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# HEMIBOREĀLO MEŽU DEGŠANAS VĒSTURE UN KOKAUDŽU ATJAUNOŠANĀS DEGUMOS

# *FOREST FIRE HISTORY AND POST-FIRE REGENERATION PATTERNS IN HEMIBOREAL FORESTS*

PROMOCIJAS DARBS
mežzinātņu doktora Dr.silv. zinātniskā grāda iegūšanai

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*for acquiring the Doctor's degree of Forest sciences*

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# ANOTĀCIJA

Klimata un antropogēno faktoru ietekmes dēļ Eiropā 21. gadsimtā palielināsies meža ugungrēku skartā platība. Lai varētu prognozēt ugunsbīstamības izmaiņas mūsu reģionā nākotnē un to potenciālo ietekmi uz koksnes resursiem un siltumnīcefekta gāzu emisijām, svarīgi izzināt ugunsgrēku vēsturi, to izraisošos faktorus un ugunsgrēku ietekmi uz meža ekosistēmas elementiem. Promocijas darba mērķis ir raksturot klimatisko un antropogēno faktoru ietekmi uz meža degšanas vēsturi un parastās priedes (*Pinus sylvestris* L.) atjaunošanos ugunsgrēka skartajās platībās.

Pētījuma rezultāti liecina, ka ikgadējās meža ugunsgrēku platības ilgtermiņa dinamika Latvijā ir līdzīga kā blakus esošajās teritorijās – Igaunijā, Lietuvā, Baltkrievijā un Pleskavas apgabalā Krievijā. Par liela mēroga atmosfēras cirkulācijas sistēmu ietekmi uz meža ugunsgrēku dinamiku liecina būtiskās korelācijas ar Baltijas un Ziemeļjūras virsmas temperatūru. Pēdējos 250 gados Slīteres Nacionālajā parkā ugunsgrēki priežu mežos ir bijuši regulārs traucējums, ko būtiski ietekmējuši gan antropogēnie, gan klimatiskie faktori. Platībās, kurās pēc ugunsgrēka veikta sanitārā vienlaidus cirte, priedes dabiskā atjaunošanās kopumā notikusi sekmīgāk – priedes augstums bija statistiski būtiski lielāks, bet biezums būtiski neatšķīrās, salīdzinot ar platībām, kurās šāda cirte netika veikta. Promocijas darbā iegūtās atziņas pielietojamas ugunsapsardzības sistēmas pilnveidošanā, dabas aizsardzības plānošanā un kā pamatinformācija turpmākiem pētījumiem par ugunsgrēku ietekmi uz dažādiem meža ekosistēmas elementiem.

Šis promocijas darbs sastāv no tematiski vienotām piecām zinātniskām publikācijām.

## ABSTRACT

The aim of our study was to assess climate and human effects on the historic forest fire regimes and to assess post-fire regeneration patterns of Scots pine (*Pinus sylvestris* L.).

To assess climate effect on regional fire activity, we used fire statistics (number of fires, burned area) over 20$^{th}$ century and climatic data (sea surface temperature and monthly drought code). The influence of large scale weather systems on the fire activity in Latvia was suggested by the similar fire activity with neighbouring countries – Estonia, Lithuania, Belarus and Pskov region in Russia and positive correlations with the SSTs in the Baltic and North seas. The history of forest fires was studied using dendroecological methods, which revealed that over the last 250 years, fire has been a common disturbance agent in Scots pine-dominated landscape in Slitere National Park, shaped by climate and human effects. The effect of salvage logging on post-fire natural regeneration pattern was assessed 23-years following fire disturbance. In post-fire areas, live remnant trees had a negative effect on the mean height of naturally regenerated Scots pine; while the abundance of Scots pine between salvage logged and no-intervention areas was rather similar.

The gained insight into the driving factors of forest fires in hemiboreal forest zone could be used to define nature-based management guidelines, to improve forest fire surveillance system, and as baseline information for further studies looking at ecological effects of fires.

# SATURS / *CONTENTS*

# PUBLIKĀCIJU SARAKSTS / *LIST OF PUBLICATIONS*

Promocijas darba pamatā ir piecas publikācijas, uz kurām atsauces tekstā veidotas, izmantojot romiešu ciparus:
*This thesis is based on five publications, referred to by Roman numerals in the text:*

I. **Kitenberga M.**, Matisons R., Jansons A., Donis J. (2018) Teleconnection between the Atlantic sea surface temperature and forest fires in Latvia and Estonia. Silva Fennica, 52 (1), 1-8. https://doi.org/10.14214/sf.7771

II. Drobyshev I., **Kitenberga M.**, Ryzhkova N. (2019) Trends and patterns in annually burned forest areas and fire weather across the European boreal zone in the 20th and early 21st centuries. (manuskripts / *manuscript*)

III. **Kitenberga M**., Drobyshev I., Elferts D., Matisons R., Adamovics A., Katrevics J., Niklasson M., Jansons A. (2019) A mixture of human and climatic effects shapes the 250-year long fire history of a semi-natural pine dominated landscape of Northern Latvia. Forest Ecology and Management, 441, 192–201. https://doi.org/10.1016/j.foreco.2019.03.020

IV. **Zadina[*] M.**, Purina L., Pobiarzens A., Katrevics J., Jansons J., Jansons A. (2014) Height-growth dynamics of Scots pine (*Pinus sylvestris* L.) in burned and clearcut areas hemiboreal forests, Latvia. In: Proceedings of the Second International Congress of Silviculture. Designing the future of the forestry sector, Florence, 443–447. http://dx.doi.org/10.4129/2cis-mz-hei

V. **Kitenberga M.**, Elferts D., Adamovics A., Katrevics J., Donis J., Baders E., Jansons A. (2019) Impact of salvage-logging on Scots pine (*Pinus sylvestris* L.) regeneration in post-fire areas in hemiboreal forests. (recenzēšanā / *in review* New Forests)

[*] mainīts uzvārds no Zadiņa uz Kitenberga/ *last name changed from Zadina to Kitenberga*

**Autoru ieguldījums publikācijās / *The contribution of the authors***

| | I | II | III | IV | V |
|---|---|---|---|---|---|
| Ideja / *Original idea* | **MK**, RM | ID, NR | AJ, MN | AJ, JJ | AJ, JD |
| Pētījuma plāns / *Study design* | RM, **MK** | ID, NR, **MK** | AJ, **MK**, AA | AJ, JK, LJ** | AJ, **MK**, AA, JK |
| Datu ievākšana / *Data collection* | **MK**, JD | ID, **MK**, NR | **MK**, AA, JK | **MK***, LJ**, AP, JK | AA, JK |
| Datu analīze / *Data analysis* | **MK**, RM | ID | **MK**, ID, DE, RM, MN | **MK***, AJ | **MK**, DE, EB |
| Manuskripta sagatavošana / *Manuscript preparation* | **MK**, RM, AJ | ID, **MK**, NR | **MK**, ID, DE, RM, MN | **MK***, AJ | **MK**, DE, EB |

AA - Andis Adamovičs, AJ - Āris Jansons, AP – Agris Pobiaržens, DE - Didzis Elferts, EB- Endijs Bāders, ID - Igor Drobyshev, JD - Jānis Donis, JJ - Jānis Jansons, JK - Juris Katrevičs, LJ - Līga Jansone, **MK - Māra Kitenberga**, MN - Mats Niklasson, NR- Nina Ryzhkova, RM - Roberts Matisons.

* mainīts uzvārds no Zadiņa uz Kitenberga / *last name changed from Zadina to Kitenberga*;
** mainīts uzvārds no Puriņa uz Jansone / *last name changed from Purina to Jansone*.

## SAĪSINĀJUMI / *ABBREVIATIONS*

SST – jūras virsmas temperatūra / *sea surface temperature*

SNP – Slīteres Nacionālais parks / *Slītere National Park*

MDC – mēneša sausuma indekss / *monthly drought code*

AMO – Atlantijas multidekāžu oscilācijas indekss / *Atlantic Multidecadal Oscillation*

LME – lineārs jaukts modelis / *linear mixed-effect model*

GLMM – vispārināts lineārs modelis / *generalised linear mixed-effects model*

LFY – lielie meža ugunsgrēku gadi / *large fire years*

# 1. IEVADS

## 1.1. Traucējumi hemiboreālajos mežos

Traucējums meža ekosistēmā ir konkrēts notikums laikā, kas būtiski izmaina esošo ekosistēmas, populācijas un sabiedrības struktūru, resursu un substrāta pieejamību vai fizisko vidi (Picket & White, 1985).

Traucējumi tiek iedalīti šādās grupās (Sousa, 1984):

1. Dabiskie traucējumi:
    - abiotiskie (vējš, uguns, ūdens u.c.),
    - biotiskie (patogēni – sēnes, baktērijas, kukaiņi, dzīvnieki);
2. Antropogēnie traucējumi (meža ciršana, augsnes nosusināšana, piesārņojums).

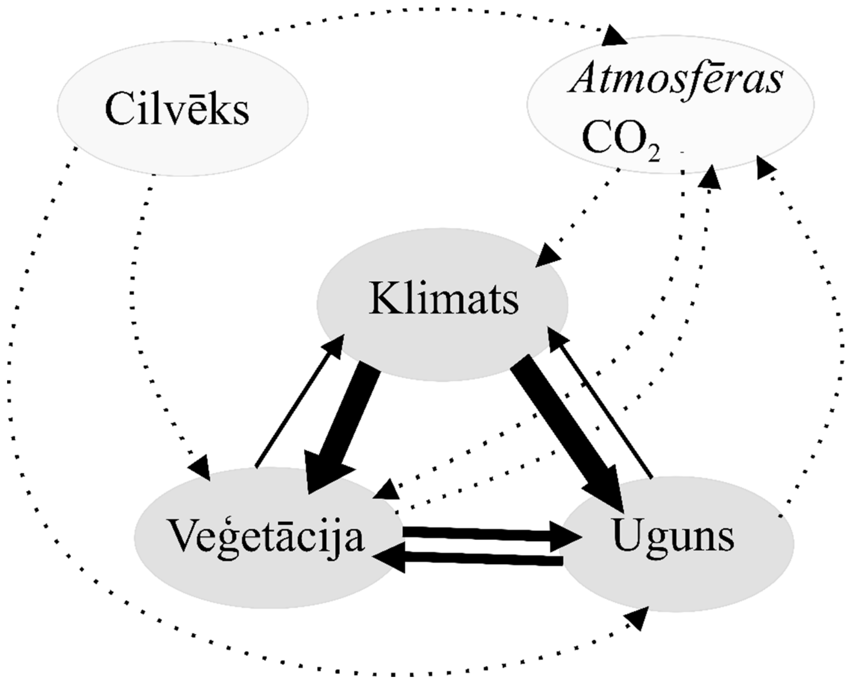
Visām meža ekosistēmām ir raksturīgi traucējumi, un bieži šo ekosistēmu attīstība ir atkarīga no specifiska traucējuma režīma. Traucējumu režīma raksturošanai tiek izmantoti šādi parametri (Sousa, 1984):

1. Traucētās platības izmērs;
2. Nozīmīgums (*magnitude*):
    - intensitāte (*intensity*),
    - ietekmes smagums (*severity*);
3. Frekvence – traucējumu notikumu skaits konkrētā laika periodā;
4. Rotācijas periods – periods, kas nepieciešams, lai traucējums skartu visu pētāmo teritoriju.

Traucējumu režīms būtiski ietekmē meža ekosistēmas strukturālo heterogenitāti, kā arī kopējo bioloģisko daudzveidību (Pickett & White, 1985; Kuuluvainen, 1994). Mežaudzes stuktūras, kas rodas dabisko traucējumu rezultātā, ir komplicētas, un nav viegli reproducējamas, izmantojot mežsaimniecības paņēmienus (Franklin et al., 2002). Nepilnīga izpratne par dabisko traucējumu ekoloģiskajām sekām vai arī to vienkāršošana var radīt mežaudzes struktūras, kas var nebūt noturīgas klimata pārmaiņu kontekstā (Kuuluvainen, 2002a).

## 1.2. Dabiskā traucējuma aģents – uguns

Ugunsgrēki ir nozīmīgs dabiskais traucējums sauszemes ekosistēmās, kas izmaina ekosistēmas un palielina oglekļa emisiju daudzumu (Bowman et al., 2009). Sarežģītā dabiskā sistēmā starp klimatu, veģetāciju un degšanu pastāv mijiedarbības un atgriezeniskās saites (1.1. att.), ko pēdējos gadsimtos būtiski ietekmējusi cilvēka darbība (Seidl et al., 2011; Bowman et al., 2014). Cilvēka saimnieciskās darbības rezultātā izmainās zemes lietojuma veids (mežs/lauksaimniecības zeme/apbūve), telpiskais izvietojums ainavā, mežaudzes struktūra (koku sugu sastāvs, vecums), kas savukārt būtiski ietekmē meža ugunsgrēku režīmu (Granström & Niklasson, 2008). Tieši cilvēka radītās klimata pārmaiņas ir bijušas galvenais virzītājspēks meža ugunsgrēku platību pieaugumam Eiropā 20. gadsimta otrajā pusē (Seidl et al., 2011).




1.1.att. **Mijiedarbības un atgriezeniskās saites starp klimatu, uguni un veģetāciju. Līnijas biezums norāda uz relatīvo mijiedarbības vai atgriezeniskās saites nozīmību. Punktētā līnija parāda cilvēka un atmosfēras $CO_2$ koncentrācijas saites ar šīs sistēmas komponentiem pēc Bowmann et al., (2014)**

Meža ugunsgrēku aktivitāte 20. gadsimtā samazinājās, lielā mērā pateicoties efektīvai uguns apsardzības sistēmai (Donis et al., 2017). Tomēr ākārtēja sausuma apstākļos (piemēram, 2018. gada vasarā), viena ugunsgrēka nodzēšana var aizņemt vairākas nedēļas un uguns ietekmētā teritorija var plesties simtos hektāru, norādot, ka nākotnē, kad tiek prognozēti arvien biežāki ekstrēmas ugunsbīstamības laikapstākļi (Lehtonen et al., 2016), pašreizējās meža ugunsgrēku apsardzības sistēmas reaģētspēja, visticamāk, būs nepietiekama. Tādēļ uguns nodarīto postījumu samazināšanai kritiski svarīga ir savlaicīgas ugunsbīstamības noteikšanas sistēmu uzlabošana. Lēmumu pieņemšanas procesā nepieciešama arī informācija par uguns īstermiņa un ilgtermiņa ietekmi, kā arī efektīvākajiem mežsaimnieciskajiem pasākumiem, lai pēc iespējas veiksmīgāk atjaunotu mežaudzes degumos.

Meža ugunsgrēki būtiski ietekmē ekoloģiskās sukcesijas un to attīstības dinamiku, izmainot augsnes īpašības, limitējot uguns jutīgās sugas un veicinot pirofīlo sugu izplatīšanos (Bond et al., 2004; Certini, 2005). Ugunsgrēka ietekmes smagums uz ekosistēmu (*fire severity*) raksturo virszemes un pazemes organisko vielu zudumu pēc meža ugunsgrēka (Keeley, 2009); tas tiek uzskatīts arī par vides izmaiņu novērtējumu pēc traucējuma. Ugunsgrēka ietekmes smagums būtiski izmaina arī augsnes ķīmisko elementu dinamiku (P, K, Mg, Ca, N) (Dzwonko et al., 2015). Ugunsgrēka ietekmes smagums uz ekosistēmu veidojas kā kombinācija starp dažādiem meža ugunsgrēka parametriem – degšanas intensitāti, degšanas ilgumu un veģetācijas mitrumu (Chatto & Tolhurst, 2004; Cram et al., 2006). Degmateriāla daudzums, struktūra, kontinuitāte un mitrums būtiski ietekmē ugunsgrēka ietekmes smagumu (Schimmel & Granström, 1996; Certini, 2005).

Atkarībā no ugunsgrēka intensitātes un ietekmes smaguma uz ekosistēmu tos iedala trīs grupās (Ņesterovs, 1954; Roga, 1979):

1. Zemdega – uguns izplatās pa zemsegu, humusa vai kūdras slāni. Iesākumā deg zemsegas / kūdras sausākās daļas, tad karstums, kas rodas degšanas procesā, izžāvē arī mitrākās daļas, kas pēc tam viegli var aizdegties. Bieži zemdegas gadījumā uguns liesmas nav redzamas virszemē, kūdras slānis var izdegt līdz minerālaugsnei vai gruntūdens līmenim.

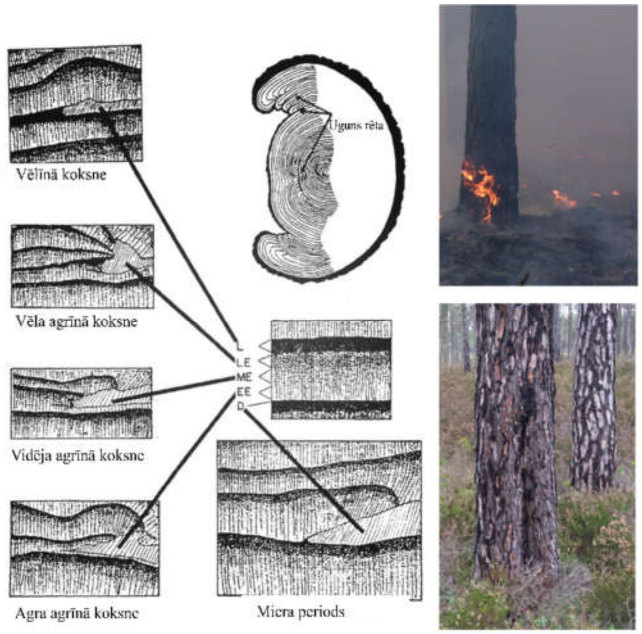
2. Skrejuguns – uguns izplatās pa zemsegu, zemsedzi, pamežu vai paaugu. Skrejuguns intensitāte variē no zemas līdz vidējai. Samērā bieži tiek bojātas saknes, kas atrodas tuvāk zemes virskārtai, un koka miza stumbra apakšējā daļā. Skrejuguns var izraisīt daļēju kokaudzes bojāeju, kā rezultātā dabiski attīstās dažāda vecuma saliktas audzes.

3. Vainaguguns – uguns izplatās pa zemsedzi un koku vainagiem. Vainaguguns parasti ir augstas intensitātes, kā rezultātā 80–100 % no mežaudzes kokiem iet bojā, tādējādi plašā teritorijā notiek liela mēroga vienlaidus traucējums. Šādos degumos parasti masveidā atjaunojas pioniersugas.

Viens no būtiskajiem faktoriem, kas ietekmē meža ugunsgrēku režīmu, ir klimats. Klimats ir raksturīgie ilgtermiņa laikapstākļi, kas nosaka ne vien meteoroloģiskos apstākļus konkrētajā vietā, bet arī to, kāda veida veģetācija šajā vietā var attīstīties (1.1. att.). Gan globālo atmosfēras cirkulāciju sistēmu, kas nosaka laikapstākļus, gan dabisko traucējumu dinamiku sauszemes ekosistēmās būtiski ietekmē atmosfēras mijiedarbība ar jūras un okeāna ūdeņiem (Heimann & Reichstein, 2008; Shabbar et al., 2011; Drobyshev et al., 2016). Pētījumi pierādījuši, ka globālo atmosfēras-okeāna cirkulāciju sistēma tās holistiskās ietekmes dēļ uz visiem meteoroloģiskajiem rādītājiem labāk izskaidro klimata lomu dažādos ekoloģiskajos procesos nekā atsevišķi meteoroloģiskie rādītāji (Hallett et al., 2004). Viena no prominentākajām un plašāk pētītajām parādībām ir Klusā okeāna dekadālās un El Ninjo – dienvidu oscilācijas (svārstības), kas iespaido klimatiskos apstākļus visā pasaulē (Behrenfeld et al., 2001). Eiropā, sevišķi ziemas sezonā, klimatiskos apstākļus būtiski ietekmē Ziemeļatlantijas oscilācijas (Trigo et al., 2002; Scaife et al., 2008). Līdz šim Ziemeļeiropā tikai vienā pētījumā analizēta atmosfēras-okeāna cirkulācijas režīma ietekme uz meža ugunsgrēku aktivitāti (Drobyshev et al., 2016). Lielākajā daļā citu pētījumu meža ugunsgrēku aktivitāte sasaistīta ar noteiktiem meteoroloģiskajiem parametriem (vidējā gaisa temperatūra, nokrišņu daudzums) vai sausuma režīmu aprakstošiem indeksiem (Drobyshev et al., 2012; Aakala et al., 2017; Donis et al., 2017), kas nesniedz vispusīgu ieskatu par klimata mainīguma ietekmi uz meža ugunsgrēku aktivitāti.

