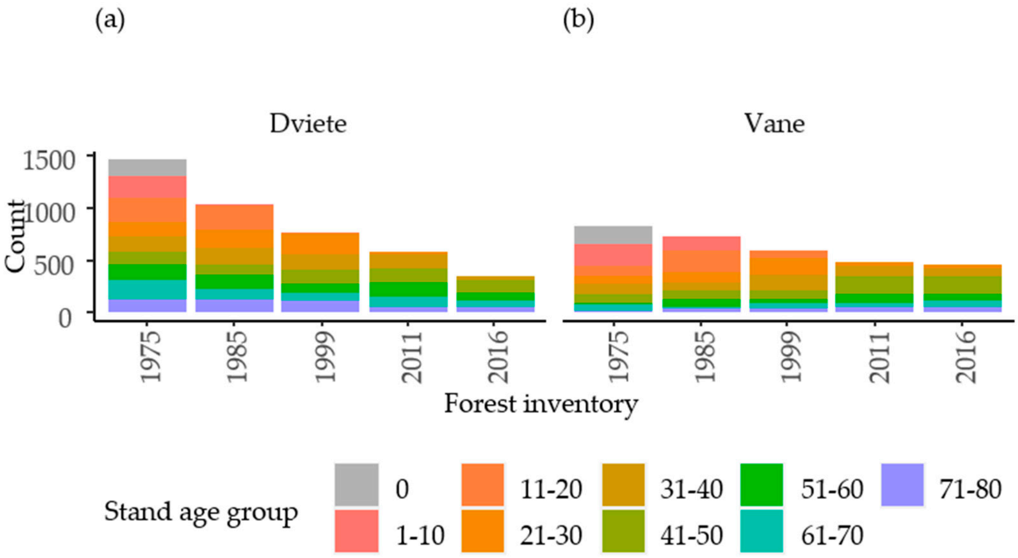

Figure 4. The dynamics of successfully transitioned Norway spruce stands (core areas) between inventories in two forested landscapes, Dviete (**a**) and Vane (**b**), respectively (only those stands that survived throughout the entire period are displayed).

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).

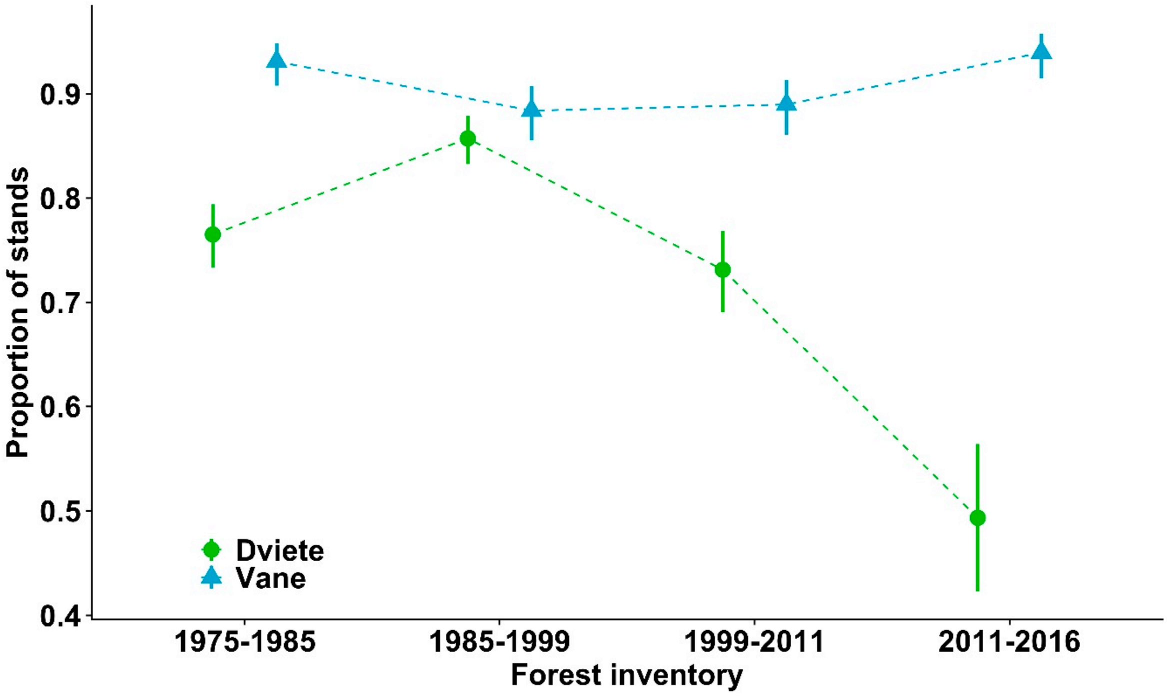

Figure 5. The transition of Norway spruce stands in two landscapes between two consecutive forest inventories (±95% confidence interval).