### 1.3. Uguns rētu veidošanās process

Meža ekosistēmās, kurās dominē zemas līdz vidējas intensitātes meža ugunsgrēki, uguns rētas uz koku stumbriem ir visplašāk izmantotā pazīme meža ugunsgrēku vēstures rekonstruēšanai (Niklasson & Granström, 2000; Drobyshev et al., 2004; Piha et al., 2013). Kokiem varbūtība izdzīvot pēc uguns radītiem bojājumiem paaugstinās, pieaugot vecumam, jo pakāpeniski palielinās kreves mizas biezums un koku vainagu augstums (Keeley, 2012). Pēc uguns rētu novietojuma koksnes gadskārtās var noteikt ne tikai degšanas gadu, bet arī sezonu (Baisan & Swetnam, 1990). Uguns rēta koksnē veidojas, kad uguns liesma uzkarsē kambija šūnas virs 60°C, izraisot to bojāeju (Gutsell & Johnson, 1996). Ar laiku uguns rētas pāraug ar blakus esošā nebojātā kambija veidotām ikgadējām gadskārtām un mizu (1.2. att.). Līdz brīdim, kad notikusi pilnīga pāraugšana, šajā stumbra daļā ir viszemākā karstuma izturība (to nepasargā miza), tāpēc atkārtota meža ugunsgrēka gadījumā var veidoties jauna uguns rēta (Gutsell & Johnson, 1996). Koki nav nevainojami ugunsgrēku vēstures pierakstītāji (Swetnam et al., 1999; Piha et al., 2013). Meža ugunsgrēku vēsture, kas tiek balstīta uz uguns rētām, visticamāk, nepietiekami atspoguļo zemas intensitātes meža ugunsgrēkus, jo parasti uguns rētas šādos ugunsgrēkos neveidojas. Savukārt augstas intensitātes meža ugunsgrēku gadījumos, kuru rezultātā lielākā daļa kokaudzes aiziet bojā, arī informācija par uguns rētām tiek iznīcināta. Lai pilnveidotu meža ugunsgrēku vēstures rekonstrukcijas precizitāti, pētījumos bieži tiek apvienota informācija no vairākiem avotiem, piemēram, uguns rētu analīzi papildinot ar datiem par esošās kokaudzes struktūru un tās elementu vecumu, kā arī ezeru-purvu nogulumiem (Drobyshev et al., 2016; Stivrins et al., 2019).




1.2.att. **Uguns rētas veidošanās process pēc Swetnam & Baisan, (1996)**

## 1.4. Meža ugunsgrēku režīms Ziemeļeiropā un Latvijā

Ziemeļeiropā vēsturiskā meža ugunsgrēku režīma izpētei visbiežāk izmanto parasto priedi. Parastā priede (*Pinus sylvestris* L.) ir viena no visizplatītākajām koku sugām Eiropas boreālajos un hemiboreālajos mežos (Angelstam & Kuuluvainen, 2004; Niklasson et al., 2010), kas ir pielāgojusies augšanai dažādos apkārtējās vides apstākļos (Keeley & Zadler, 1998; Keeley, 2012). Pētījumu rezultāti liecina, ka parastā priede spēj saglabāt dzīvotspēju vairākos zemas līdz vidējas intensitātes meža ugunsgrēkos (Östlund et al., 1997; Kuuluvainen et al., 2002b), kas, izraisot daļēju kokaudzes bojāeju, veicina kohortas dinamikas attīstību ar dažāda vecuma kokiem (Angelstam & Kuuluvainen, 2004; Kuuluvainen & Aakala, 2011). Lai arī vairums meža ugunsgrēku Eiropas boreālajos un hemiboreālajos priežu mežos ir ar zemu līdz vidēju intensitāti, ir sastopami arī augstas intensitātes meža ugunsgrēki, kā rezultātā lielākā daļa kokaudzes iet bojā, veicinot vienvecuma audžu attīstību (Agee, 1993; Zin et al., 2015).

Pēdējos gadsimtos meža ugunsgrēku dinamiku Eiropā būtiski ietekmējusi cilvēka saimnieciskā un sociālā darbība (Granström & Niklasson, 2008), izmainot galvenokārt meža ugunsgrēku skaitu, telpisko izplatību un sezonalitāti. Dažādos reģionos un laika periodos cilvēka ietekme uz meža ugunsgrēkiem bijusi kardināli atšķirīga. Piemēram, Fenoskandija pēdējo 600 gadu laikā var izdalīt vairākus būtiski atšķirīgus periodus meža ugunsgrēku vēsturē, ko galvenokārt ir ietekmējusi cilvēka saimnieciskā darbība (Granström & Niklasson, 2008). Periodā 1650–1870, kad Fenoskandija dominēja ziemeļbriežu vai liellopu audzēšana un uzturēšana, meža ugunsgrēki bija 2,9 reizes biežāk nekā periodā 1499–1650. Savukārt vēlākajā periodā, sākot no 18. – 19. gs. vidus, kad būtiski pieauga kokmateriālu vērtība, meža ugunsgrēki praktiski vairs nav reģistrēti (Niklasson & Granström, 2000).

Pētījumi rāda, ka Belovežas gāršā, periodā 1653–1700, vidējais audzes uguns atgriešanās intervāls (FRI) bija ~18 gadi. Šajā periodā Belovežā plaši izplatīta bija biškopība un darvas dedzināšana (Niklasson et al., 2010). Šajā periodā lielākā daļa meža ugunsgrēku bijuši zemas intensitātes par ko liecina fakts, ka ugunsgrēkā spēja izdzīvot koki ar vidēji ~5 cm diametru, kā arī salīdzinoši neliela radiālā pieauguma samazināšanās pēc ugunsgrēka (Zin et al., 2015). Periods ar ļoti zemu meža ugunsgrēku aktivitāti sācies 19.gs. beigās, kad kopumā pieauga kokmateriālu vērtība (Niklasson et al., 2010).

Straujš meža ugunsgrēku pieaugums novērots 17. gs. beigās Vienansalo, Fenoskandija austrumos, kas, visticamāk, skaidrojams ar labvēlīgu nodokļu politiku, lai cilvēkus motivētu pārcelties uz iepriekš neapdzīvotām teritorijām. Savas dzīves vietas ierīkošana tieši saistījās ar līdumu lauksaimniecību šajā laika periodā, par ko netieši liecina arī samērā īsais meža ugunsgrēku cikls (~75 gadi). Savukārt, kopš 19. gs. vidus meža ugunsgrēku skaits šajā reģionā strauji samazinājies, uguns cikls ~400 gadi, kas visticamāk skaidrojams ar kokmateriālu vērtības pieaugumu un efektīvāku ugunsgrēku dzēšanu (Wallenius et al., 2004).

Latvijas teritorijā vissenākie pierādījumi par cilvēka darbības ietekmi uz meža degšanu sniedzas līdz mezolīta un agrīnajiem neolīta periodiem, kad šo teritoriju apdzīvoja Baltijas mednieku-vācēju ciltis (Dietze et al., 2018). Sākot no 1.–2. gadsimta līdz pat 19. gadsimta beigām, Latvijas un pārējo Baltijas valstu teritorijās plaši izplatīta bija uguns izmantošana līdumu lauksaimniecībā (Dumpe, 1999; Strods, 1999).

Ezeru nogulumu pētījumi Latvijas teritorijā rāda, ka agrajā holocēnā 11,7–7,5 tūkst. kal.g.p.m (preboreālais klimatiskais periods), kad dominēja *Pinus sylvestris* un *Betula* spp. ar nelielu platlapju piejaukumu (*Ulmus*, *Tilia*, *Corylus avellana*), uguns atgriešanās intervāls (FRI) bija ~280 gadi. Vidusholocēna klimatiskajā optimumā, kad dominēja platlapju sugas *Ulmus*, *Corylus avellana*, *Tilia*, *Quercus* un *Carpinus* (7,5–4,5 tūkst. kal.g.p.m), FRI bija ievērojami ilgāks ~630 gadi. Savukārt, vēlajā holocēnā (subboreālais subatlantiskais klimatiskais periods) 4,5–0 tūkst. kal.g.p.m, kad dominēja boreālās koku sugas (*Picea abies*, *Betula* spp., *Pinus sylvestris*), FRI bija visīsākais ~190 gadi. Ezera ogļu nogulumi rāda, ka periodā, kurā dominēja priede-bērzs, meža ugunsgrēki bija bieži, galvenokārt, zemas intensitātes ar atsevišķiem augstas intensitātes ugunsgrēkiem. Savukārt, periodā, kurā dominēja mērenajai joslai raksturīgie lapukoki, meža ugunsgrēki bija ievērojami retāki. Periodā, kurā dominējā parastā egle, meža ugunsgrēki galvenokārt bija augstas intensitātes (Feurdean et al., 2017).

Līdzšinējie pētījumi Latvijas teritorijā par meža ugunsgrēku aktivitāti ir veikti, izmantojot ezeru-purvu nogulumus, kas sniedz informāciju par ilgtermiņa dinamiku pa desmitgadēm-simtgadēm (Dietze et al., 2018), savukārt pētījumi, kas, balstoties uz ugunsrētām, spētu sniegt precīzāku informāciju par ugunsgrēku norises gadu / sezonu un platību, līdz šim nav veikti. Priežu meži ar uguns rētām atrodami Slīteres Nacionālajā parkā (SNP) Latvijas ziemeļrietumu daļā, kas saglabājušies praktiski neskarti nabadzīgās augsnes, purvaino apstākļu un aizsardzības statusa dēļ (Brumelis et al., 2005; SNP dabas aizsardzības plāns, 2010). Vēsturiskās meža degšanas izpēte priežu mežos sniegs ieskatu par šī traucējuma ilgtermiņa dinamiku, kā arī par galvenajiem to ietekmējošiem faktoriem. Šāda informācija nepieciešama gan dabas aizsardzības, gan uguns apsardzības sistēmas pilnveidošanai.

### 1.5. Mežaudzes atjaunošanās pēc deguma

Degumos meža dabiskās atjaunošanās gaita un sugu sastāvs ir atkarīgs no attāluma līdz tuvākajam sēklu avotam (Moser et al., 2010), ugunsgrēka ietekmes smaguma (Dzwonko et al., 2015), iepriekšējās mežaudzes elementiem (*disturbance legacies*) (Jõgiste et al., 2017) un saimnieciskās darbības (Parro et al., 2015). Koku atjaunošanās deguma platībās ir atkarīga arī no sugu atjaunošanās un turpmākās attīstības stratēģijas (Noble & Slatyer, 1980; Ryan, 2002).

Atjaunošanās stratēģija:

1. Uz veģetatīvās atjaunošanās spēju balstīta stratēģija:

   V sugas: spēj atjaunoties no atvasēm, ja uguns bojā agrā vecumā;

   W sugas: spēj izdzīvot pēc uguns bojājumiem pieaugušā vecumā un turpināt attīstīties (uguns nogalina jaunākos kokus).

2. Uz sēklu izplatību balstīta stratēģija:

D sugas: sēklas spēj izplatīties plašā apvidū;
S sugas: sēklas spēj ilgtoši saglabāties augsnē;
C sugas: sēklas saglabājas koku vainagā.

Sugu attīstības stratēģijas:

T sugas: spēj strauji atjaunoties pēc uguns traucējuma un ilgtermiņā attīsīties, ja nav atkārtots uguns traucējums;
R sugas: spēj atjaunoties deguma teritorijā tikai pēc tam, kad ir izveidojušies piemēroti apstākļi (ēna vai tml.);
I sugas: spēj strauji atjaunoties deguma teritorijā (pioniersugas), bet salīdzinoši ātri pašas iet bojā bez atkārtota traucējuma.

Uguns ietekmes smagums būtiski ietekmē visu stratēģiju kokaugu atjaunošanās potenciālu (Granström & Schimmel, 1993). Ugunsgrēki ar augstāku ietekmes smagumu negatīvi ietekmē sugas ar V un W stratēģiju. Jo augstāks ir potenciālais bojājums auga veģetatīvām daļām, jo grūtāk tām ir atjaunoties (Ryan, 2002).

Boreālajos un hemiboreālajos mežos visizplatītākās koku sugas, kas atjaunojas degumos, ir parastā priede, bērzs un parastā apse (Hille & den Ouden, 2004; Dzwonko et al., 2015; Parro et al., 2015). Pētījumi liecina, ka bērza un priedes dabiskā atjaunošanās veiksmīgāk norit teritorijās, kurās ugunsgrēka ietekmes smagums bijis augstāks, nekā vietās, kur tas bijis zemāks. Tas skaidrojams ar lielāku zemsegas traucējumu, kā rezultātā tiek atsegta minerālā augsne, kurā jaunajiem kokiem ir vieglāk attīstīties. Atjaunošanos veicinošs faktors ir pelni kā papildus barības vielu avots (Hille & den Ouden, 2004; Dzwonko et al., 2015).

Degumos veicot sanitārās cirtes, mežizstrādes tehnika rada papildus traucējumu šajās teritorijās, kas var atstāt ilgstošu negatīvu ietekmi uz bioloģisko daudzveidību, augsnes kvalitāti un kokaudzes un zemsedzes veģetācijas atjaunošanās dinamiku (Thorn et al., 2017; Leverkus et al., 2018). Igaunijā pētījumā secināts, ka sausās, nabadzīgās smilts augsnēs sanitārā vienlaidus cirte pēc deguma negatīvi ietekmēja dabiski atjaunojušos koku skaitu, savukārt pozitīvi ietekmēja to vidējo augstumu (Parro et al., 2015). Tomēr kopumā trūkst informācijas par sanitārās vienlaidus cirtes ietekmi uz dabisko atjaunošanos kūdras augsnēs un mitrās minerālaugsnēs, kas ir samērā plaši izplatītas Latvijas teritorijā.

### 1.6. Promocijas darba mērķis

Promocijas darba mērķis ir raksturot klimatisko un antropogēno faktoru ietekmi uz meža degšanas vēsturi un parastās priedes (*Pinus sylvestris* L.) atjaunošanos ugunsgrēka skartajās platībās.

### 1.7. Promocijas darba uzdevumi

Promocijas darbā izvirzīti četri uzdevumi:

1. novērtēt klimatisko faktoru ietekmi uz ugunsgrēku skaita un platības ilgtermiņa dinamiku;
2. raksturot meža degšanas vēsturi Piejūras zemienē Latvijas ziemeļrietumu daļā;
3. salīdzināt priedes jaunaudžu parametrus stādījumos pēc sanitārās vienlaidus cirtes degumā un pēc vienlaidus atjaunošanas cirtes;
4. novērtēt sanitārās vienlaidus cirtes ietekmi uz dabisko atjaunošanos degumos.

## 1.8. Promocijas darbā izvirzītās tēzes

Promocijas darbā izvirzītas divas tēzes:

1. liela mēroga klimatiskajām sistēmām ir būtiska ietekme uz meža ugunsgrēku biežumu un platību Baltijas jūras reģionā;
2. sanitārajai vienlaidus cirtei pēc meža ugunsgrēka ir būtiska ietekme uz priedes dabisko atjaunošanos.

## 1.9. Pētījuma novitāte

Promocijas darbā pirmo reizi apzināta liela mēroga klimatisko sistēmu ietekme uz meža ugunsgrēku skaitu un platību Baltijas jūras reģionā. Pirmo reizi Baltijas valstīs novērtēta antropogēno un klimatisko faktoru ietekme uz vēsturisko meža ugunsgrēku režīmu 250 gadu ilgā laika posmā. Novērtēta deguma ilglaicīga ietekme uz stādītu priedes jaunaudžu parametriem dažādos meža tipos. Novērtēta sanitārās vienlaidus cirtes (pēc deguma) ietekme uz priedes dabisko atjaunošanos, turklāt pirmo reizi – tik ilgu laika posmu pēc ugunsgrēka meža tipos kūdras augsnēs.

## 1.10. Promocijas darba uzbūve

Promocijas darbs sastāv no piecām publikācijām. Promocijas darba pirmajā publikācijā analizēta meža ugunsgrēku aktivitātes dinamika un tās saistība ar liela mēroga klimatiskajām sistēmām Latvijā un Igaunijā. Otrajā publikācijā analizēta meža ugunsgrēku saistība ar klimatiskajiem apstākļiem plašākā reģionā, iekļaujot Skandināviju un daļu no Krievijas boreālo mežu reģioniem. Trešajā publikācijā analizēta informācija par vēsturisko meža ugunsgrēku režīmu Piejūras zemienē un tā saistību ar klimatiskajiem un antropogēnajiem faktoriem. Ceturtajā publikācijā apskatīta uguns ietekme uz priedes augstuma pieauguma veidošanos stādītās jaunaudzēs. Piektajā publikācijā apskatīta meža apsaimniekošanas veida ietekme uz dabisko mežaudzes atjaunošanos uguns skartās platībās.

## 1.11. Promocijas darba aprobācija

Ziņojumi par pētījuma rezultātiem prezentēti 5 starptautiskās konferencēs:

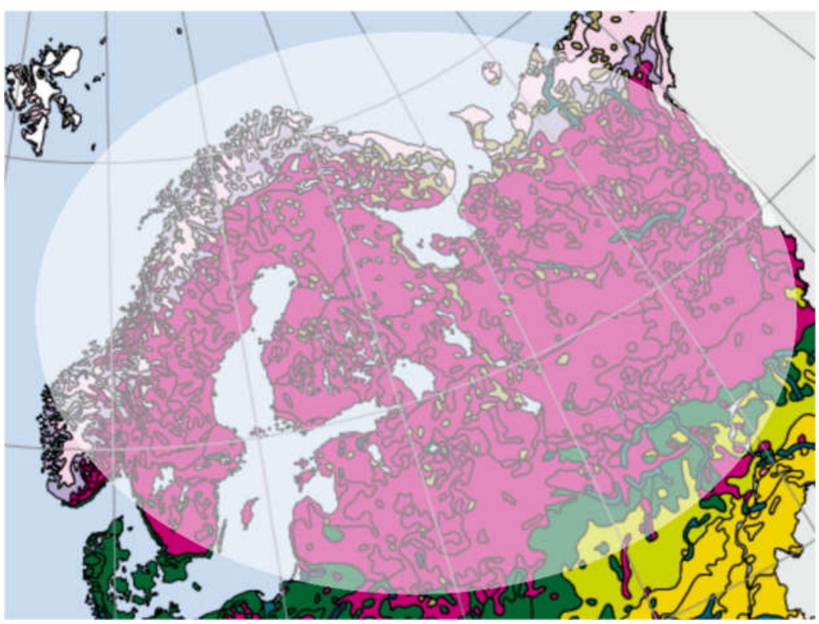
1. 26.-29.11.2014. Florence, Itālija. Refertāts: ‘Height-growth dynamics of Scots pine (*Pinus sylvestris* L.) in burned and clearcut areas in hemiboreal forests, Latvia’ otrajā starptautiskajā mežzinātnes kongress ‘Accademia Italiana di Scienze Forestali’.
2. 23.-24.04.2015. Rīga, Latvija. Stenda referāts ‘A 247-year tree-ring width chronology of Scots pine (*Pinus sylvestris* L.) from Slitere National Park’ starptautiskajā konferencē ‘Adaptation and mitigation: strategies for management of forest ecosystems’.
3. 15.-16.09.2015. Rīga, Latvija. Stenda Referats: ‘Post-fire regeneration of Scots pine (*Pinus sylvestris* L.) in Latvia’ starptautiskajā konferencē Nordic-Baltic Forest Conference 2015 ‘Wise Use of Improved Forest Reproductive Material’.
4. 04.-06.11.2015. Rīga, Latvija. Stenda referāts: ‘Influence of forest fire on Scots pine (*Pinus sylvetris* L.) age structure and regeneration pattern’ starptautiskajā zinātniskajā konferencē ‘Knowledge based Forest Sector’.

5. 06.-10.09.2017. Tartu, Igaunija. Refarāts: 'Dendrochronological reconstruction of the forest fire regime in a *Pinus sylvestris*-dominated forest in the Slitere National Park, Latvia' starptautiskajā konferencē 'Eurodendro'.

## 2. MATERIĀLS UN METODES

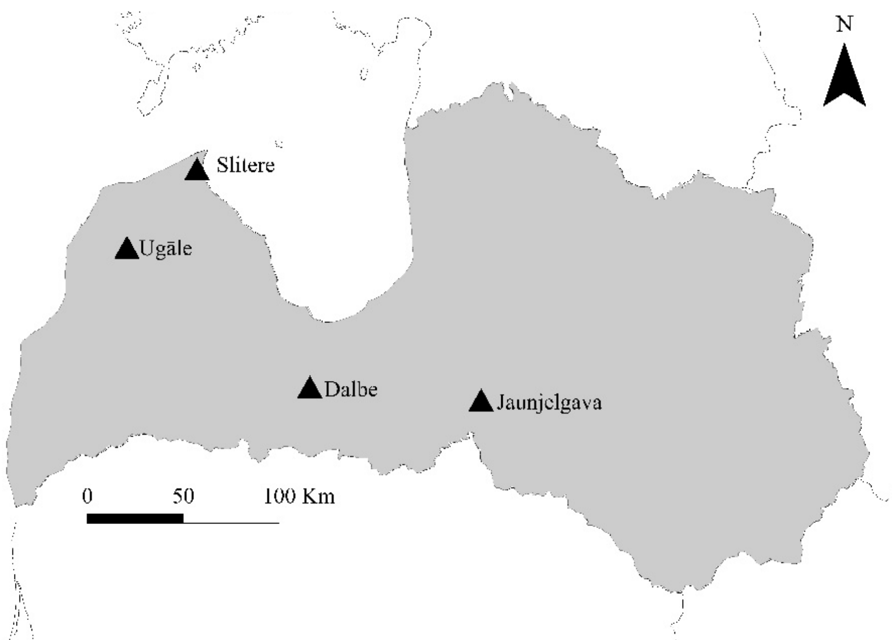
Pirmajā un otrajā publikācijā meža ugunsgrēku aktivitātes raksturošanai izmantotie statistikas dati par ugunsgrēku skaitu un platību Latvijā laikposmā no 1922. līdz 2014. gadam iegūti no vairākiem literatūras avotiem un datu bāzēm (Donis et al., 2017), savukārt Igaunijā laikposmā no 1923. līdz 2014. gadam – no Igaunijas Vides aģentūras. Dati par mēneša vidējo jūras virsmas temperatūru (SST) un Atlantijas multidekāžu oscilācijas indeksu (AMO) iegūti no Lielbritānijas Meteoroloģijas Hadleja centra datubāzes (Rayner et al., 2003; Trenberth & Shea, 2006). Ugunsgrēku skaita un platības dati logaritmēti, lai normalizētu datu izkliedi. Sakarības starp Latvijas un Igaunijas meža ugunsgrēku skaitu un platību novērtētas, izmantojot Pīrsona korelācijas un sinhronizācijas koeficientus. Lai novērtētu saistības starp meža ugunsgrēkiem un klimatiskajiem rādītājiem, izmantota Pīrsona korelācijas analīze *Climate Explorer* programmā (Trouet & Oldenborgh, 2013). Korelāciju būtiskums noteikts ar divpusējo Stjūdenta t-testu, ņemot vērā laikrindas autokorelāciju. Katras korelācijas būtiskums vizualizēts kartē (Wilks, 2006).

Otrajā publikācijā analizēta meža ugunsgrēku aktivitāte plašākā reģionā, iekļaujot ne tikai Baltijas valstis, bet arī Skandināviju un daļu no Krievijas boreālajiem reģioniem (2.1. att.). Klimatisko apstākļu raksturošanai izmantots mēneša sausuma indekss (MDC), kuru aprēķina, izmantojot mēneša kopējo nokrišņu daudzumu, minimālās un maksimālās mēneša gaisa temperatūras no CRU TS v. 4.02 datu bāzes (Harris et al., 2014). Hierarhiskā klāsteranalīze izmantota, lai noskaidrotu, kuros reģionos bija līdzīga uguns aktivitāte. Izmantojot iespējamības (*contingency*) analīzi, noteikti reģionāli lielie meža ugunsgrēku gadi (LFY), kuros uguns skārusi vislielākās platības. Ar *Superposed epoch* analīzes palīdzību noteikta LFY saistība ar 500 hPa spiediena laukiem, izmantojot Hadleja centra jūras līmeņa spiediena datus (Allan & Ansell, 2006).



2.1.att. **Mezofītisku un higromezofītisku skujkoku un lapkoku-skujkoku mežu reģions pēc Bohn et al., (2000) un EEA (2006)**

Trešajā publikācijā rekonstruēta meža degšanas vēsture SNP Bažu purva kangaru un vigu kompleksā Latvijas ziemeļrietumu daļā (2.2. att.). Apsekojot aptuveni 2360 ha lielu platību, ievākti koksnes ripu šķērsgriezumi no kritalām saskaņā ar Arno & Sneck (1977) un McBride (1983) izveidotām paraugu ievākšanas vadlīnijām (2.3. att.). Laboratorijā paraugi izžāvēti, noslīpēti un datēti, izmantojot *Cybis AB CooRecorder* un *CDendro* 7.7 programmas (Larsson, 2013). Kopumā ievākti 350 koksnes paraugi, no kuriem bija iespējams datēt 287 (82%). Atbilstoši uguns rētas novietojumam noteikts tās izveidošanās gads un, ja iespējams, arī sezona (rēta gadskārtas agrīnajā vai vēlīnajā koksnē). Lai rekonstruētu degumu platības, pētījuma teritorija sadalīta regulāros kvadrātos (šūnās), izmantojot četrus dažādus telpiskus režģus ar šūnu izmēru 100×100, 300×300, 500×500 un 700×700 m. Lai noskaidrotu, kurš no šiem četriem režģiem visprecīzāk raksturo nodegušo platību, iegūtās rekonstruētās platības salīdzinātas ar faktiski uzmērīto 1992. gada meža ugunsgrēka platību. Individuāla režģa šūna tika uzskatīta par "aktīvu" (t.i., tā sniedz informāciju par meža degšanas vēsturi konkrētā gadā), ja tajā atradās vismaz viens paraugs ar attiecīgā gadā veidojušos gadskārtu. Individuāla šūna tika uzskatīta par "degušu" tajos gados, kad vismaz vienam koksnes paraugam no attiecīgās šūnas bija uguns rēta konkrētajā gadā. Degušo platību rekonstrukcijai izmantoti divi rādītāji – visas šūnas platība un šūnā ietilpstošā meža platība. Analizējot vēsturisko meža degšanu, aprēķināts uguns cikls, kas ir periods (gados), kurā uguns būtu skārusi platību, kas vienāda ar pētījuma teritorijas kopējo platību (Van Wagner, 1978). Papildus aprēķināts vidējais punktveida uguns atgriešanās intervāls, kas ir vidējais gadu skaits starp divām uguns rētām vienam kokam. Izmaiņas uguns ciklā novērtētas, izmantojot secīgu t-testu (*sequential t-test*) (Rodionov, 2004). Lai novērtētu saistību starp meža degšanu SNP un SST Ziemeļatlantijas okeānā, izmantota *Superposed epoch* analīze, kas veikta *Climate explorer* programmā (Trouet & Oldenborgh, 2013).




2.2.att. **Pētījuma objektu izvietojums**


2.3.att. **Koksnes paraugu ievākšana meža ugunsgrēku vēstures rekonstruēšanai Slīteres Nacionālā parkā**

Ceturtajā publikācijā novērtēta meža ugunsgrēka ietekme uz priedes augstuma pieauguma veidošanos. Pētījums veikts saimnieciskajos mežos, četrās degumu platībās, kurās pēc sanitārās vienlaidus cirtes veikta atjaunošana, stādot priedi: Slīterē (mētrājs, 1992. gada degums), Ugālē (mētru ārenis, 2004. gada degums), Jaunjelgavā (mētrājs, 2006. gada degums) un Dalbē (šaurlapju ārenis, 2006. gada degums); kopumā 124 parauglaukumi (2.2. att.). Kontroles parauglaukumi (52) izveidoti tuvumā esošās atbilstoša vecuma un meža tipa priežu jaunaudzēs, kas atjaunotas, stādot pēc vienlaidus atjaunošanas cirtes. Katrā apļveida parauglaukumā (100 $m^2$) noteikts priežu skaits un pēdējo trīs gadu augstuma pieaugumi. Datu analīzei izmantots Stjūdenta t-tests, lai novērtētu atšķirību būtiskumu starp jaunaudzēm degumos, kur veikta sanitārā vienlaidus cirte, un kontroli, t.i., jaunaudzēm atjaunošanas ciršu platībās.

Piektajā publikācijā saimnieciskās darbības (sanitārās vienlaidus cirtes) ietekme uz turpmāku mežaudzes dabisko atjaunošanos novērtēta SNP 1992. gada deguma teritorijā 23 gadus pēc meža ugunsgrēka (2.2. att.). Deguma teritorijās, kurās nav notikusi nekāda saimnieciskā darbība, izveidoti 220 apļveida parauglaukumi, bet teritorijās, kurās pēc deguma veikta sanitārā vienlaidus cirte, – 340 parauglaukumi (25 $m^2$). Pētījums veikts piecos dažādos meža tipos – silā, mētrājā, slapjajā mētrājā, purvājā un niedrājā; jaunaudžu mērķtiecīga apsaimniekošana nevienā no platībām nav veikta. Katrā parauglaukumā noteikts koku ($h > 30$ cm) skaits un uzmērīts to augstums. Teritorijās bez saimnieciskās darbības ap katru parauglaukumu izveidota 10 m buferjosla, kurā identificēti dzīvie iepriekšējās paaudzes koki. Novērtēti faktori, kas ietekmē audzes dabisko atjaunošanos raksturojošos parametrus – audzes biezumu (izmantots negatīvs Puasona vispārināts lineārs modelis GLMM) un koku augstumu (izmantots lineārs jaukta efekta modelis LME). Neparametriskā dispersijas analīze ANOSIM izmantota, lai salīdzinātu audzes sastāva atšķirības starp abiem apsaimniekošanas veidiem.

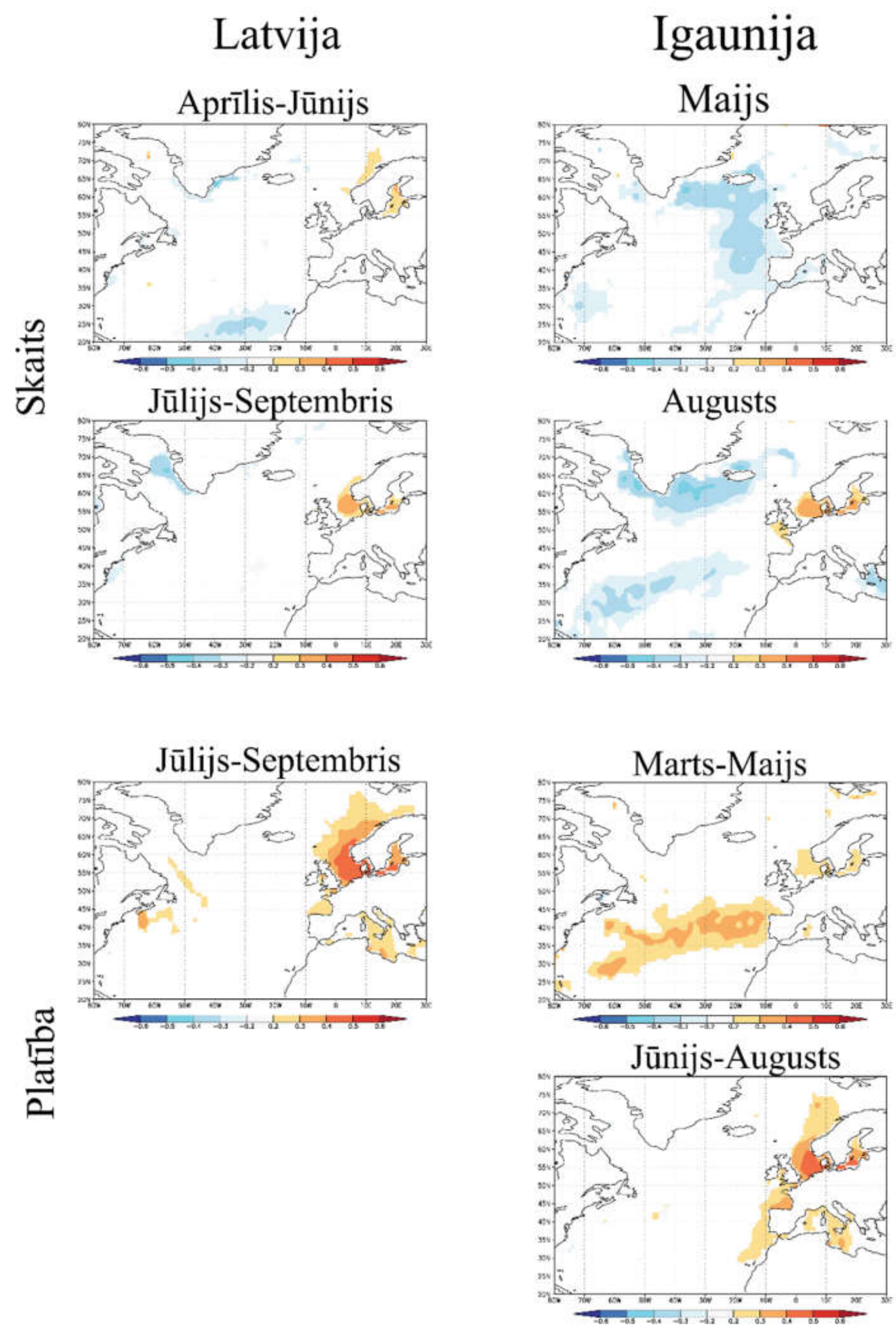
Visi aprēķini veikti R programmā (v. 3.5.0, R Core Team 2018), izmantotas paketes *MASU* (Venables & Ripley, 2002), *lme4* (Bates et al., 2015), *multcomp* (Hothorn et al., 2008), *vegan* (Oksanen et al., 2019), *NLME* (Pinheiro et al., 2018).

# 3. REZULTĀTI UN DISKUSIJA

## 3.1. Meža ugunsgrēku saistība ar klimatiskajiem faktoriem
(I un II publikācija)

Meža ugunsgrēku statistikas datu (1922/23–2014) analīze liecina, ka starp ugunsgrēku platību Latvijā un to platību Igaunijā pastāv ciešāka korelācija ($r$=0.74) salīdzinājumā ar sakarību starp ugunsgrēku skaitu abās valstīs ($r$=0.43). Savukārt, starp abiem ugunsgrēkus raksturojošajiem rādītājiem – platību un skaitu – Latvijā konstatēta ciešāka korelācija nekā Igaunijā – attiecīgi $r$=0.70 un 0.38. Visas sakarības bija statistiski būtiskas. Latvijas un Igaunijas meža ugunsgrēku platības un skaita statistikas datiem vidējais sinhronizācijas koeficients bija 0.75. Salīdzinoši augstie sinhronizācijas un korelācijas koeficienti norāda uz samērā līdzīgu meža ugunsgrēku aktivitāti Latvijā un Igaunijā 20. gadsimtā, kas, visticamāk, saistīta ar līdzīgiem klimatiskajiem apstākļiem. Atšķirības starp abu valstu meža ugunsgrēku statistikas datiem savukārt varētu būt skaidrojamas ar dažādu ģeogrāfisko novietojumu un topogrāfiju (Drobyshev et al., 2012). Zemas frekvences izmaiņas, it īpaši ugunsgrēku platībai abās valstīs, aptuveni atbilda AMO tendencei.

Gan Latvijā, gan Igaunijā ugunsgrēku skaitam un platībai konstatētas vairākas būtiskas korelācijas ar jūras virsmas temperatūru (SST) (3.1. att.). Igaunijā ugunsgrēku skaitam konstatēta negatīva korelācija ar SST pavasarī un vasarā (īpaši maijā un augustā) Atlantijas okeāna ziemeļu daļā, bet pozitīva – ar SST vasarā Ziemeļjūrā un Baltijas jūrā. Ugunsgrēku platībai šajā valstī konstatēta pozitīva korelācija ar pavasara SST Atlantijas okeāna vidējos platuma grādos, Ziemeļjūrā un Baltijas jūrā, kā arī ar vasaras SST Atlantijas okeāna Eiropas piekrastē (t.sk., Ziemeļjūrā un Baltijas jūrā). Latvijā ugunsgrēku skaitam un platībai novērota pozitīva korelācija ar pavasara un vasaras SST Baltijas jūrā un Ziemeļjūrā.

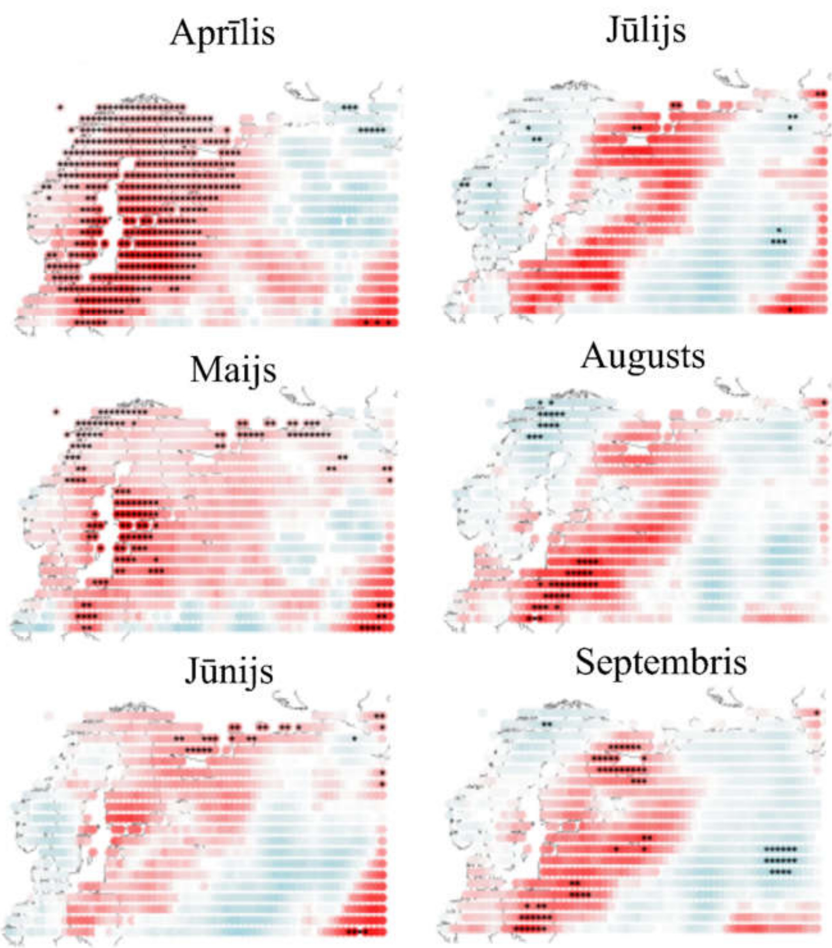



3.1. att. **Būtiskās sakarības starp jūras virsmas temperatūru un ugunsgrēku skaitu un platību Latvijā un Igaunijā**

Konstatētās sakarības starp meža ugunsgrēkiem un SST (Atlantijas okeānā, Ziemeļjūrā, Baltijas jūrā) liecina par liela mēroga atmosfēras cirkulācijas procesu ietekmi uz meža ugunsgrēku aktivitāti Latvijā un Igaunijā. Pētījumā, ko veikuši Drobyshev et al. (2016), konstatētas saistības starp meža ugunsgrēkiem Zviedrijas ziemeļdaļā un negatīvām pavasara SST anomālijām Atlantijas okeānā. Mūsu pētījumā novērotā Igaunijas meža ugunsgrēku saistība ar negatīvām SST pavasara anomālijām Atlantijas okeānā kopumā ir mazāk izteikta, kas, visticamāk, skaidrojams ar Igaunijas ģeogrāfisko novietojumu uz dienvidiem no 60° ziemeļu platuma paralēles. Šī paralēle Zviedrijā Drobyshev et al. (2016) pētījumā identificēta kā robeža, no kuras uz ziemeļiem saistība starp meža ugunsgrēkiem un Atlantijas okeāna SST novērota visizteiktāk. Mūsu pētījumā Igaunijā un Latvijā konstatētā ciešā pozitīvā ugunsgrēkus raksturojošo rādītāju korelācija ar Baltijas jūras SST pavasara un vasaras mēnešos norāda uz būtiskākām sakarībām, kas, visticamāk, saistītas ar reģionālu atmosfēras-jūras mijiedarbību (Stramska & Bialogrodzka, 2015). Augsta atmosfēras spiediena sistēmas un meridionālā cirkulācija ar ziemeļu gaisa plūsmu veicina sausu laikapstākļu veidošanos Baltijas jūras reģionā (Jaagus et al., 2010; Kļaviņš & Rodinovs, 2010), kā rezultātā intensīvāk izžūst nobiras mežos un palielinās meža ugunsbīstamība (Donis et al., 2017).