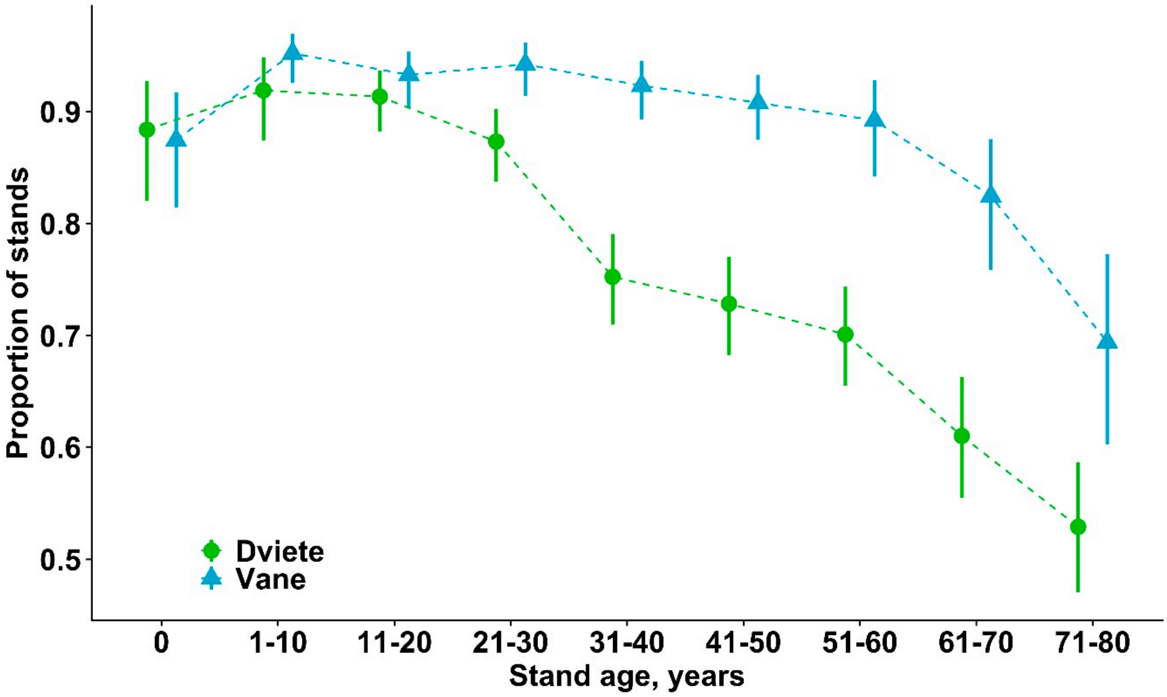

Figure 6. The site effect on the mean proportion of survival of Norway spruce stands between different age groups (±95% confidence interval).

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.

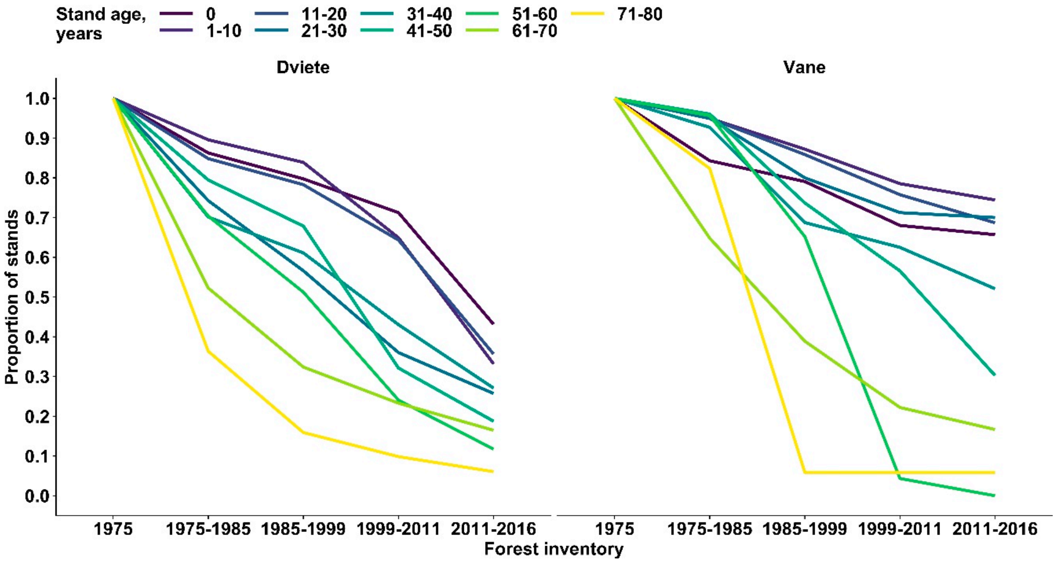

Figure 7. The proportion of successfully transitioned Norway spruce stands in both landscapes between observation periods by stand age group in 1975: In each forest inventory, the remaining part from the initial number of Norway spruce stands in a particular age group is shown.