Analizējot ilgtermiņa meža ugunsgrēku platību dinamiku ar hierarhisko klāsteranalīzi, konstatēts, ka Ziemeļeiropas reģions iedalāms piecās grupās, apvienojot ģeogrāfiski tuvākos reģionus ar līdzīgu meža ugunsgrēku platību dinamiku. Kā atsevišķa grupa izdalīta Baltijas jūras austrumdaļas reģions, kurā ietilpst Baltijas valstis un Pleskavas apgabals Krievijā. Šī klāstera ietvaros visatšķirīgākā no pārējiem reģioniem bija Lietuva.

Baltijas jūras reģionā (Skandināvija, Somija, Baltijas valstis, Baltkrievija) un Krievijā (Karēlijas republika, Murmanskas apgabals) 20. gadsimtā un 21. gadsimta sākumā būtiski palielinājušās mēneša sausuma indeksa MDC vērtības aprīlī (3.2. att.). Līdzīgi arī maijā statistiski būtiski augstākas MDC vērtības novērotas Baltijas valstīs, Somijas dienviddaļā, Norvēģijas ziemeļdaļā, Arhangeļskas apgabalā. Daļā pētījuma teritorijas (Lietuvā un Baltkrievijā) konstatēts, ka MDC vērtības pieaugušas arī vasaras beigās (augustā un septembrī). Šīs tendences, kā rezultātā pagarinās periods ar augstu ugunsbīstamību un, iespējams, pieaug postošu ugunsgrēku risks, visticamāk, liecina par klimata pārmaiņām. Līdzīgi arī citos pētījumos (Donis et al., 2017) konstatēts, ka 20. gadsimta otrajā pusē pieauga meža ugunsgrēku skaits pavasarī – martā un aprīlī.




3.2. att. **Mēneša sausuma indeksa tendences 20. un 21. gadsimta laikā. Būtiskās novirzes no vidējās vērtības atzīmētas ar melniem punktiem**

### 3.2. Meža degšanas vēsture Piejūras zemienē Latvijas ziemeļrietumu daļā

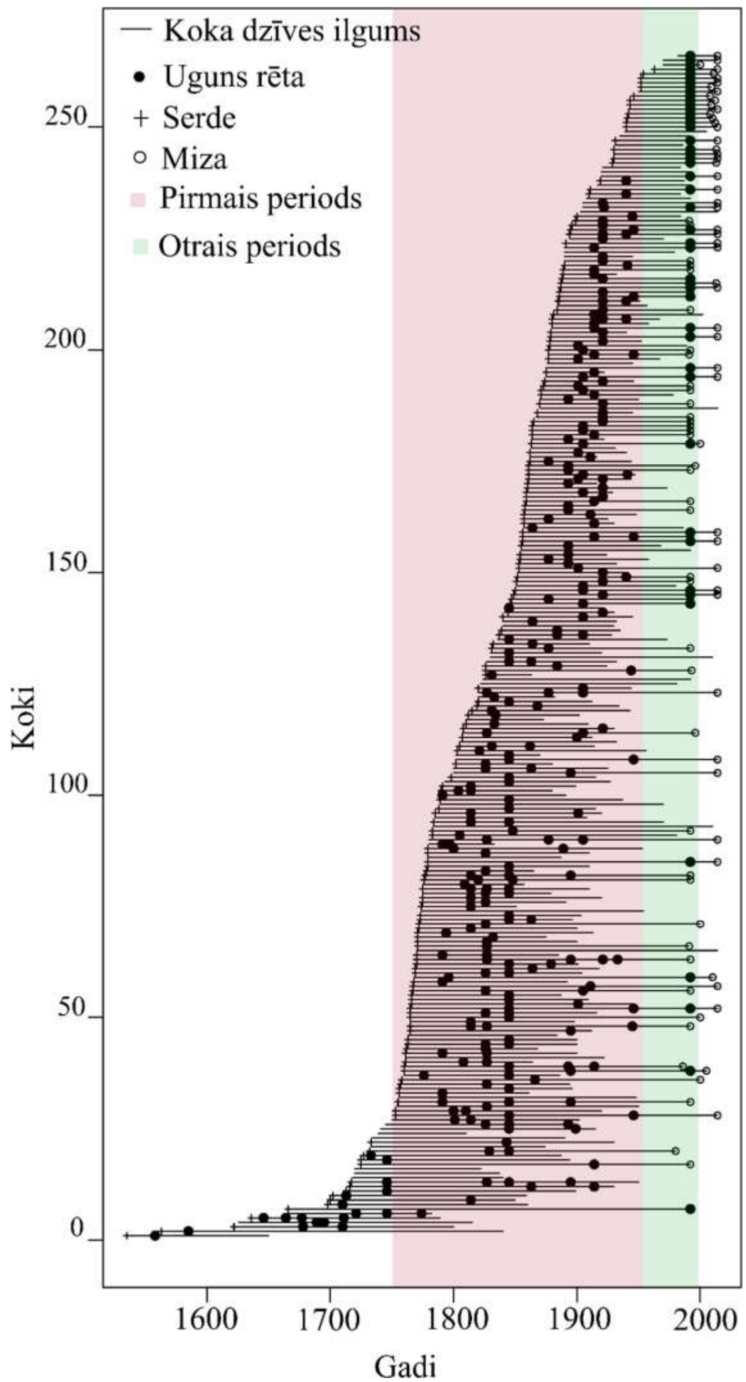
(III publikācija)

Slīteres Nacionālajā parkā Bažu purva apkārtnē senākā uguns rēta koksnes paraugā datēta ar 1558. gadu, bet jaunākā – ar 1992. gadu (3.3. att.). Uguns skartās platības rekonstruētas periodā 1750–2014, kad vismaz 30% no visām režģa šūnām bija "aktīvas". Visā novērojumu periodā (1558–1992) vidējais punktveida uguns atgriešanās intervāls bija 46 ± 33.5 gadi (vidējais ± standartnovirze).

Pārbaudot četrus dažāda izmēra šūnu režģus, vistuvākais rezultāts faktiski uzmērītajai 1992. gada meža ugunsgrēka platībai iegūts, rekonstrukcijā izmantojot 500×500 un 700×700 m režģa šūnas. Uguns cikla izmaiņas konstatētas 20. gadsimta vidū (3.3. att.). Agrākajā laika periodā (1750–1950) uguns cikls atkarībā no izvēlētā šūnas izmēra un tās platības (šūnas kopējā vai meža platība) variēja no 45 līdz 68 gadiem, savukārt vēlākajā periodā (1960–2000) – no 58 līdz 80 gadiem.

Agrākajā laika periodā (1750–1950), kurā uguns cikls bija īsāks, Latvijā plaši izplatīta prakse bija uguns izmantošana lauksaimniecībā un līdumu līšanā (Dumpe, 1999). Meža ugunsgrēku ierobežošanas mēģinājumi sākās jau 16. gadsimtā, tomēr to ieviešanas efektivitāte bija zema sociāli politisku un ekonomisku faktoru dēļ. Uguns izmantošana līdumu līšanā mazinājās 19. gadsimta beigās (Dumpe, 1999; Strods, 1999).

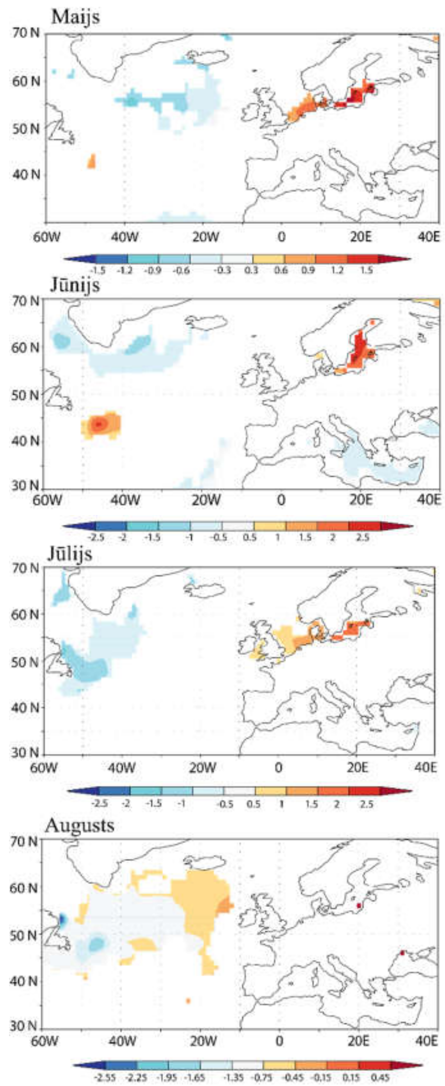
Par antropogēnā faktora ietekmi uz SNP meža degšanas vēsturi liecina arī augstais uguns rētu īpatsvars gadskārtas agrīnās koksnes daļā (65%). Uguns rētas, kas atrodas šajā koksnes daļā, norāda, ka ugunsgrēks, visticamāk, izcēlies agrīnās koksnes veidošanās periodā, t.i., pavasarī vai vasaras pirmajā pusē. Piekrastes reģionos zibens aktivitāte, kas varētu dabiski izraisīt meža ugunsgrēku, pavasarī un vasaras pirmajā pusē ir zema, jo Baltijas jūras virsma ir auksta un augšupejošās gaisa plūsmas – vājas, tāpēc pērkona negaisa veidošanās iespējamība ir zema (Enno et al., 2013). Tādējādi pavasarī un vasaras sākumā notikušo meža ugunsgrēku lielais īpatsvars, visticamāk, skaidrojams ar cilvēku saimniecisko darbību. Līdz 20. gadsimta sākumam daļa vigu Bažu purva apkārtnē tika izmantotas lauksaimniecībā kā ganības un pļavas (Abaja, 2011), un izplatīta bija lauksaimniecības augsnes ielabošana, dedzinot koku zarus un čiekurus pļavās (Gustiņa, 2016). Nereti uguns no lauksaimniecības zemēm mēdza izplatīties tuvējos mežos. Par to, ka šādi gadījumi nebija retums, liecina īpaši izdoti noteikumi 18. gadsimtā (Strods, 1999).



3.3.att. **Uguns rētu hronoloģija Slīteres Nacionālajā parkā**

20. gadsimta vidū notika pāreja uz periodu (1960–2000) ar garāku uguns ciklu, kurā konstatēts viens meža degšanas gadījums 1992. gadā. Izmaiņas uguns ciklā, visticamāk, radušās sociāli politisku pārmaiņu rezultātā, kas norisinājās, Latvijai nokļūstot Padomju Savienības sastāvā pēc Otrā pasaules kara. Padomju okupācijas laikā būtiski izmainījās zemes izmantošanas, nodarbinātības un lauksaimniecības sistēmas Latvijā (Hiden & Salmon, 2013). Šajā periodā Ziemeļkurzemes piekrastes teritorija tika iekļauta armijas militārajā zonā, un tikai atsevišķos piejūras ciemos bija atļauta zveja. Lauksaimniecībā privāto zemnieku saimniecību vietā tika izveidotas kolektīvās padomju saimniecības, kā rezultātā mazāk produktīvās lauksaimniecības zemes tika pamestas zemās rentabilitātes dēļ. Šajā periodā, kopumā samazinoties reģiona saimnieciskajai aktivitātei, visticamāk, attiecīgi samazinājās arī antropogēni izraisīto meža ugunsgrēku skaits.

Lai novērtētu saistību starp meža degšanu SNP un SST Ziemeļatlantijas okeānā, *Superposed epoch* analīzē izmantoti četri LFY – 1905., 1914., 1921. un 1992. gads, kuros rekonstruētā degusī platība bija vismaz 30% no pētījuma teritorijas jeb > 1 km$^2$. Lielie uguns gadi SNP bija saistīti ar pozitīvām SST anomālijām Baltijas jūrā no maija līdz jūlijam (3.4. att.). Līdzīgas asociācijas maijā un jūlijā novērotas arī ar SST Ziemeļjūrā. Pozitīva saistība starp lieliem uguns gadiem un Baltijas jūras un Ziemeļjūras vidējo mēneša SST, visticamāk, atspoguļo abu procesu atkarību no augsta spiediena apgabaliem vasaras periodā. Līdzīgi rezultāti iegūti arī, analizējot Latvijas un Igaunijas 20. gadsimta meža ugunsgrēku statistikas datu saistības ar SST Atlantijas okeāna ziemeļu daļā, Baltijas jūrā un Ziemeļjūrā (Kitenberga et al., 2018).



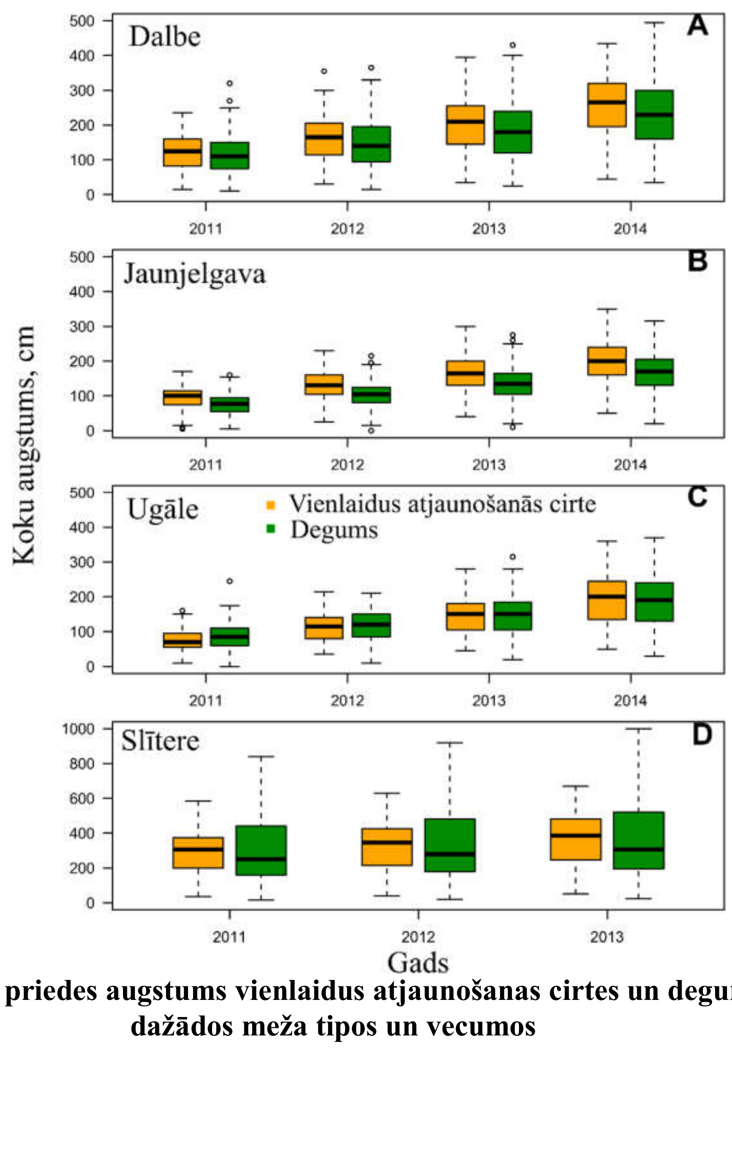

3.4. att. **Saistības starp jūras virsmas temperatūru un lielajiem meža ugunsgrēku gadiem Slīteres Nacionālajā parkā no 1870. līdz 2000. gadam (*Superimposed epoch analysis*)**

### 3.3. Uguns ietekme uz priedes augstuma pieaugumu

(IV publikācija)

Stādītajās jaunaudzēs šaurlapju ārenī Dalbē un mētrājā Jaunjelgavā priedes vidējais augstums 8 gadu vecumā vienlaidus atjaunošanas cirtes platībās bija būtiski ($p$=0.001) lielāks nekā degumos, turklāt augstuma starpība pēdējo trīs gadu laikā palielinājusies. Vislielākā vidējā augstuma starpība starp vienlaidus atjaunošanas cirtes un deguma platībām (36 cm) novērota 8 gadu vecumā mētrājā Jaunjelgavā (3.5. att.). Savukārt priedes vidējais augstums 10 gadu vecumā mētru ārenī Ugālē un 19 gadu vecumā mētrajā Slīterē būtiski neatšķīrās starp vienlaidus atjaunošanas cirtes un deguma platībām, kas norāda, ka šajos gadījumos meža ugunsgrēkam nav bijusi ilgtermiņa ietekme. Pētījumā iekļauto degumu savstarpēju salīdzināšanu apgrūtina tas, ka katram meža ugunsgrēkam raksturīga gan noteikta intensitāte (enerģija, kas izdalās degšanas procesā), gan ietekmes smagums uz ekosistēmu (*fire severity*) (Keeley, 2012). Kā parāda iepriekšējie pētījumi, atkarībā no ugunsgrēka ietekmes smaguma uz augsni būtiski mainās atjaunojušās kokaudzes un zemsedzes veģetācijas sastāvs, kā arī to atjaunošanās dinamika (Dzwonko et al., 2015). Visticamāk, Ugālē un Slīterē ugunsgrēka ietekmes smagums uz augsni bijis zemāks, jo 10 un 19 gadu vecumā priežu jaunaudzēs netiek novērotas būtiskas augstuma atšķirības starp deguma un vienlaidus cirtes platībām. Savukārt Dalbē un Jaunjelgavā, visticamāk, uguns ietekmes smagums uz augsni bijis lielāks, par ko liecina pieaugošās vidējā augstuma atšķirības līdz 8 gadu vecumam.

Priedes augstumam visās deguma platībās konstatēts lielāks variācijas koeficients nekā vienlaidus atjaunošanas cirtes platībās. Degumā ugunsgrēka ietekmes smagums – galvenokārt, reljefa un degmateriāla atšķirību dēļ – ir heterogēns. Uguns ietekme uz augsni veģetācijas atjaunošanos var sekmēt, vai tieši pretēji – aizkavēt (Certini, 2005; Dzwonko et al., 2015; Parro et al., 2015). Visticamāk, heterogēns ugunsgrēka ietekmes smagums uz augsni nosaka lielāku priedes augstuma variāciju degumos nekā vienlaidus atjaunošanas cirtes platībās.




3.5. att. **Parastās priedes augstums vienlaidus atjaunošanas cirtes un deguma platībās dažādos meža tipos un vecumos**

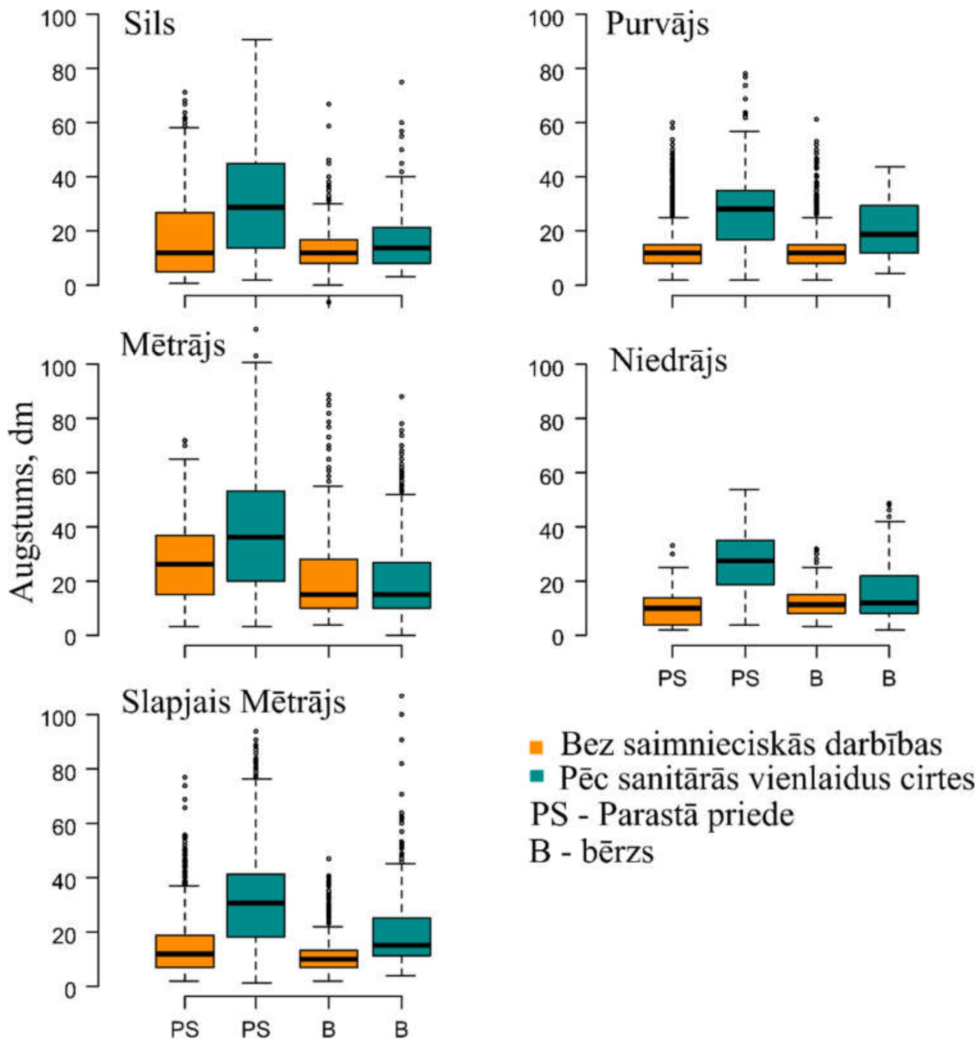
## 3.4. Sanitārās vienlaidus cirtes ietekme uz mežaudzes dabisko atjaunošanos degumos

(V publikācija)

Sanitārās vienlaidus cirtes ietekme uz jaunaudžu parametriem novērtēta SNP 1992. gada deguma teritorijā. Visizplatītākās koku sugas 23 gadus pēc meža ugunsgrēka bija priede un bērzs (*Betula pendula* Roth un *Betula pubescens* Ehrh.), veidojot 70 līdz 100% no kopējā atjaunojušos koku skaita visos analizētajos meža tipos. Visaugstākais jaunaudzes biezums konstatēts sanitārās vienlaidus cirtes platībās purvājā (25 440 koki $ha^{-1}$), slapjajā mētrājā (21 222 koki $ha^{-1}$) un niedrājā (17 360 koki $ha^{-1}$). Izmantojot GLMM modeli, noskaidrots, ka priedei atjaunojušos koku skaitu būtiski ietekmēja meža tips, telpiskā autokorelācija, kā arī meža apsaimniekošanas veida (ir/nav veikta sanitārā vienlaidus cirte) un meža tipa faktoru mijiedarbība. Platībās, kurās pēc ugunsgrēka netika veikta sanitārā vienlaidus cirte, priede bija dominējošā koku suga (pēc skaita) visos analizētajos meža tipos, izņemot niedrāju. Savukārt vienlaidus cirtes teritorijās priede dominēja silā, mētrājā un slapjajā mētrājā. Starp meža apsaimniekošanas veidiem priedes biezums nevienā no meža tipiem būtiski neatšķīrās, vienīgais izņēmums bija niedrājs. Sanitārās vienlaidus cirtes teritorijās salīdzinoši lielākā biezumā atjaunojies bērzs, kas norāda, ka papildus gaisma, kas rodas, veicot vienlaidus cirti, kā arī augsnes skarifikācija mežizstrādes laikā veicinājusi šīs koku sugas atjaunošanos. Augsnēs ar lielāku mitruma saturu (kūdras un mitrās minerālaugsnēs) bērzi atjaunojušies lielākā skaitā nekā sausās un nabadzīgās smilšainās augsnēs. Augsnes mitruma pozitīvā ietekme uz bērzu dīgšanu un augšanu novērota arī citos pētījumos (Karlsson, 1996; Karlsson et al., 1998).

Veicot ANOSIM analīzi, konstatēts, ka atjaunojušos koku sugu sastāvs starp abiem apsaimniekošanas veidiem būtiski atšķīrās divos meža tipos – slapjajā mētrājā (stat. $r$=0.16, $p$=0.001) un niedrājā (stat. $r$=0.29, $p$=0.006). Sausajos nabadzīgajos meža tipos (sils, mētrājs) un nabadzīgās kūdras augsnēs (purvājs), visticamāk, kokaudzes dabisko atjaunošanos limitē barības vielu trūkums augsnē, tāpēc sanitārā vienlaidus cirte būtiski neietekmēja atjaunojušos koku sugu sastāvu.

Izmantojot LME modeli, noskaidrots, ka priedes vidējo augstumu būtiski ($p$<0.05) ietekmēja meža tips, meža apsaimniekošanas veids, iepriekšējās paaudzes koku skaits, iepriekšējās paaudzes priežu esamība, telpiskā autokorelācija, kā arī mijiedarbība starp faktoriem: meža tips* iepriekšējās paaudzes koku skaits un meža tips* iepriekšējās paaudzes priežu esamība. Visos meža tipos sanitārās vienlaidus cirtes teritorijās priedes vidējais augstums bija ievērojami lielāks (par 22% līdz 61%) nekā teritorijās bez saimnieciskās darbības, kas norāda, ka iepriekšējās paaudzes koku aizvākšana būtiski uzlabojusi augšanas apstākļus jaunajiem kokiem (3.6. att.). Līdzīgi arī bērza vidējais augstums bija lielāks platībās, kurās veikta sanitārā vienlaidus cirte, tomēr bērzam augstuma atšķirības nebija tik ievērojamas kā priedei. Tātad labāka gaismas pieejamība sanitārās vienlaidus cirtes platībās īpaši veicinājusi priedes augstuma pieauguma veidošanos. Līdzīgi arī Igaunijā veiktā petījumā secināts, ka pēc meža ugunsgrēka sanitārās vienlaidus cirtes teritorijās priede straujāk kļuva par dominējošu koku sugu nekā platībās, kurās cirte netika veikta (Parro et al., 2015).




3.6.att. **Parastās priedes un bērza vidējais augstums divos apsaimniekošanas režīmos 1992. gada deguma teritorijā Slīteres Nacionālajā parkā**

# SECINĀJUMI

1. Pēdējo 250 gadu laikā meža ugunsgrēki ir bijuši regulārs dabiskais traucējums priežu audzēs Piejūras zemienē Ziemeļkurzemē ar īsu uguns ciklu (45–68 gadi) senākā pagātnē (1750.–1950. gads) un relatīvi garāku (58–80 gadi) – nesenākā (1950.–2000. gads). Abos periodos konstatējama cieša saistība starp ugunsgrēku režīmu un sociāli politisko situāciju Latvijā un vienlaikus vidējo ūdens virsmas temperatūru Baltijas jūrā un Ziemeļjūrā vasaras sezonā, norādot uz šo abu faktoru – antropogēnā un klimatiskā – komplementāru ietekmi.

2. Atmosfēras cirkulāciju ietekmi uz meža ugunsgrēku dinamiku apstiprina arī Latvijā un Igaunijā konstatētās būtiskās pozitīvās korelācijas starp Baltijas jūras vidējo ūdens virsmas temperatūru pavasara-vasaras sezonā un meža ugunsgrēkus raksturojošiem rādītājiem – ikgadējo ugunsgrēku skaitu un to kopējo platību. Mēneša sausuma indeksa vērtību pieaugums aprīlī un maijā liecina par ugunsbīstamības paaugstināšanos pavasarī 20. gadsimtā.

3. Nav konstatēta viennozīmīga ilgtermiņa negatīva meža ugunsgrēka ietekme uz atjaunojušos priežu augstumu (pieaugumu). Deguma teritorijās stādītajās jaunaudzēs bija lielāka priedes augstuma variācija nekā jaunaudzēs, kuras stādītas pēc vienlaidus atjaunošanas cirtes, kas norāda uz deguma ietekmes heterogenitāti.

4. Salīdzinot priedes dabisko atjaunošanos (bez mērķtiecīgas jaunaudžu apsaimniekošanas) 23 gadus pēc deguma, konstatēts, ka platībās, kurās netika veikta sanitārā vienlaidus cirte, priede bija dominējošā koku suga (vismaz 51%) silā, mētrājā, slapjajā mētrājā, purvājā. Savukārt, teritorijās, kurās tika veikta sanitārā vienlaidus cirte pēc deguma, minerālaugsnēs (silā, mētrājā un slapjajā mētrājā) dominēja priede, kūdras augsnēs (niedrājs, purvājs) – bērzs. Priedes biezums starp abiem meža apsaimniekošanas paņēmieniem statistiski būtiski atšķīrās tikai niedrājā: sanitārajai vienlaidus cirtei bija pozitīva ietekme.

5. Dzīvajiem iepriekšējās paaudzes kokiem bija statistiski būtiska negatīva ietekme uz atjaunojušos priežu vidējo augstumu. Platībās, kurās tika veikta sanitārā vienlaidus cirte, priede bija koku suga ar lielāko augstumu, turklāt tajās priedes vidējais augstums bija statistiski būtiski lielāks nekā neapsaimniekotās platībās.

# PRIEKŠLIKUMI

1. Priedes atjaunošanās veicināšanai degumos rekomendējams veikt sanitāro vienlaidus cirti.
2. Palielināta augstas intensitātes ugunsgrēku izcelšanās iespēja agrāk pavasarī akcentē atbilstošas ugunsapsardzības infrastruktūras uzturēšanas un attīstības nepieciešamību.
3. Vēsturiskais meža ugunsgrēku režīms priežu audzēs Piejūras zemienē Ziemeļkurzemē, kas ietekmējis šīs teritorijas sugu un biotopu izplatību, nevar tikt uzskatīts par dabisku meža ugunsgrēku režīmu hemiboreālajos priežu mežos būtiskās antropogēnā faktora ietekmes dēļ. Informāciju par vēsturisko ugunsgrēku režīmu var izmantot šīs teritorijas ilgtermiņa apsaimniekošanas plānošanā.

# PATEICĪBAS

Autore pateicas darba vadītajam Ārim Jansonam par pētījuma ideju, kā arī sniegto atbalstu un padomiem promocijas darba izstrādes gaitā. Izsaku pateicību darba vadītājam Igoram Drobiševam (Igor Drobyshev) par sniegtajām zināšanām un prasmēm, rekonstruējot meža degšanas vēsturi, kā arī par pacietību un neatlaidību, sniedzot atbalstu datu analīzē un publikācijas rakstīšanā. Izsaku pateicību LVMI Silava kolēģiem un īpaši Unai Neimanei par sniegto morālo atbalstu un profesionālām diskusijām promocijas darba tapšanas gaitā. Izsaku pateicību Endijam Bāderam par tehnisko palīdzību, veidojot kartogrāfisko materiālu. Vēlos izteikt pateicību Robertam Matisonam un Didzim Elfertam par palīdzību datu statistiskajā apstrādē. Vēlos izteikt pateicību Jurim Katrevičam un Andim Adamovičam par palīdzību lauka darbos. Paldies, ģimenei par morālo atbalstu, īpaši pēc labojumu saņemšanas no rakstu recenzentiem.

Autore pateicas Dabas aizsardzības pārvaldes Kurzemes reģionālajai administrācijai par atļauju veikt pētījumu Slīteres Nacionālā parka teritorijā.

# 1. INTRODUCTION

## 1.1. Hemiboreal forest disturbances

In forest ecology, disturbance is defined as 'any relatively discrete event in time that disrupts ecosystem, community, or population structure and changes resource pools, substrate availability, or the physical environment' (Picket & White, 1985).

Disturbances can be classified based on the type of disturbance agent according to Sousa, (1984):

1.Natural disturbances:

- Abiotic (wind, fire, water etc)
- Biotic (patogens – fungi, bacteria, beetles, insects, mammals)

2. Antropogenic distrubances (tree harvesting, drainage, pollution)

Natural distrubances are common in all forest ecosystems. Hence, often forest ecosystems have adapted to specific natural distrubance regime, which has a crucial role for its development and ecological succesion (Kuuluvainen, 2002a). Characteristics of disturbance regime according to Sousa, (1984):

1. Distrubed area (size);
2. Magnitude:
    - Intensity - characterizes the energy released from the fire;
    - Severity – describes the loss of organic matter;
3. Frequency – number of fires in certain area in defined period;
4. Rotation period – period (in years) required to disturb all study area.

Heterogenity and biodiversity of forest ecosystems is shaped by disturbance regime (Pickett & White, 1985; Kuuluvainen, 1994). Forest structures created by natural distrubance regime are not easliy replicated by silvicultural practices (Franklin et al., 2002). Insufficient knowledge of natural distrubance role in shaping natural forest dynamics or simplification of these effects, might create forest structures, which can be highly vulnerable in climate change context (Kuuluvainen, 2002a).

## 1.2. Fire as natural disturbance agent in forests

Fire is an integral part of the natural disturbance regime in terrestrial ecosystems, altering the structure and composition of vegetation, and affecting carbon emissions. Worldwide, climate and primary productivity are the main drivers of fire activity (Bowman et al., 2009). Human activities have altered the interdepended system between climate, vegetation, and fire (Fig. 1.1.) (Seidl et al., 2011; Bowman et al., 2014). Human activities directly affect forest fire regime by altering land-use patterns (forested areas - agricultural land/infrastructure objects/settlements), land cover, forest structure (tree species composition, age) as well as ignition pattern. In Europe over the second half of the twentieth century, climate change has been the key driver of the increase in fire activity (Seidl et al., 2011).

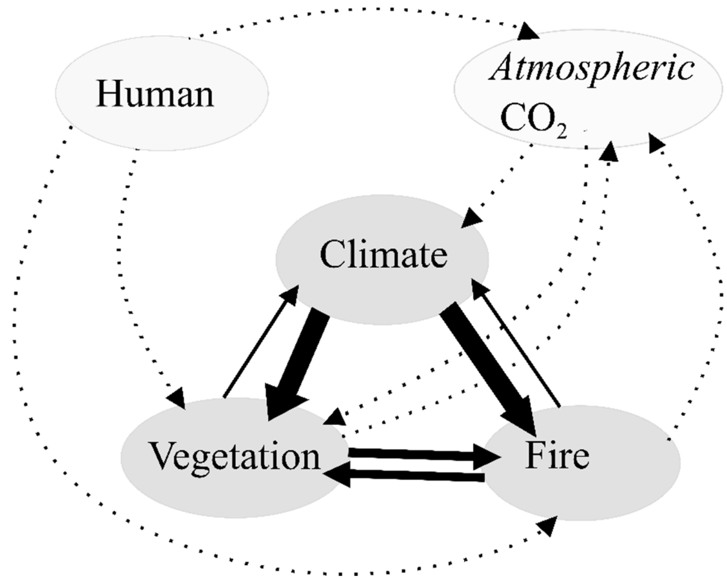



Fig. 1.1. **Interactions and feedback links between climate, fire and vegetation. The thickness of the line indicates the relative importance of interaction or feedback. The dotted line shows human and atmospheric CO2 concentration links with components of this system. Source: Bowmann et al., (2014)**

In Latvia over the 20th century, fire activity has decreased largely due to improvement of fire suppression system (Donis et al., 2017). However, when fire occurs in period of severe drought (summer 2018), suppression of single fire can take up to few weeks and affected area by fire can easily extent over several hundreds of hectares. In Europe, the risk of large-scale forest fires is predicted to increase substantially due to climate change (Seidl et al., 2011; Lehtonen et al., 2016). In near future, current fire suppression systems will have a great challenge to fight fires in more extreme conditions. Hence, improvements of the prediction skills of fire-weather forecasting systems must be implemented as soon as possible (Turco et al., 2018).

Fire shapes the successional pathways and dynamics of forest ecosystems by promoting fire tolerant and eliminating fire sensitive species, and altering soil conditions (Bond et al., 2004; Certini, 2005). Fire severity describes a loss of aboveground and belowground organic matter after the fire (Keeley, 2009). It is also a measure of transformation of the initial habitat following the disturbance event. The dynamics of soil elements (e.g. P, K, Mg, Ca, and N) have been intricately linked to burn severity (Dzwonko et al., 2015). Fire severity is a result of the combination between fire intensity, flaming period, and vegetation dryness (Chatto & Tolhurst, 2004; Cram et al., 2006). Fire severity is significantly affected by the fuel amount, structure, continuity, and dryness (Schimmel & Granström, 1996; Certini, 2005).

Depending on fire intensity and severity, forest fires are commonly classified in three categories (Ņesterovs, 1954; Roga, 1979):

1. Ground fire – fire spreads in duff, peat or humus layer. Commonly it is a smoldering combustion. Often without visible flames above ground level. Smoldering eliminates when mineral soil or groundwater level is reached.
2. Surface fire – fire spreads in litter and undergrowth vegetation. The heat intensity usually ranges from low to moderate. In surface fire, commonly are damaged surface roots and bark close to tree root collar. Surface fire can cause partial morality of the stand, which enhance development of multi-aged stands with cohort dynamics.
3. Crown fire – fire spreads from tree crown to crown. Usually high intensity stand-replacing fires, which cause 80–100 % of canopy tree mortality. Following stand-replacing fires, natural regeneration composition and dynamics depend on site

ecological condition and seed sources. Rather often in these sites are observed wave-like regeneration of pioneer tree species, which promote establishment of even-aged forest stand (Zin et al., 2015).

Climate is one of the main driving factors of fire activity. Climate not only shapes weather conditions but also development and structure of vegetation. Atmospheric-ocean interactions drive climate fluctuations (Heimann & Reichstein, 2008) and natural disturbance dynamics in terrestrial ecosystems (Shabbar et al., 2011; Drobyshev et al., 2016). Studies have shown that atmospheric-oceanic teleconnections due to the concurrent influence on several climatological variables provide a better explanation of ecological processes than specific climate variables (Hallet et al., 2004). One of the most prominent and widely studied phenomena is the el Niño southern oscillation, which affects climate variability worldwide (Behrenfeld et al., 2001). In Europe, especially in the winter season, North Atlantic oscillations affect climate variability (Trigo et al., 2002; Scaife et al., 2008). In northern Europe, a single study has linked atmospheric-ocean circulation patterns to fire activity (Drobyshev et al., 2016). The majority of other studies have linked fire activity to certain climate variables or drought indices (Drobyshev et al., 2012; Aakala et al., 2017; Donis et al., 2017), which provides limited information about the influence of climate variability on fire regime.