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.

Author Contributions: Conceptualization, Ā.J. and J.D.; methodology, E.B., Ā.J., J.D., and D.E.; data curation, E.B., J.D., and O.K.; writing—original draft preparation, E.B. and O.K., writing—review and editing, Ā.J., I.J., and J.D. All authors have read and agreed to the published version of the manuscript.

Funding: This study was carried out as an ESF project, “Measures to increase resilience of Norway spruce forests against impact of climatic changes” (No. 1.1.1.2/VIAA/1/16/120).

Acknowledgments: We acknowledge the input of the reviewers, who helped to improve the manuscript significantly.

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

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Structural Root-Plate Characteristics of Wind-Thrown Norway Spruce in Hemiboreal Forests of Latvia

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Received: 19 August 2020; Accepted: 26 October 2020; Published: 28 October 2020

Abstract: An increase in extreme weather events is predicted with increasing climate changes. Changes indicate major problems in the future, as Norway spruce (*Picea abies* L. Karst.) is one of the most important forestry species in Northern Europe and one of the most susceptible to damage from extreme weather events, like windstorms. Root architecture is essential for tree anchorage. However, information of structural root-plate volume and characteristics in relation to tree wind resistance in drained deep peat soils is lacking. Individual tree susceptibility to wind damage is dependent on tree species, soil properties, tree health and root-plate volume. We assessed the structural root-plate dimensions of wind-thrown Norway spruce on freely drained mineral and drained deep peat soils at four trial sites in Latvia, and root-plate measurements were made on 65 recently tipped-up trees and 36 trees from tree-pulling tests on similar soils. Tree height, diameter at breast height, root-plate width and depth were measured. Measurements of structural root-plate width were done in five directions covering 180° of the root-plate; rooting depth was measured on the horizontal and vertical axes of root-plate. Root-plate volume was higher in drained peat soils in comparison to mineral soils, and root-plate width was the main driver of root-plate volume. A decreasing trend was observed in structural root depth distribution with increasing distance from the stem (i.e., from the center to the edge of the root plate) with a greater decrease in mineral soils.

Keywords: root architecture; root depth; structural roots; wind resistance

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1. Introduction

Climate change scenarios predict an increase in extreme weather events (windstorm frequency and intensity) [1]. Increasing frequency of storms causes loss of economic and ecological value in European forests [2]. Yet another effect of climate change is warming of the winter season, which causes long periods of unfrozen, wet soil [3], when tree anchorage is the weakest and wind damage probability is higher. Fully measured tree anchorage properties can help predict the response of trees to more severe climate change induced storms. Furthermore, trees deploy their roots in response to mechanical forces (slope and/or prevailing wind) by devoting increased root resources downslope and toward the windward direction to improve stability [4].

Individual tree stability varies among tree species and in regard to stand properties and tree health [5,6]. Tree rooting strategy is an important part of the general growth strategy for trees, and it determines root architecture [7]. The formation of tree roots depends mainly on the soil conditions because roots continuously adapt to the temporal and spatial fluctuations in their growth [8]. Root architecture and the size of root-soil plates determines tree anchorage and stability [7]. However, tree mechanical stability can be reduced by diseases such as root rot (*Heterobasidion* spp.) [9,10].

Norway spruce (*Picea abies* (L.) Karst.) is an economically important tree species in Northern Eurasia, including Latvia [11,12]. Norway spruce is able to grow under a wide range of soil (physical and chemical) and climatic conditions [13]. In addition, Norway spruce has a high susceptibility to windstorm damages because of its shallow root system and relatively dense crown [14–16].

Windstorms can create large gaps in forest stands, from which rapid natural regeneration emerges [17], because wind-throw damage in spruce forests causes many tree tip-ups, and root-plate volume determines the size of patches with open soil after the wind-throw. The most favorable microsites (suitable seed beds) for tree regeneration are tree-fall (root-plate) pits, tip-up mounds and logs [18–20]. However, in most cases, natural regeneration results in the establishment of dominant species other than Norway spruce [21]. In fact, spruce forms larger root-plate areas than other native tree species of the hemiboreal region [22], and thus creates large areas of open soil in the stand. After the collapse of the uprooted (tipped-up) root-ball, as the roots decay, the soil mass typically settles into the mound [23]. Thus, larger root-plate systems will create diverse microsite legacy effects.