### 1.3. Proxy of forest fire activity

In Scots pine-dominated forests, fire scars are the most commonly used proxy to investigate forest fire history (Niklasson & Granström, 2000; Drobyshev et al., 2004; Piha et al., 2013). The probability of pine to survive fire damage increases with age, when gradually increases the bark thickness and the height of tree crown (Keeley, 2012). Based on the fire scar position within the tree ring, the year of the fire event and the season can be distinguished (Fig. 1.2.) (Baisan & Swetnam, 1990). A fire scar is formed when flames heat up the cambium cells to above 60°C, causing irreparable damage (Gutsell & Johnson, 1996). With time, the fire scar is overgrown by adjacent undamaged cambium and bark. Until it is fully overgrown, the fire scarred part of the tree stem is the most susceptible to subsequent fires due to its lower resistance to heat (Gutsell & Johnson, 1996). The trees are not flawless recorders of fire history (Swetnam et al., 1999; Piha et al., 2013). Forest fire history based on fire scars most likely underestimates the frequency of low-intensity forest fires because, in many cases, the intensity of the fire is too low to form a fire scar. However, high-intensity stand-replacing fire events consume the majority of all the canopy trees, permitting reconstruction based on fire scars. To improve the estimates of forest fire history, fire scar data are often combined with stand composition, age-class, charcoal, and fungal spore data (Drobyshev et al., 2016; Stivrins et al., 2019).

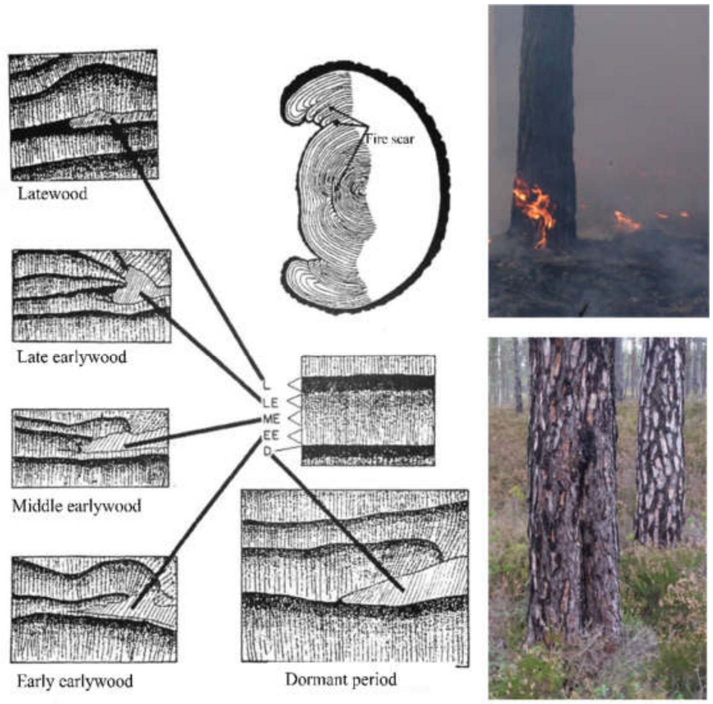



Fig. 1.2. **Fire scar formation. Source: Swetnam & Baisan, (1996)**

### 1.4. Forest fire regime in Northern Europe and Latvia

The Scots pine is one of the most common tree species in European boreal and hemiboreal forest zones (Angelstam & Kuuluvainen, 2004; Niklasson et al., 2010), which is adapted to growth under different environmental conditions (Keeley & Zadler, 1998; Keeley, 2012). Studies show that Scots pine can survive several low-to-moderate severity fires (Östlund et al., 1997; Kuuluvainen et al., 2002b). Such fires cause partial mortality of the canopy and promote cohort dynamics with multi-aged stands (Angelstam & Kuuluvainen, 2004; Kuuluvainen & Aakala, 2011). Although the majority of forest fires in European boreal and hemiboreal pine forests are low-to-moderate severity, occasional stand-replacing fire episodes initiate a wave of pine regeneration, promoting even-aged stand development (Agee, 1993; Zin et al., 2015).

Over the last centuries, fires in European forests are not only a natural but also a cultural phenomenon (Granström & Niklasson, 2008). Ignition frequency, spatial distribution and seasonality of forest fires have been altered by human activates since Mesolithic and early Neolithic periods (Granström & Niklasson, 2008; Dietze et al., 2018). The anthropogenic effect on various characteristics of fire regime have greatly varied on spatial and temporal scales. For example, in Fennoscandia over the last 600 years, several shifts in forest fire regime linked to human cultural use of fire have been observed (Granström & Niklasson, 2008). In Fennoscandia during the period 1650–1870, dominated reindeer herding and cattle farming, forest fires were 2.9 times more frequent than during the prior period (1499–1650). While, during the later period (from the begging of the 18th until middle of 19th century), when timber value increased forest fire almost completely disappeared from the landscape (Granström & Niklasson, 2008).

In the Belowieza forest during the period 1653–1700, beekeeping and tar burning was a common occupation for local society. During this period, the mean fire return interval (FRI) was ~ 18 years (Niklasson et al., 2010). Small diameter at the first fire scar, as well as minor decline in radial growth following fire scar, suggests that during this period, forest fires were low severity (Zin et al., 2015). Similar to Fennoscandia in the Belowieza forest at the end of 19th century when the timber value increased, fire activity drastically decreased (Niklasson et al., 2010).

In Vienansalo region in Fennoscandia, significant increase in fire activity (~ fire cycle 75 years) was observed following policy change in 17th century. The increase in fire activity during this period was linked to the tax discounts and slash-and-burn agriculture practices. Similar to other regions, fire activity sharply declined (fire cycle ~ 400 years) in this region in 19th century when timber value increased and improved efficiency of fire suppression system (Wallenius et al., 2004).

In the territory of Latvia, the earliest evidence of human influence on fire activity dates to the Mesolithic and early Neolithic periods, when Baltic hunter-gatherer cultures lived in this area (Dietze et al., 2018). Since the second century in the territory of Baltic countries, slash-and-burn was a common agricultural practice (Dumpe, 1999). The first attempts to limit the spread of slash-and-burn agriculture were in 16th century, however due to poor governance and political instability, it continued until the late nineteenth century in the territory of Latvia (Dumpe, 1999; Strods, 1999).

The study of charcoal content in the lake sediments, showed that during early Holocene 11.7–7.5 thousand cal yr BP, when dominated boreal tree species (*Pinus sylvestris* and *Betula* spp.) with admixture of broadleaved tree species (*Ulmus*, *Tilia*, *Corylus avellana*), FRI was ~ 280 years in the territory of Latvia. During Mid-Holocene warm period, when dominated broadleaved tree species *Ulmus*, *Corylus avellana*, *Tilia*, *Quercus* and *Carpinus* (7.5–4.5 thousand cal yr BP), FRI was the longest ~630 years. In the Late Holocene (4.5–0 thousand cal yr BP), when dominated boreal tree species (*Picea abies*, *Betula* spp., *Pinus sylvestris*), FRI was the shortest ~ 190 years. Generally, when the landscape is dominated by *Pinus sylvestris–Betula* spp., forest fires were rather frequent with occasional high-intensity fire episodes. While, in periods when dominated broadleaved tree species, forest fires were rare. In periods, when dominated *Picea abies,* high-intensity forest fires prevailed (Feurdean et al., 2017).

In the Baltic countries, studies based on peatland-lake sediments provide the insight in the long-term fire activity dynamics on decadal/century-scale (Dietze et al., 2018). While, fire-scar proxy records provide explicit information about seasonality and spatial extent of forest fires. However, currently such studies have not been carried out in the Baltic countries, as areas with intact natural forests are rare (Brumelis et al., 2005; Terauds et al., 2011). One of the few places, where semi-natural forests with well-defined pine cohorts have been preserved is Slitere National Park (SNP) in north-western Latvia due to its distant location, challenging topography, and poor soil conditions (Brumelis et al., 2005; SNP Dabas aizsardzības plāns, 2010). The information about forest fire activity could be used in long-term conservation and management planning in nature protection areas as well as to improve fire suppression system.

### 1.5. Tree regeneration following fire in hemiboreal forests

The abundance of forest regeneration and composition following fire disturbance depends on the distance from the seed sources (Moser et al., 2010), fire severity (Dzwonko et al., 2015), biological legacies (Jõgiste et al., 2017), and post-fire management activities (Parro et al., 2015). Depending on regeneration and communal strategies, tree species are classified in the following categories (Noble & Slatyer, 1980; Ryan, 2002):

1. Based on vegetative strategy:
   V species: regenerated by sprouting, when damaged at the juvenile age;
   W species: resilient to fire damage in the old age (fire kills juvenile age).
2. Based on propagule dispersal strategy:

D species: long-distance propagule dispersal;
S species: propagules stored in soil;
C species: propagules stored in canopy.

Communal strategies:

T species: quickly regenerate following fire disturbance and can persist in long-term in the absence of further disturbance

R species: can regenerate in post-fire areas when certain conditions prevail (shadow etc.)

I species: quickly can regenerate following fire disturbance (rapid growth pioneers); however, rather soon die out without repeated disturbance.

Fire severity significantly affects tree species in all categories of reproduction and communal strategies (Granström & Schimmel, 1993). Higher intensity fires can negatively affect tree species with V and W strategies. The more severe damage to different vegetative parts of the tree, the harder to regenerate (Ryan, 2002).

In boreal and hemiboreal forests, the most common tree species that regenerate following a fire disturbance are the Scots pine, silver birch, and trembling aspen *Populus tremula* (Hille & den Ouden, 2004; Dzwonko et al., 2015; Parro et al., 2015). Studies show that a higher abundance of natural regeneration of silver birch and Scots pine has been observed in more severely burned areas, which is explained by higher forest floor disturbance, more exposed mineral soil, which is suitable substrate for tree germination (Hille & den Ouden, 2004; Dzwonko et al., 2015).

Salvage logging in post-fire areas causes two consecutive disturbance effects in post-fire areas, which can have a long-term negative effect on biodiversity and regeneration patterns (Thorn et al., 2017; Leverkus et al., 2018). In Estonia study showed, that on dry-poor sandy soils salvage-logging negatively affected the abundance of regenerating trees; however, had a positive effect on the mean height (Parro et al., 2015). Yet, information about salvage-logging effects on natural regeneration pattern on peat and wet-mineral soils is scarce. These forest soil types are rather common in hemiboreal and boreal forest zone.

### 1.6. The aim of the thesis

The aim of our study was to assess climate and human effects on the historic forest fire regimes and to assess post-fire regeneration patterns of Scots pine (*Pinus sylvestris* L.).

### 1.7. Thesis objectives

The specific objectives of the thesis were:

1. to assess the climate impact on the regional forest fire activity (Papers I and II);
2. to describe the forest fire history of the coastal lowlands in north-western Latvia (Paper III);
3. to compare the growth of planted Scots pine in post-fire and clear-cut areas (Paper IV);
4. to assess the effect of salvage logging on the post-fire natural regeneration (Paper V).

### 1.8. Thesis statements

1. Large-scale weather systems have a significant influence on forest fire activity in the eastern Baltic Sea region.

2. In the post-fire areas, salvage logging has a significant effect on the pattern of natural regeneration of the Scots pine.

### 1.9. Scientific novelty

In the thesis, for the first time, the influence of large-scale climate systems on forest fire activity in the Baltic countries has been assessed (Papers I and II). We provide the first annually resolved dendrochronological reconstruction of the forest fire history from the eastern Baltic Sea region, revealing the role of fire during the last 250 years in semi-natural Scots pine-dominated forests of the European hemiboreal forest zone (Paper III). The effects of salvage logging on natural regeneration have been assessed for the first time 23 years following the fire disturbance in forest types on peat soils (Paper V).

### 1.10. Thesis structure

The doctoral thesis consists of five papers. In the first paper, the effects of large scale weather systems on the historic fire activity in Latvia and Estonia are analyzed. In the second paper, climate effects on forest fire activity in Baltic countries, Fennoscandia and Russian boreal forest regions are analyzed. In the third paper, climate and human effects on the forest fire history in pine-dominated forests in north-western Latvia was investigated. In the fourth paper, the influence of fire on the height growth of Scots pine was investigated. In the fifth paper, the influence on salvage logging on the abundance and mean height of natural regeneration of Scots pine was analyzed.

### 1.11. Approbation of research results (conferences)

1. 26.-29.11.2014. Florence, Italy. Oral presentation: ‘Height-growth dynamics of Scots pine (Pinus sylvestris L.) in burned and clearcut areas in hemiboreal forests, Latvia’, Second International Congress of Silviculture ‘Accademia Italiana di Scienze Forestali’.
2. 23.-24.04.2015. Riga, Latvia. Poster: ‘A 247-year tree-ring width chronology of Scots pine (Pinus sylvestris L.) from Slitere National Park’, International Scientific Conference ‘Adaptation and mitigation: strategies for management of forest ecosystems’.
3. 15.-16.09.2015. Riga, Latvia. Poster: ‘Post-fire regeneration of Scots pine (Pinus sylvestris L.) in Latvia’, Nordic-Baltic Forest Conference 2015 ‘Wise Use of Improved Forest Reproductive Material’.
4. 04.-06.11.2015. Riga, Latvia. Poster: ‘Influence of forest fire on Scots pine (Pinus sylvetris L.) age structure and regeneration pattern’, International Scientific Conference ‘Knowledge based Forest Sector’.
5. 06.-10.09.2017. Tartu, Estonia. Oral presentation: ‘Dendrochronological reconstruction of the forest fire regime in a Pinus sylvestris-dominated forest in the Slitere National Park, Latvia’, International Scientific Conference ‘Eurodendro’.

# 2. MATERIALS AND METHODS

For Paper I, the time series for the twentieth century for the area burned (AF) and the number of fires (NF) with annual resolution for Estonia and Latvia were obtained from Environment Agency of the Republic of Estonia and from Donis et al. (2018), respectively. The monthly sea surface temperature (SST) and annual Atlantic multi-decadal oscillation (AMO) data were obtained from the UK Met Office Hadley Centre observation datasets (Rayner et al., 2003; Trenberth & Shea, 2006). We used the Pearson correlation analysis to assess the relationships between the North Atlantic SST and the national fire chronologies. The analysis was conducted in the Climate Explorer (Trouet & Van Oldenborgh, 2013). The significance of the correlations was determined using a two-sided student t-test, accounting for the autocorrelation in the time series (Trouet & Van Oldenborgh, 2013). For each correlation map, the field significance was visualised, which described the strength of the correlation at the scale of the studied region (Wilks, 2006).

For Paper II, the time series for the twentieth century of AF for Fennoscandia, Lithuania, and Russia (Fig. 2.1.) were obtained from the official forest fire statistics datasets and the Global Fire Emission Database (Giglio et al., 2013). The climate data, including the total monthly precipitation and the minimum and maximum monthly temperatures were obtained from CRU TS (v. 4.02; Harris et al., 2014). The principal component analysis and hierarchical clustering methods were used to identify the AF groups based on similarities and distance. The response function analysis was used to identify the best climatic predictors of the regional AF. The superimposed epoch analysis (SEA) was used to assess the relationship between the AF and 500 hPa pressure field using the Hadley Centre Sea Level Pressure dataset (Allan & Ansell, 2006).

Fig. 2.1. **Mesophytic and hygromesophytic coniferous and broadleaved-coniferous forest region. Source: Bohn et al., (2000) and EEA (2006)**

For Paper III, the forest fire history was investigated within the inter-dune peatland complex of SNP in the north-western part of Latvia (57°68′– 57°70′ N, 22°46′–22°52′ E) (Fig. 2.2.). We inventoried an area of 2000 ha, which was burned in a fire in 1992. The studied pine stands grew on nutrient-poor, sandy dunes in *Cladinoso-callunosa* and *Vacciniosa* forests (Bušs, 1976). We collected full or partial cross sections of deadwood, following the procedure described by Arno and Sneck (1977) and McBride (1983) (Fig. 2.3.). Out of 350 deadwood samples, we dated 287 trees (82%), including 44 deadwood samples with no fire scars. We used the scar position within the annual rings to assign the calendar year and, when possible, the fire season to each past fire. To reconstruct the spatial extent of the area burned, we used a regular spatial grid, which encompassed the whole study area. The grid cell was considered burned in a year, when at least one sample within the cell had a fire scar recorded the year in question. For whole period for which we reconstructed the spatial extent of the area burned, we calculated the fire cycle, which is a period (in years) needed to burn the area equal to the total study area (Van Wagner, 1978). The mean point-scale fire return interval (FRI) is the mean number of years between two successive fire scars recorded by a single tree. We assessed the regime shifts in the fire cycle using a sequential t-test algorithm (Rodionov, 2004). We used the SEA to assess the relationships between fire activity in SNP and the SST dynamics in the subpolar North Atlantic. In the analysis, we correlated the fire data with the SST in the subpolar North Atlantic, averaged over the May-September period. The analysis was conducted using Climate Explorer (Trouet & Van Oldenborgh, 2013).

For Paper IV, to assess the forest fire influence on the growth height of the Scots pine, we placed sampling plots in four post-fire areas, which have been salvage logged and regenerated artificially with the Scots pine. In Slitere, fire occurred in 1992 (*Vacciniosa* forest type). In Ugale, fire occurred in 2004 (*Vacciniosa mel.*), and in Jaunjelgava and Dalbe, fire occurred in 2006 (*Vacciniosa* and *Myrtillosa mel.,* respectively) (Fig. 2.2.). In each sampling plot, the height of the Scots pine and other tree species was measured. The student's t-test was used to assess the significant differences between the burned and controlled areas.

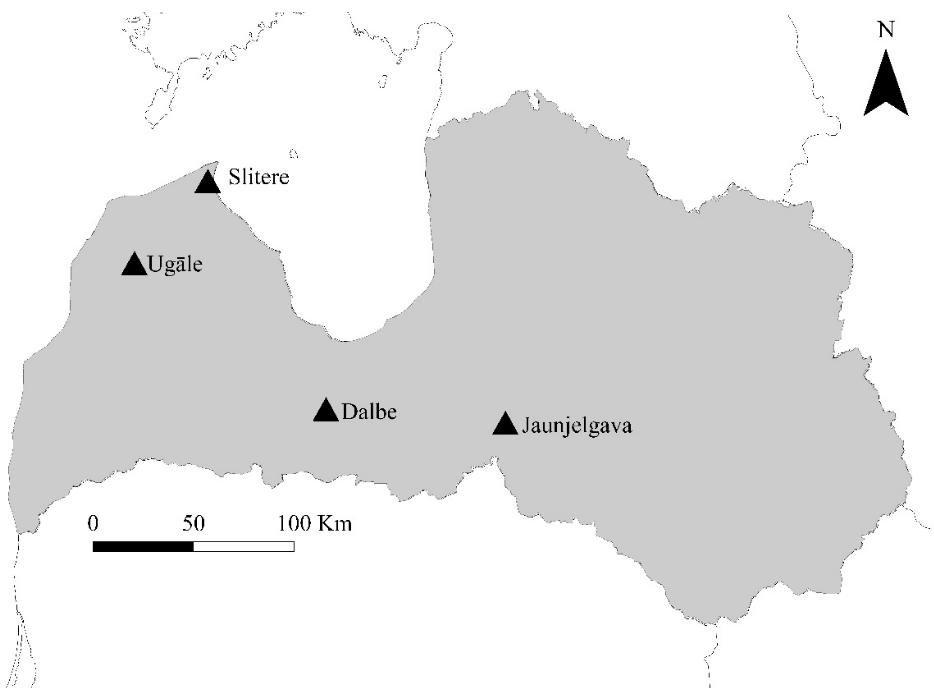



Fig. 2.2. **Study site locations**


Fig. 2.3. **Sampling of fire-scarred material to reconstruct forest fires history in Slitere National Park**

For Paper V, to assess the influence of post-fire management on the natural regeneration of the Scots pine and other tree species, we placed sampling plots in the SNP area, which was burned in 1992 (Fig. 2.2.). In total, we placed 220 and 340 sampling plots in salvage-logged and no-intervention areas, respectively. The effect of post-fire management treatment on natural regeneration was assessed in five different forest site types (Bušs, 1976): dry and poor *Cladinoso-callunosa*, dry and less poor *Vacciniosa*, wet and poor *Vaccinioso-sphagnosa*, poor-peat *Sphagnosa*, and medium fertility peat *Caricoso-phragmitosa*. In each sampling plot, the height of all regenerating tree species (height >30 cm) was measured. In the no-intervention treatment, we identified large live trees within a 10-m radius from the outer margin of the sampling plot. To assess the effect of post-fire management and other factors on the natural regeneration abundance, we employed a Poisson generalised linear mixed-effects model (GLMM). To assess the effect of post-fire treatment and other factors on the height values of the Scots pine, we used linear mixed-effect model (LME). We used a non-parametric analysis of variance-like analysis of similarities (ANOSIM) to compare the natural regeneration composition between post-fire treatments.