Previous studies have analyzed root system development [8], belowground biomass [24,25], fine root or coarse root distribution in spruce stands [26,27] and mixed forest stands [26,28]. In addition, several studies of tree-pulling (winching) experiments have been conducted to assess the mechanical stability of Norway spruce [10,29,30]. However, root-plate volume for wind resistance assessment has been studied less [31], and in deep peat soils such information is even more scarce. Currently, the most common methods for root-plate measurements are direct measurements in laboratory or on site that involve excavating roots from the soil [32] and high-resolution geophysical imaging, such as ground-penetrating radar (georadar) [33]. Root measurements usually include length, density, growth angle and topological structure; however, as technology has improved, image processing has evolved to automatic detection and analysis [34]. Root distribution is dependent on soil characteristics, tree size and tree species; therefore, we assessed the root-plate volume of Norway spruce across many trees from diverse forest stands on two soil types.

The aim of the study was to assess the root-plate dimensions of uprooted Norway spruce in mineral and drained peat soils. We hypothesized that root-plate volume would be higher in drained peat soils compared to mineral soils.

2. Materials and Methods

This study was carried out in Latvia, with study sites located in North-West Latvia—Skede (57°14′ N 22°42′ E), Neveja (57°34′ N 22°18′ E), Central Latvia—Jelgava (56°40′ N, 23°53′ E) and East Latvia—Kalsnava (56°41′ N, 23°88′ E).

Altogether, 64 recently (no longer than 1 year) tipped-up trees by wind-throw (all available tipped-up trees in study sites) were selected for structural root-plate measurements to characterize the rooting of wind-thrown spruce trees. Materials were collected in similar stands in terms of age and parameters, such as stand density and tree dimensions of canopy trees, soil conditions, wind climate and species composition. These were pure even-aged commercial Norway spruce stands growing on freely drained mineral and drained deep peat soils (peat layer > 50 cm) [35]. In Latvia, stand density before the final harvest in such stands is reduced to approximately 700–900 trees per ha^{-1}. These soil types are common in Latvia, representing 51% and 12% of the soils in spruce forests, respectively [36]. The territory of Latvia is covered by a thick layer of sediments; thus, bedrock cannot limit rooting depth. In the studied sites, naturally well-drained podzolic soils formed on well-drained fine/loamy sand parent materials, and artificially drained deep peat soils were also found.

For a control, we selected data from tree-pulling (winching) tests conducted in commercial Norway spruce stands with similar characteristics as the wind-thrown stands. Control data from trees situated on drained peat soils were obtained from a study published previously [10]. For mineral soils, root-plate dimension data from pulling tests carried out in summer 2020 at the Jelgava site were used.

For each tree height (H), diameter at breast height (DBH), root-plate width, height and depth were measured (including soil particles attached) (Table 1). Structural root-plate width was measured parallel to the land surface and perpendicular to the tree stem. Root-plate surface width measurements covered 180° of the root-plate in five directions from stem side: left side (L), halfway left to center (L45), center (C), halfway right to center (R45) and right side (R) (at 0°, 45°, 90°, 135° and 180°, respectively) (Figure S1). In cases where the length of the root exceeded the length of the root-soil ball, the width was measured to the furthest root. These values were used as the radius of the root-plate for root-ball shape and volume calculations.

Table 1. Dimensions of sampled trees.

Variable		**Wind-Throw**		**Tree-Pulling Tests (Control)**	
Site		**Neveja-Skede**	**Kalsnava**	**Jelgava**	**Kalsnava**
Soil Type		**Freely Drained Mineral Soil**	**Drained Deep Peat Soil**	**Freely Drained Mineral Soil**	**Drained Deep Peat Soil**
N		39	25	26	10
DBH (cm)	Min	13.0	23.3	17.8	26.5
	Max	50.0	46.5	42.0	37.7
	Mean	25.5 ± 2.7	31.2 ± 2.6	28.0 ± 2.4	32.0 ± 3.0
Height (m)	Min	12.7	21.6	16.9	24.8
	Max	32.3	31.7	33.4	29.6
	Mean	21.6 ± 1.6	26.0 ± 1.1	25.6 ± 1.6	27.2 ± 0.9
Root-plate width (m)	Min	0.3	0.7	0.9	3.4
	Max	3.6	3.5	3.0	5.5
	Mean	1.4 ± 0.2	2.0 ± 0.3	1.7 ± 0.2	4.5 ± 0.4
Root-plate height (m)	Min	0.2	1.0	0.5	1.5
	Max	1.8	2.4	2.8	2.5
	Mean	1.1 ± 0.1	1.6 ± 0.1	1.2 ± 0.2	2.1 ± 0.2
Root-plate depth (cm)	Min	9.3	23.3	26.8	40.0
	Max	45.5	82.5	84.0	80.0
	Mean	28.3 ± 2.3	44.7 ± 5.3	49.2 ± 6.6	57.1 ± 8.5

For structural root-plate depth distribution assessment, we measured roots with diameters greater than 10 mm instead of total rooting depth (due to the fact that fine roots could be found in deeper layers than coarse roots). Rooting depth was assessed on the vertical and horizontal axes (center and right), where root-plate depth, including root-soil ball, was measured (Figure S1) for assessment of the structural root depth distribution. The first depth measurement was taken as close as possible to the stem, and the rest were taken every 0.2 m.

Pearson's correlations were calculated to assess the relationship between tree size, measured and calculated variables, such as H, DBH, root-plate width, depth, volume and the relationship between H and DBH (HD^2). Root-plate volume was estimated based on calculating the structural root depth distribution shape using an elliptic cone volume equation:

$$V = \left(\frac{1}{3}\right) * \pi * a * b * h, \tag{1}$$

where h is the mean root-plate center (0–20 cm) height (depth); a is the vertical radius of the root-plate; b is the mean horizontal radius of the root-plate.

Tree wind resistance was estimated using Peltola's [29] approach where tree height was multiplied by DBH squared to get an idea of tree stem susceptibility to tip-up. In the generalized additive model, relative root depth and relative distance from the stem were used as predictors to calculate structural root depth distribution. All steps of the data analysis were carried out using the statistical software R 4.0.0. [37].

3. Results

3.1. Structural Root Horizontal Surface Shape

To assume the structural root-plate horizontal surface is an ellipse, the horizontal and vertical measured width can be used to calculate the 45° angle of the actual geometric ellipse. The halfway left to center (L45) and halfway right to center (R45) radius was on average 0.89 ± 0.22 (mean ±95% CI) and 0.93 ± 0.32 (mean ±95% CI) of the center (C) height for mineral and drained peat soils, respectively. Taking into account the average of the vertical and horizontal widths, the average of L45 and R45 was 1.09 ± 0.06 (mean ±95% CI) and 1.01 ± 0.04 (mean ±95% CI) of a true ellipse in mineral and drained peat soil, respectively; thus, L45 and R45 were 9% and 1% higher than radii of an actual geometric ellipse, respectively. Therefore, we assumed that an ellipse is a good approximation of the horizontal root-plate shape.

3.2. Structural Root Depth Distribution of Tipped-Up Trees

Structural root-plate depth was assessed using the relative root-plate depth distribution and the relative distance from the stem (Figure 1). If the measurement point distance from the stem increased, the root-depth decreased; thus, a negative relationship ($r = -0.99$) between the distance from the stem and rooting depth was measured in both drained peat and mineral soils. No limitations to root vertical growth were observed, as no compacted soil layers were found in the studied stands or below the wind-thrown trees. In addition, the shape of the vertical roots did not indicate difficulties of penetration.

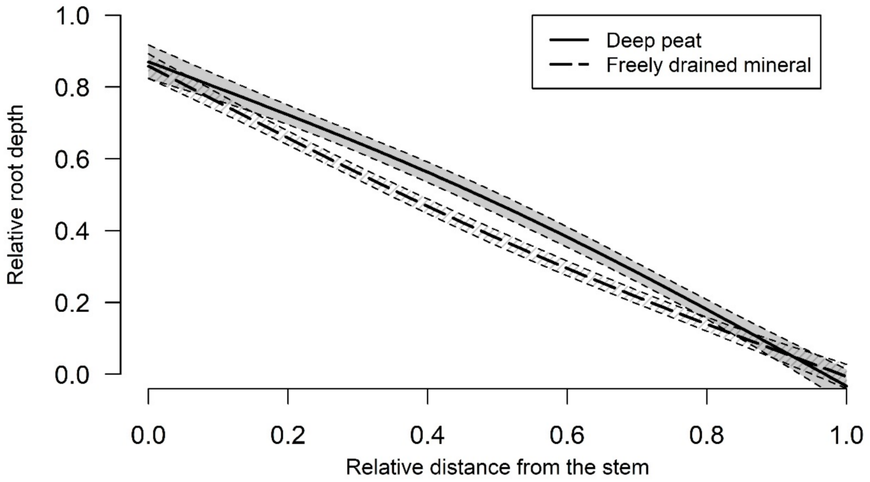

Figure 1. Relative structural root-plate depth distribution of measurement points at relative distance from the stem of wind-thrown trees. (Grey area denotes 95% confidence interval.)