For Papers I, II, III, IV, and V, all calculations were performed using R software (v. 3.5.0, R Core Team, 2018), using the package MASS (Venables & Ripley, 2002) for the GLMM, the package lme4 (Bates et al., 2015) for the LME, the package multcomp (Hothorn et al., 2008) for Tukey multiple comparisons, the package vegan (Oksanen et al., 2019) for ANOSIM, and the package NLME (Pinheiro et al., 2018) for the generalised least squares model. The R package treeclim (Zang & Biondi, 2015) was used for the response function analysis, and the package stats (R Development Core Team, 2018) was used for the principal component analysis.

# 3. RESULTS AND DISCUSSION

## 3.1. The national fire chronologies

(I and II paper)

The fire chronologies (1922/23–2014) of Latvia and Estonia suggest that correlation coefficients between AF are stronger (*r*=0.74) than between NF (*r*=0.43). In Latvia, NF and AF showed stronger correlations than in Estonia (*r*=0.70 and *r*=0.38, respectively. The mean synchrony coefficient between countries was 0.75, suggesting a common regional climatic force on the fire activity. The differences in fire chronologies might be related to the differences in topography and atmospheric circulation (Drobyshev et al., 2012). The low-frequency variation particularly in the AF of both countries roughly followed the trend in AMO.

Several significant correlations between the fire chronologies and SST were detected. The NF in Estonia was negatively correlated with the SST in the North Atlantic during spring and summer (May and August), and a positive correlation was observed with the summer SSTs in the North Sea and Baltic Sea (Fig. 3.1.). The AF in Estonia showed a positive correlation with spring SSTs in the mid-latitude Atlantic and summer SSTs along the Atlantic coast of Europe. Spring and summer SSTs in the Baltic Sea and the North Sea positively correlated with the NF and AF in Latvia. The observed significant correlation between fire activity and SSTs in the North Atlantic, North Sea, and Baltic Sea suggests a large-scale atmospheric circulation influence on fire activity. In the study performed by Drobyshev et al. (2016), a teleconnection between fire activity in North Sweden above the 60°N parallel and North Atlantic SSTs was detected. In our study, we observed a less pronounced pattern of correlations between North Atlantic SSTs and NF in Estonia, which might be related to the N-S gradient of large-scale atmospheric circulations (Drobyshev et al., 2016) and regional landscape specifics (Hellberg et al., 2004). The positive correlations between Baltic Sea SSTs and fire chronologies in both countries might be related to regional atmospheric-sea interactions (Stramska & Bialogrodzka, 2015). In summer in the Baltic Sea region the meridional circulation pattern prevails (Keevallik et al., 1999), which stimulates the establishment of dry and fire-prone weather conditions when combined with high-pressure systems (Jaagus et al., 2010; Kļaviņš & Rodinovs, 2010; Donis et al., 2017).

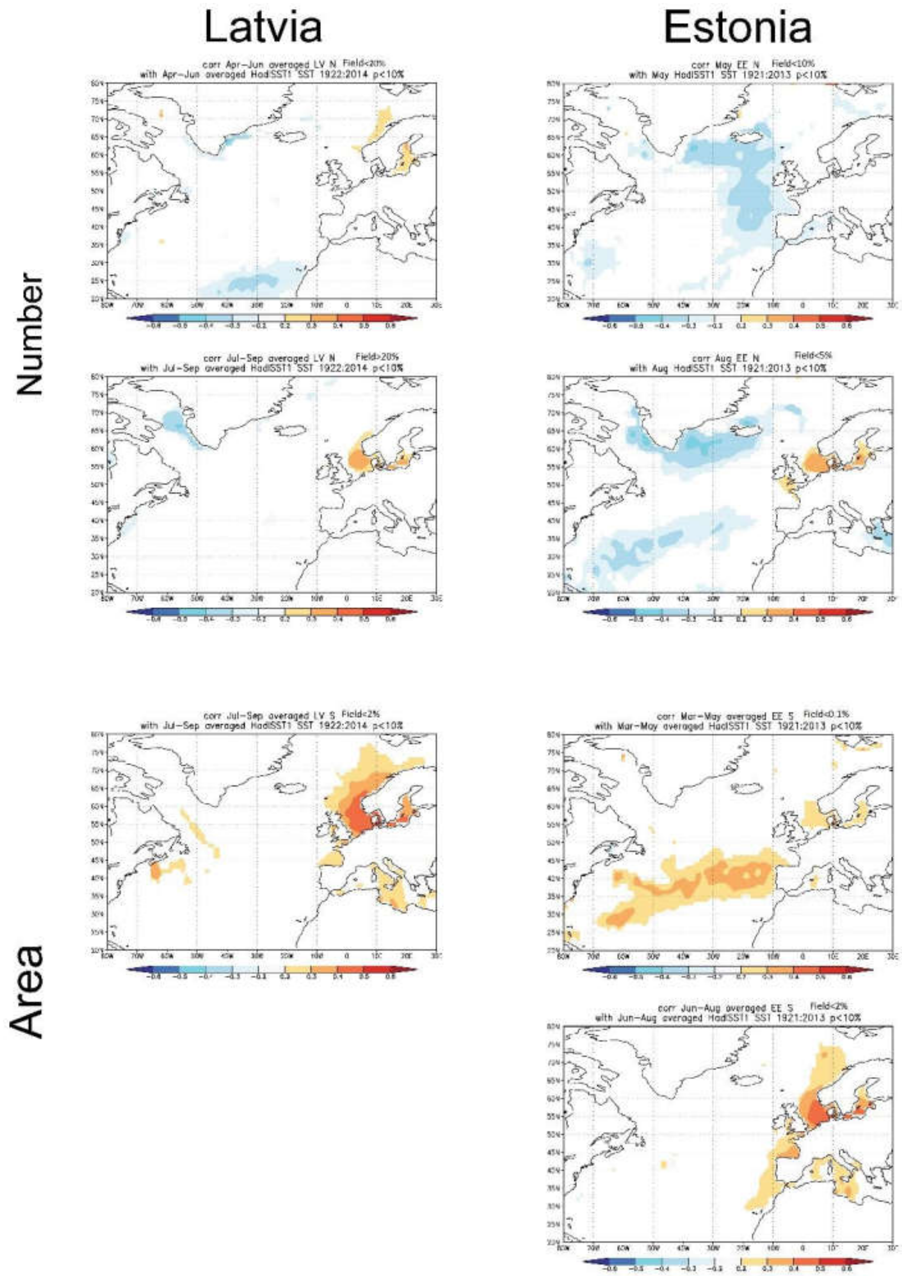



Fig. 3.1. **Correlation between the sea surface temperature and chronologies of number and area of forest fires in Latvia and Estonia during the periods of 1922–2014 and 1921–2013, respectively**

Five clusters were identified using the hierarchical clustering analysis, combining the geographically adjacent regions with similar forest fire activity. The cluster of the eastern Baltic Sea region includes the Baltic States, Belorussia, and the Russian region of Pskov. Within the cluster, Lithuania was the most distinguished from all other regions.

During the twentieth and early twenty-first centuries, the drought conditions characterised by the Monthly Drought Index (MDC) increased during the early spring period (April and May) in the Baltic Sea region (Fennoscandia, Baltic States, and Belarus) and Russia (Republic of Karelia and the Murmansk region) (Fig. 3.2.). The increase in MDC values was also observed at the end of summer (August and September) in Lithuania and Belarus. These observations of increase in the MDC also indicate an increase in fire hazard during the start and end of the fire season, suggesting a longer and possibly more intensive fire season. In addition, other studies during the second half of the twentieth century detected an increase in fire occurrences during the start of the fire season (March and April; Donis et al., 2017).

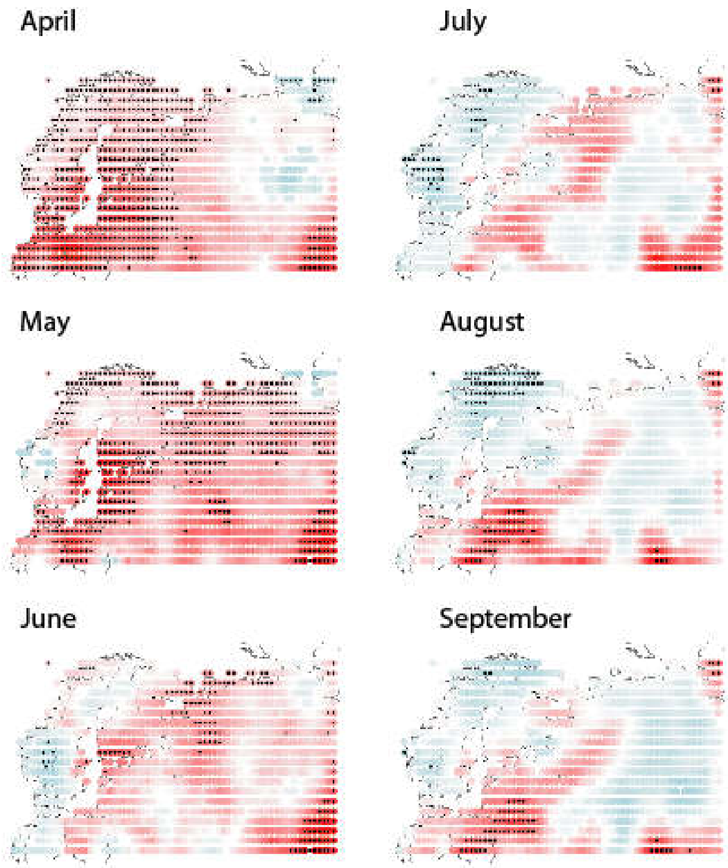



Fig. 3.2. **Trends in MDC over the 20th and the early 21st century. Significant departures are indicated with black dot**

### 3.2. Forest fire history in the north-western Latvia
(III paper)

In SNP, the earliest fire scar was dated to 1558, but the latest was in 1992. For the whole study period (1558–1992), the mean point-scale FRI was 46 with a standard deviation of ±33.5 years (Fig. 3.1.). We reconstructed the burned area and the fire cycle from 1750 to 2014, for which at least 30% of all grid cells were recorded.

Over the 1750–2000 period, we assessed the regime shifts separately for the forested area and the whole study area, using two different grid-cell sizes (500×500 m and 700×700 m). The shifts in the fire regime were identified in the 1950s, by both grids based on the forested area and the whole grid area. The earlier epoch (1750–2000) had a shorter fire cycle than the last epoch (1960–2000), 45–68 and 58–80 years, respectively (Fig. 3.3.). In the earlier epoch (1750–1950), higher fire activity likely was promoted by slash-and-burn agriculture that was rather frequently practiced until middle of the nineteenth century (Dumpe, 1999; Strods, 1999).

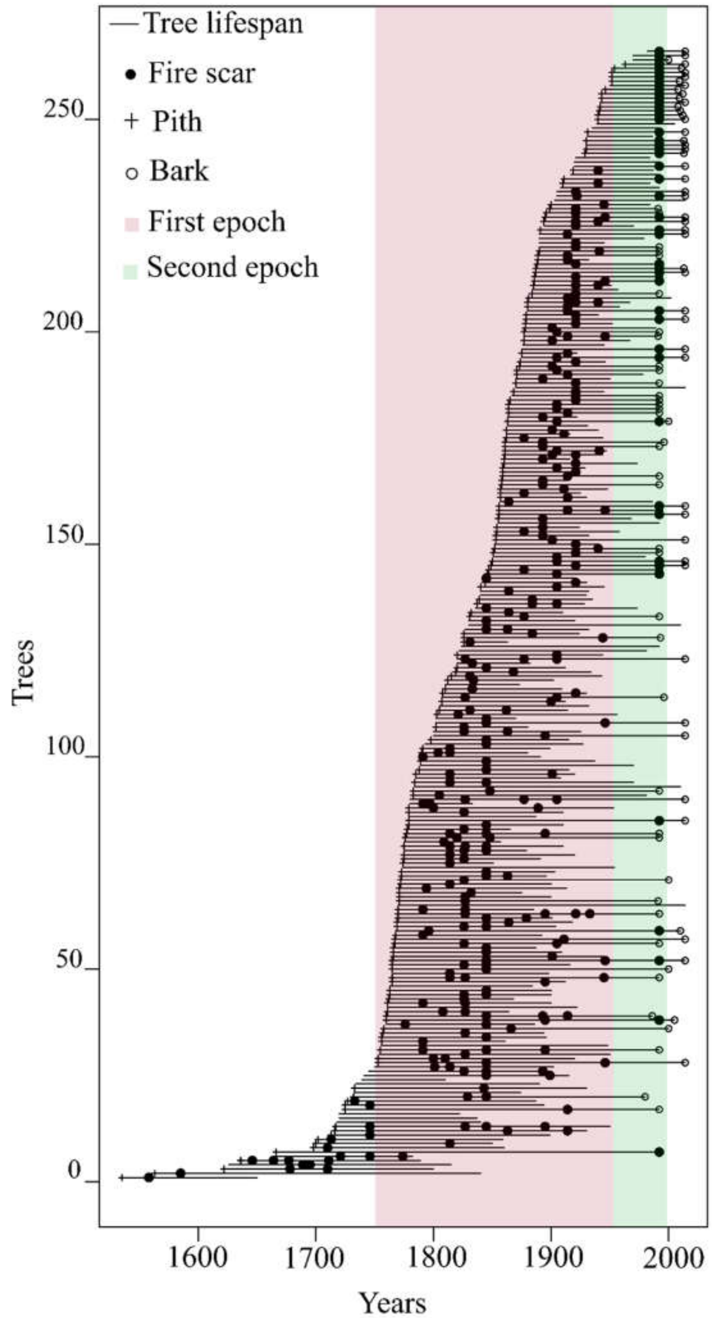


Fig. 3.3. ***Fire scar chronology in Slitere National Park***

The shift in the fire regime occurred in the middle of the twentieth century. During the second epoch (1950–2000) only a single large fire occurred in 1992. This pattern is a likely result of a drastic change in the land-use, employment, and agricultural systems in Latvia, which took place during the Soviet Union period (Hiden & Salmon, 2013). The western coastline zone of the Baltic Sea and a part of the SNP after the Second World War was allocated exclusively for military aims. Largely, coastal fishery was prohibited in this region; the exception was only for a few coastal villages. In parallel, the agricultural system was changed from private to collective farming, which led to the abandonment of many fields and meadows (Ržepicka & Ziemelniece, 2017). Consequently, the overall decline in economic activity likely decreased the occurrence human-related ignition.

A substantial proportion of early-season fires (65%) in the study area points to human influence on fire activity. Several inter-dune depressions, which are located nearby the study area, were used as meadows until the 1920s (Abaja, 2011). We assume that the higher fire frequency during the spring and early summer period might be a result of fires escaping from grassland burnings, which were a common soil fertility improvement method until the early twentieth century (Gustiņa, 2016; Strods, 1999). The significance of human-related ignition during early-season fires is also supported by the lightning patterns in the area. In coastal regions, lightning activity in the spring and the first half of summer is low because the formation of thunderstorms is hindered by the weak upward moving airflows (Enno et al., 2013).

The SEA was operated with four large fire years: 1905, 1914, 1921, and 1992, in which the burned area was greater than 1 km² (Fig. 3.4.). Fire activity in SNP was linked to SSTs in the North Atlantic, Baltic, and North Seas. The fires in the SNP were associated with positive SST anomalies in the Baltic Sea from May to July. Similar associations were also observed in the North Sea in May and July. The positive correlation between the fire activity and mean monthly SSTs of the Baltic and North Seas likely reflects the dependence of both processes on the presence of a high-pressure cell developing during the summertime and leading to the drying of the forest fuels and warming of the SSTs (Høyer & Karagali, 2016). Comparable results were obtained using the long-term official fire statistics data (Kitenberga et al., 2018).

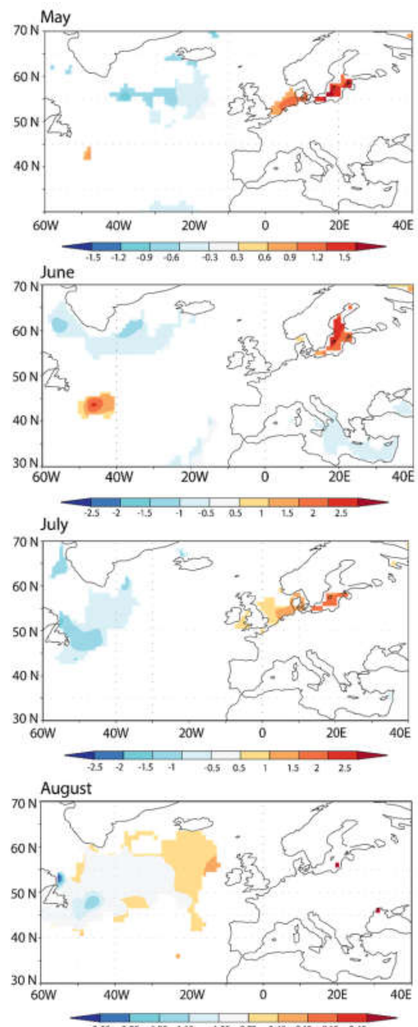



Fig. 3.4. **Superimposed epoch analysis of gridded sea surface temperature in the North Atlantic from May to August during the large fire years in Slitere National Park (burned area > 1 km2) over the 1870–2000 period. Colour delineations indicate SST anomalies significant at *p*<0.10**.

### 3.3. Fire influence on Scots pine growth

(IV paper)

In Dalbe (*Myrtillosa mel.* forest type) and Jaunjelgava (*Vacciniosa* forest type), at the age of 8 years, the mean height of the Scots pine was significantly ($p$=0.001) higher in the clear-cut areas than in the post-fire areas. Nevertheless, during the last 3 years, the mean height differences between both treatments steadily increased. Between the treatments, in Jaunjelgava in the *Vacciniosa* forest type, the largest mean height differences were observed (36 cm) (Fig. 3.5.). At the age of 10 years in Ugale for the *Vacciniosa mel.* forest type and at the age of 19 years in Slitere for the *Vacciniosa* forest type, no significant differences between the treatments were detected in the mean height of the Scots pine.

The ecological effects of fire on the forest ecosystem are affected by fire intensity (energy released from the combustion process) and severity (amount of fire-consumed organic matter; Keeley, 2012). Previous studies show that fire severity significantly affects soil conditions and the composition of natural regeneration (Dzwonko et al., 2015). We assume that the fire severity in Ugale and Slitere was lower than that in Dalbe and Jaunjelgava because, at the age of 10 and 19 years, the mean height differences were insignificant. In Dalbe and Jaunjelgava, however, the trend at the age of 8 years showed increased mean height differences.