Vertical rooting depth governs tree susceptibility to wind-throw. Mean depth at the center of the root-plate was 28.3 ± 2.3 (mean ±95% CI) cm and 49.2 ± 6.6 (mean ±95% CI) cm for mineral and drained peat soil, respectively. Mean rooting depth in the first meter (from the center to the edge of the root plate) was 22.4 ± 3.4 (mean ±95% CI) cm for mineral soil and 38.9 ± 5.8 (mean ±95% CI) cm for drained peat soil. The maximum depth values were observed in the center of the root-plate (0 cm from the stem). Maximum depth value in drained peat soils was 82.5 cm, while in mineral soils it reached the highest value of 45.5 cm. With increasing distance from the stem, relative rooting depth in mineral soil decreased more rapidly than in drained peat soils. Relative rooting depth differed significantly ($p < 0.05$) between soil types except at the center and the edge of the root-plate.

3.3. Root-Plate Volume

Root-plate volume of tipped-up trees in mineral soil varied from 0.02 m^3 to 2.01 m^3, and in drained peat soil the root-plate volume ranged from 0.4 m^3 to 3.2 m^3. In tree-pulling tests (control), root plate volume ranged from 0.3 m^3 to 5.9 m^3 and from 4.0 m^3 to 7.6 m^3 in mineral and drained peat soil, respectively. The difference of root-plate volume between soil types was statistically significant ($p < 0.001$), and the results differ noticeably (Figure 2). Root-plate volume was lower for trees growing on mineral soil, while trees on drained peat soils tended to have larger values. Mean root-plate volume of tipped-up trees in mineral soil was 0.50 ± 0.14 (mean ±95% CI) m^3 and 1.5 ± 0.3 (mean ±95% CI) m^3 in drained peat soils. In addition, mean root-plate volume of control trees was significantly higher than that of root-plate volume of tipped-up trees, as the mean volume was 1.3 ± 0.5 (mean ±95% CI) m^3 and 5.5 ± 1.0 (mean ±95% CI) m^3 in mineral and drained peat soils.

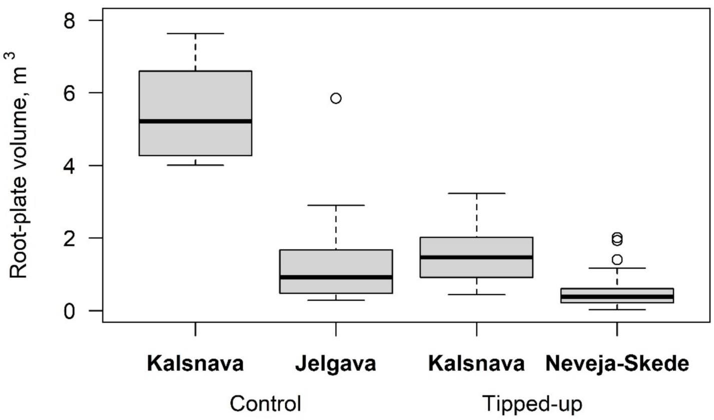

Figure 2. Root-plate volume of tipped-up trees and control (tree-pulling test) in two different soil types: deep peat (Kalsnava) and freely drained mineral soil (Jelgava and Neveja-Skede).

Results indicate differences in root-plate volume of tipped-up trees and trees from pulling (winching) experiments (Figures 3 and 4), as root-plate volume of tipped-up trees was significantly smaller than those of control. Differences between tipped-up and control trees were marked in both soil types; however, in drained peat soil the differences were even more pronounced (Figure 4). In addition, the mean width of the root-plate was highly correlated ($r = 0.92$) with root-plate volume; therefore, as tree roots grow wider (i.e., further from the stem), the root plate volume also increases. Moderate correlation ($r = 0.47$) was observed for root-plate center depth and root-plate width.

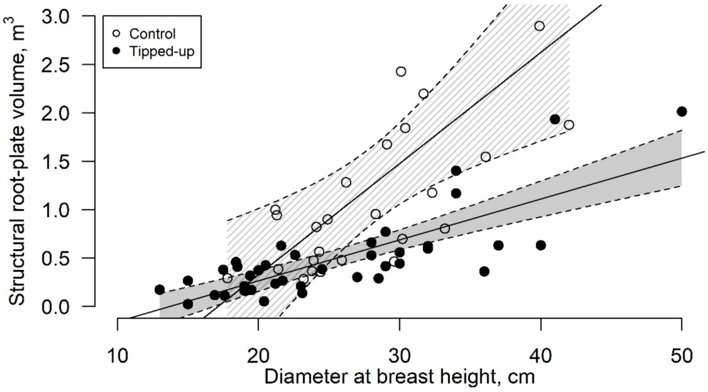

Figure 3. Root-plate volume *vs.* diameter at breast height in freely drained mineral soil. Grey area indicates 95% confidence interval.

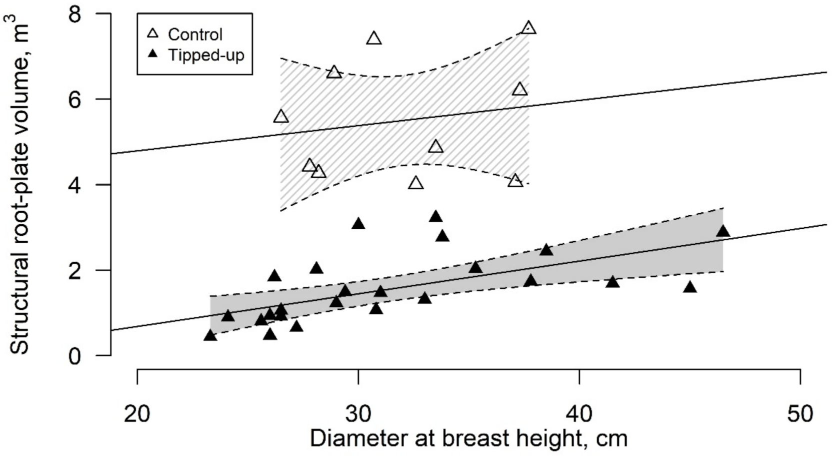

Figure 4. Root-plate volume *vs.* diameter at breast height in drained deep peat soil. Grey area indicates 95% confidence interval.

Our results indicate the importance of DBH in determining root-plate volume (Figure 3) and potentially in increasing tree wind resistance to uprooting from wind disturbances. Therefore, we calculated HD^2, which is known to indicate tree wind resistance to uprooting in mineral soils [29]. Results show the difference of tree wind resistance between soil types, as HD^2 values in mineral and drained peat soils were 1.94 ± 0.66 (mean ±95% CI) m^3 and 2.46 ± 0.57 (mean ±95% CI) m^3, respectively. Even though mean values for mineral soil were lower, with increasing root-plate volume, the estimated wind resistance values increased more rapidly in mineral soils in comparison to drained peat soils (Figure 5). The HD^2 values showed a good linear model fit as indicated by the coefficient of determination in mineral (r^2 = 0.84) and drained peat (r^2 = 0.39) soils.

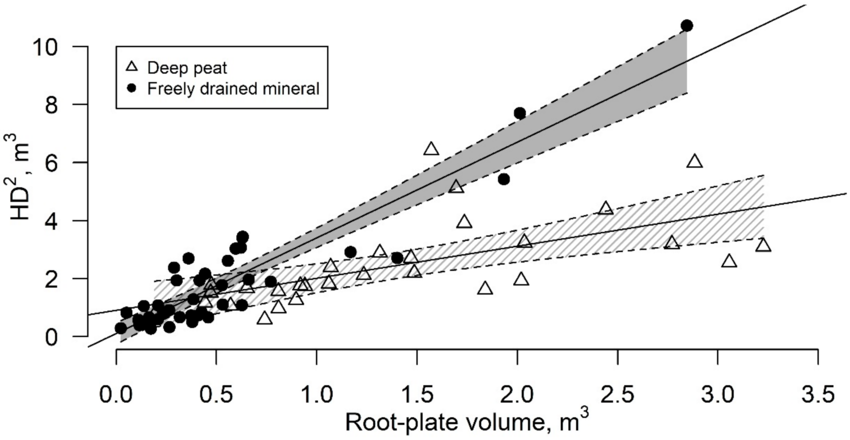

Figure 5. HD^2 in relation to root-plate volume in two soil types. Grey area indicates 95% confidence intervals.

4. Discussion

Assuming the structural root-plate horizontal surface shape as an ellipse was appropriate, the average lengths of L45 and R45 were only 9% and 1% larger in comparison to a true ellipse in mineral and drained peat soil, respectively. Structural root distributions provide physical stability of trees to windthrow, and deep penetration by roots is important for the anchorage; trees with varying root-plate morphologies respond differently to stress and competition [8]. The maximum depth values differed between soil types, with drained peat soils having higher maximum depth values than mineral soils. Overall, a decreasing trend was observed in structural root depth distribution with increasing distance from the stem (Figure 1). Mean depth in the center and first meter of the root-plate was higher for drained peat soils than for mineral soils; however, with increasing distance from the stem, a more rapid decrease was observed for mineral soils than for drained peat. The exception was the edge of the root-plate of drained peat soils where a rapid depth decrease in the relative rooting depth was observed. In addition, if the vertical root system is weakly developed, spruce depends on a horizontal network of supporting lateral roots [8]. With increasing tree age, the capacity of the root system to adapt or rebuild anchorage is lowered [8], thus affecting capability to recover and continually resist wind damage.

Root-plate volume in drained peat soils was more than three times higher than root-plate volume in mineral soils (Figure 2); thus, the hypothesis of the study was confirmed. This could be explained by the fact, as reported in other studies, that trees on deep peat soils flex more as trees sway and adapt their roots to the wind environment (develop eccentric cross-sectional root-system shape) and are better prepared to resist bending in the stronger winds than trees on mineral soil [30]. In both soil types, an increase in root-plate volume was observed with an increase in tree DBH (Figures 3 and 4). A close relationship between tree size parameters and root-plate system development has been reported in previous studies, where dominant large trees form the largest root systems, while average-sized trees develop well-shaped root systems and suppressed trees form poorly developed root systems [8]. Results show that the main determining factor of root-plate volume is root-plate width ($r = 0.92$). Thus, if the root distribution (i.e., root-plate diameter) is wider, the root-plate volume is greater, as also reported in other studies [38]. With similar tree dimensions, root-plate depth and width was larger for drained peat soils in comparison to mineral soils (Table 1). Therefore, larger patches of open soil in the forest stand after wind-throw are formed by trees with larger root-plate width and by trees growing on drained peat soils than for trees with the same dimensions on mineral soil. In addition, trees adapt their root systems to the applied mechanical forces by the prevailing winds and slope and devote additional root resources towards improving tree stability, thus increasing root volume, resistance and adapting root shape [4].

Comparison of root-plate volume between tipped-up trees and control trees, as well as trees from tree winching experiments, indicates significantly higher root-plate volume compared to windthrown trees, especially in drained peat soils (Figure 4). Trees with the weakest root systems are the first ones tipped-up in storms in both soil types. However, with increasing climate change and prolonged periods of wet, unfrozen soil in the winter, the wind damage probability increases [3]. Furthermore, comparisons of data obtained from windthrows and tree-winching tests can be applied in wind risk models to improve the model parametrization of tree resistance against overturning. Nevertheless, a larger root-ball does not always ensure greater wind resistance, as root binding with drained peat soils is weaker and soil mass is lighter in comparison to root binding with mineral soils [4]. In our research, root adaptation was not studied, but root distribution against the prevailing wind direction and root shape was found to be important for wind resistance. However, there are many other factors affecting wind resistance and wind damage probability, such as tree stem and root system adaptation, soil conditions in winter, recent silvicultural measures (thinning) and even diseases such as root and stem rot (*Heterobasidion* spp.) [10,39,40].

Differences in tree wind resistance between soil types were indicated, as spruce trees on drained peat soils had larger root-plate volumes and greater mean tree wind resistance values (Figure 5). Yet, spruce on mineral soil had a more rapid increase in wind resistance values with increasing root-plate volumes, indicating higher overall wind resistance than drained peat soils. This assumption is in accordance with previous studies that show trees on drained peat soils are more susceptible to wind damage than trees on mineral soils [30]. Observed differences could be explained by differences in soil conditions, rigidity, water table depth and structural root-system architecture that might differ between forest and soil types [41,42]. In our study, we used root-plate measurement data from tipped-up trees, which introduces a systematic bias since trees with weaker root systems are uprooted in storms [40] and because some soil from the root-soil plate might be lost before the measurements, even if the measurements were done shortly after the wind-throw.

From an economic point of view, in order to reduce wind damage risks, timely applied thinning of the stands could improve and help develop larger and stronger tree root systems. In addition, low-density Norway spruce stand establishment could help to improve the root system due to reduced competition in the stand.

5. Conclusions

An overall decreasing trend of structural rooting depth was observed in both (mineral and drained peat) soil types, with more rapid depth decrease for mineral soils. Root-plate volume differed significantly between soil types, and it was higher for drained peat soils in comparison to mineral soil even with equal tree parameters (DBH). The width of the root-plate was the main determining factor for root-plate volume. However, tree wind resistance in mineral soils increased more rapidly with increasing root-plate volume in comparison to drained peat soils.

Supplementary Materials: The following are available online at http://www.mdpi.com/1999-4907/11/11/1143/s1, Figure S1: Schematic image of root-plate measurement methodology.

Author Contributions: Conceptualization, Ā.J. and O.K.; methodology, J.D.; formal analysis, V.S.; writing—original draft preparation, O.K. and V.S.; writing—review and editing, J.D and Ā.J.; project administration, Ā.J. All authors have read and agreed to the published version of the manuscript.

Funding: This study was funded by the European Regional Development Fund Project Development of decision support tool for prognosis of storm damages in forest stands on peat soils (No. 1.1.1.1/16/A/260).

Acknowledgments: The support of the European Regional Development Fund Project Development of decision support tool for prognosis of storm damages in forest stands on peat soils (No. 1.1.1.1/16/A/260) is acknowledged.

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

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