The mean height of the Scots pine was more variable in all the post-fire areas compared to the clear-cut areas. Depending on the fire severity, the effect on natural regeneration and soils can be either positive or negative (Certini, 2005). In most cases, due to differences in terrain and fuel structure, fire severity varies across the burned area (Vacchiano et al., 2014; Dzwonko et al., 2015). We assume that the spatial heterogeneity of the fire severity could be the main reason for the larger height differences in post-fire areas compared to that in clear-cut areas.

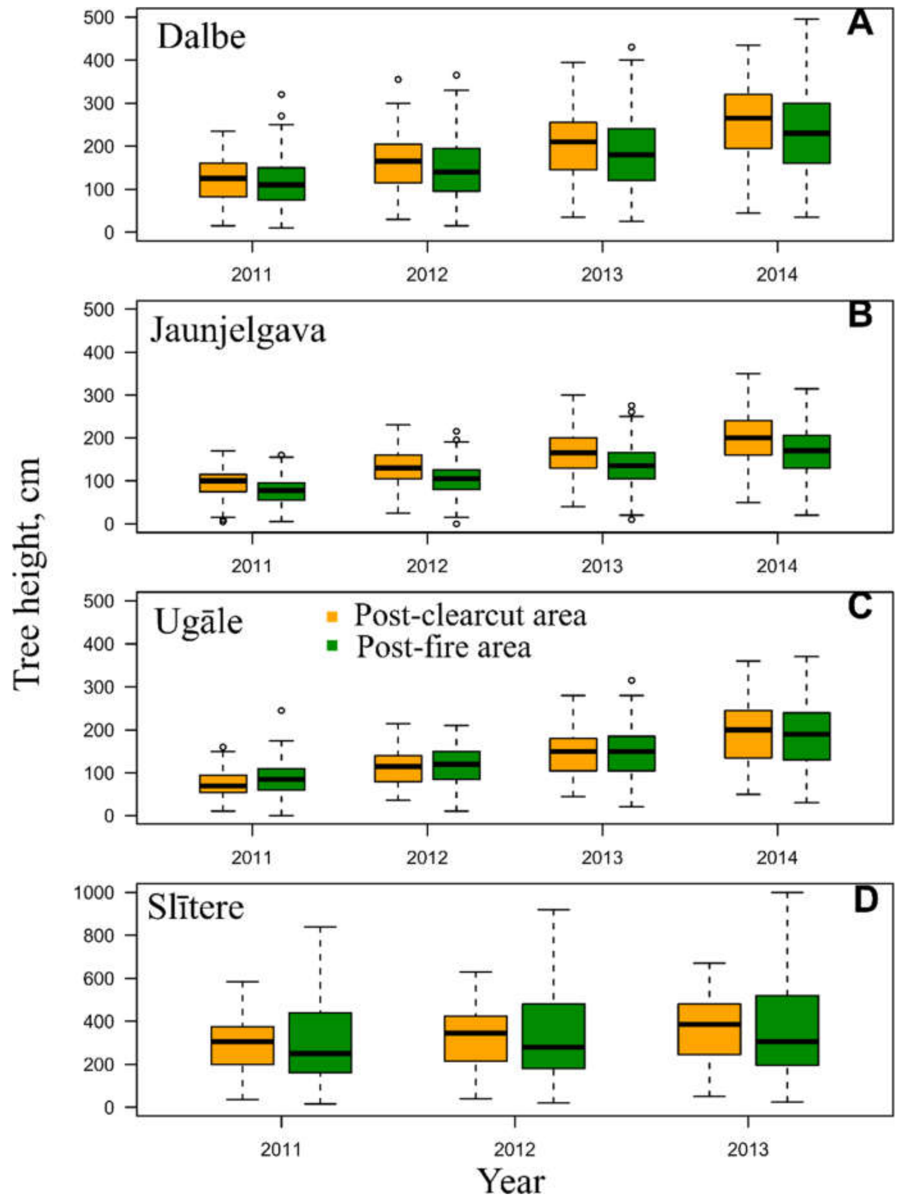


Fig. 3.5. **The mean height of Scots pine in post-clearcut and post-fire areas in different years**

### 3.4. Forest management influence on post-fire regeneration patterns
(V paper)

In 1992, in the burned SNP area, the Scots pine and birch were the most common tree species, accounting for 70% to 100% of the total abundance of regenerating tree species. The post-fire regeneration abundance of the Scots pine was significantly affected by the forest site type, spatial covariate, and interactions between forest site type and treatment, which was assessed using the GLMM. The highest total post-fire regeneration abundance was observed in the salvage-logged *Sphagnosa* site (25.440 $ha^{-1}$), followed by the salvage-logged *Vaccinioso-sphagnosa* and *Caricoso-phragmitosa* sites with 21.222 $ha^{-1}$ and 17.360 $ha^{-1}$, respectively (Paper V, Table. 2). In the no-intervention areas, the Scots pine was the most abundant tree species on all forest site types, except *Caricoso-phragmitosa*, while in salvage-logged areas in *Cladinoso-callunosa*, *Vacciniosa,* and *Vaccinioso-sphagnosa* sites, suggesting that soil scarification and the removal of large trees favoured the establishment of other pioneer tree species, such as the birch. On poor-sandy and poor-peat soils, the Scots pine was the most common tree species, whereas birch more successfully regenerated on soils with a higher moisture content and fertility. The positive influence of higher moisture on the germination success and growth of birch trees has also been observed in other studies (Karlsson, 1996; Karlsson et al., 1998).

The ANOSIM analysis showed that tree species composition of natural regeneration significantly differed (stat. $r$=0.16, $p$<0.01) between post-fire treatments on *Vaccinioso-sphagnosa* (stat. $r$=0.13, $p$<0.01) and *Caricoso-phragmitosa* (stat. $r$=0.29, $p$<0.01) sites. For the forest site types *Cladinoso-callunosa*, *Vacciniosa*, and *Sphagnosa*, the differences between treatments were insignificant.

The mean height of the Scots pine was significantly ($p$<0.05) affected by the treatment, forest site type, number of remnant trees, presence of remnant pines, spatial covariate, and interactions between factors (site type* number of retained trees and site type* remnant pines. In all forest types in the salvage-logged areas, the mean height of the Scots pine was considerably higher than in no-intervention areas by 22% to 61%, suggesting that the removal of large live trees favoured height growth (Fig. 3.6.). Similarly, the height growth of the birch was promoted by salvage logging, yet the height differences between the treatments were not as high as for the Scots pine, highlighting that salvage logging especially favoured the growth of the Scots pine. Similar observations were reported by Parro et al., (2015), who also noted that salvage logging promoted the growth of the Scots pine and helped it become a dominant tree species earlier than in the no-intervention areas.

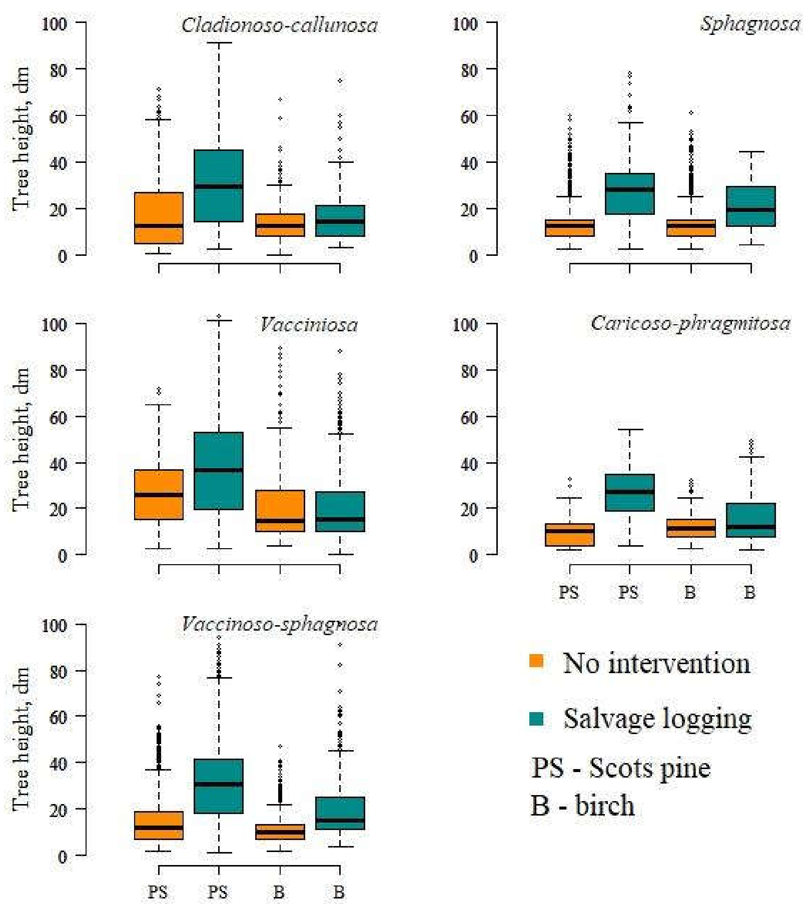



Fig. 3.6. ***The mean height of Scots pine and birch under two silvicultural treatments in post-fire area of 1992 fire in Slitere National Park***

# CONCLUSIONS

1. Over the last 250 years in the SNP, forest fires have been an important disturbance agent. We identified periods of high (1750–1950) and low (1960–2000) fire activity, with fire cycles being 45–68 and 58–80 years, respectively. The fire activity appeared to be intricately linked to the socio-political situation in Latvia and to the SST in the Baltic and North Seas.
2. Large scale weather systems affect fire activity in Latvia and Estonia as indicated by the significant positive associations between the area and number of forest fires and increased SSTs in the Baltic and North Seas during spring and summer. Over the 20th century, the forest fire danger has increased in the Baltic countries during April and May.
3. No evident long-term negative effect of fire on the growth of the Scots pine was detected. In the post-fire areas, the mean height of the artificially regenerated Scots pine had a higher coefficient of variation than in clear-cut areas, likely indicating the influence of spatial heterogeneity in fire severity.
4. In no-intervention areas in SNP, the Scots pine was the most abundant tree species in *Cladinoso-callunosa*, *Vacciniosa*, *Vaccinioso-sphagnosa*, and *Sphagnosa* forest types 23 years following the fire disturbance, while in salvage logged areas pine dominated only on poor sandy soils (*Cladinoso-callunosa*, *Vacciniosa*, *Vaccinioso-sphagnosa*), on peat soils (*Sphagnosa* and *Caricoso-phragmitosa*) dominated birch. Salvage logging significantly and positively affected the regeneration abundance of Scots pine in *Caricoso-phragmitosa* forest type only.
5. In post-fire areas, live remnant trees significantly and negatively affected the mean height of naturally regenerated Scots pine. In salvage logged areas, Scots pine had the greatest mean height of all tree species, and it was significantly greater in such areas as compared to no-intervention areas.

# RECOMMENDATIONS

1. In order to enhance the growth of Scots pine in post-fire areas, removal of large live trees may be recommended.
2. Feasibility of higher intensity forest fires in spring period, highlight the necessity of maintenance and development of forest fire surveillance system.
3. The composition and successional pathways of the forest ecosystems in SNP most likely have been shaped by historic forest fire regime; however, the strong anthropogenic influence on the past fire regime suggests that the estimates of fire cycles cannot be regarded as a reference representing solely natural (human-free) forest fire activity. A knowledge of the SNP fire history can help to define the long-term goals of nature-based management guidelines in this area.

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# Teleconnection between the Atlantic sea surface temperature and forest fires in Latvia and Estonia

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**Highlights**

- Forest fire activity in Latvia and Estonia was related to conditions in the Atlantic.
- Teleconnections differed regionally.
- Negative correlation between number of fires in Estonia and SST in the North Atlantic was detected.
- Area of forest fires in Estonia and activity of fires in Latvia were positively correlated with SST in the Baltic, North and Mediterranean Seas in summer.

**Abstract**

Forest fire is one of the natural disturbances, which have important ecological and socioeconomical effect. Although fire activity is driven by weather conditions, during past two centuries forest fires have been strongly anthropogenically controlled. In this study, teleconnection between sea surface temperature (SST) in the Atlantic, which influences climate in Europe, and forest fire activity in Latvia and Estonia was assessed using "Climate explorer" web-tool. Factors affecting number and area of forest fires in Latvia and Estonia differed, suggesting regional specifics. In Estonia, the number of fires correlated with the SST in the North Atlantic in spring and summer, which affects the inflow of cool and dry air masses from the Arctic, hence the aridity and burnability. The area of fires in Estonia and in Latvia was associated with increased SST in Baltic Sea and near the European coast in summer, which likely were consequences of occurrence of warm high-pressure systems in summer, causing hot and dry conditions. Nevertheless, the observed teleconnections could be used to predict activity of forest fires in Latvia and Estonia.

**Keywords** atmospheric circulation; weather systems; fire meteorology; disturbance regime
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# 1 Introduction

Forest fires, which are a part of natural disturbance in boreal and hemiboreal ecosystems, have considerable ecological and socioeconomical importance (Jogiste et al. 2017). During the past two centuries, forest fires have been considerably reduced by the advances in fire suppression systems (Niklasson and Granström 2000), still variation in activity of fires, i.e. ignition, behaviour, and spread, is driven by weather conditions (Wotton and Beverly 2007; Drobyshev et al. 2012). Hence, information on climatic drivers is necessary for projections of future forest fire activity under shifting climate (Bowman et al. 2009; Lehtonen et al. 2016).

Weather in the Northern Europe is largely determined by large scale weather systems forming above the Atlantic Ocean, which control inflow of warm and moist air mases, thus determine temperature and moisture regime (Sutton and Hudson 2005). The influence of such large-scale systems expresses annual, as well as multi-decadal variations e.g., North Atlantic Oscillation, Atlantic Multidecadal Oscillation (AMO), etc., which result from ocean-atmosphere interactions (Schubert et al. 2016). Accordingly, linkage between forest fires and conditions in the Northern Atlantic (e.g., surface water temperature that influence latitudinal distribution of summer precipitation) have been documented in Scandinavia (Drobyshev et al. 2016). Nevertheless, these teleconnections appeared regional, as the linkage of forest fires with sea surface temperature (SST) of the Northern Atlantic was the most pronounced in the northern part of Sweden (Drobyshev et al. 2016), hence regional analysis is needed (Bowman et al. 2009). Still, such teleconnections have been poorly studied (Drobyshev et al. 2016). The aim of this study was to assess linkage between number (NF) and area (AF) of forest fires in Latvia and Estonia and SST in the Northern Atlantic during the past century. We hypothesised that such teleconnections can be detected, yet the drivers of forest fires in Latvia and Estonia differ due to geographic location.

# 2 Material and methods

Time series of AF and NF with annual resolution for Estonia (59.651–57.475°N, 21.829–28.191°E) and Latvia (56.640–58.066°N, 20.950–28.245°E) for the periods 1921–2013 and 1922–2014 were obtained from Environment Agency of Republic of Estonia and Latvia Environment, Geology and Meteorology Centre, respectively. Some data during the World War II period was missing. Monthly SST and Annual AMO data were obtained from the UK Met Office Hadley Centre observations datasets (Rayner et al. 2003; Trenberth and Shea 2006).

Considering changes in forest cover, fire data was expressed per unit of forest area. The time series were log transformed to ensure normality of the distributions, and detrended. A simple linear function was used to remove low frequency (century) trends, likely associated with the advance of fire management systems, yet preserving medium- and high-frequency variation. Pearson correlation analysis was applied to assess the relationships between the SST for the available data points within the area limited by 20–80°N and 80°W–30°E, and the national chronologies of NF and AF. The analysis was conducted for the maximum period covered by the chronologies. The SST for the January–October period average for months and three-month intervals were tested. The significance of the correlations was determined by a two-sided Student t-test, accounting for the autocorrelation in time series, when adjusting the critical t-values (Trouet and Oldenborgh 2013). For each correlation map, field significance, which describes the strength of correlation at the scale of the studied region, was calculated (Wilks 2006). The “Climate Explorer” web-tool was used for the analysis (Trouet and Oldenborgh 2013).

## 3 Results

The produced national chronologies of NF and AF (Fig. 1) contained high- and medium-frequency variation. The range and variant of indices was higher for AF rather than NF; nevertheless, the chronologies were rather synchronous, as the mean synchrony coefficient was 0.75 (Table 1).

In Latvia, NF and AF showed stronger correlation than in Estonia (Table 1). The correlation coefficients between the chronologies were lower (average) (mean r = 0.52), suggesting differing sources of variation. The highest correlation was observed between AF in Latvia and Estonia, suggesting regional signal, yet the lowest correlation occurred between AF in Latvia and NF in Estonia, likely due to differences in medium-frequency variation. The low-frequency variation particularly in AF roughly followed the trend in AMO (Fig. 1).

Chronologies of AF and NF in Latvia and Estonia correlated with the SST of the Atlantic (Fig. 2), yet the effect (strength of correlation) and periods (months) of influence differed. The NF in Estonia was negatively correlated with the SST in North Atlantic during spring and summer, particularly in May and August, yet positive correlation was observed with summer SST in the North Sea and in the Baltic Sea. The AF in Estonia showed positive correlation with spring SST in mid-latitude Atlantic and summer SST along Atlantic coast of Europe. Spring SST in mid-latitude Atlantic negatively correlated with NF in Latvia, while positive relationships were observed with summer SST in the Baltic Sea and the North Sea. The calculated field significance was intermediate (<0.10), implying probable teleconnections.

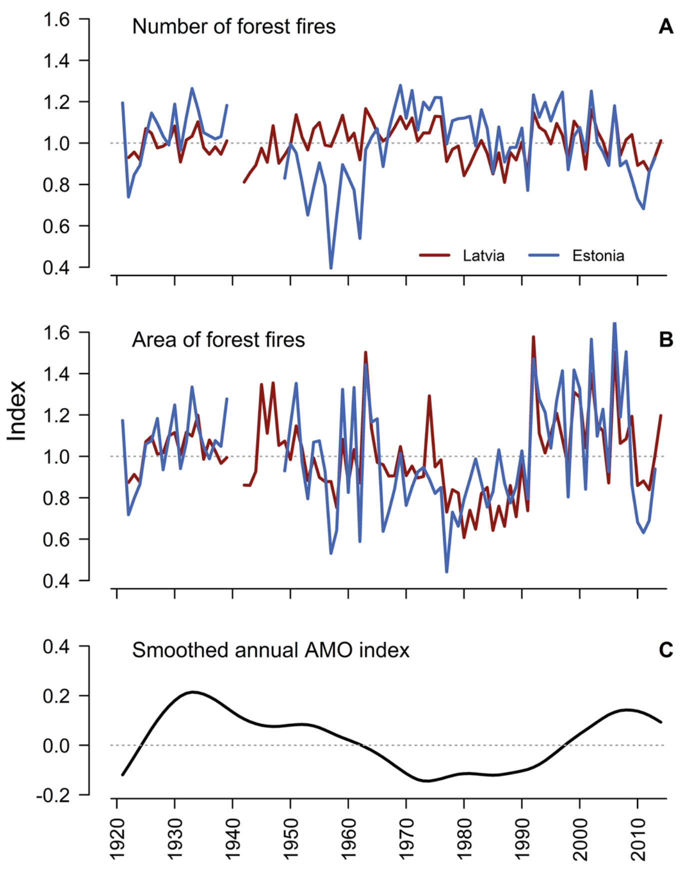


**Fig. 1.** Chronologies of number (A) and area (B) of forest fires in Latvia and Estonia, and smoothed annual Atlantic Multidecadal Oscillation index (C).

**Table 1.** Pearson correlation (upper diagonal part shows coefficients, lower diagonal part shows their p-values) and synchrony coefficients calculated between chronologies of number and area of forest fires (per unit of area) in Latvia and Estonia for the period 1922–2014 and 1921–2013, respectively.

Pearson correlation coefficient

| | | Latvia | | Estonia | |
|---|---|---|---|---|---|
| | | Number | Area | Number | Area |
| Latvia | Number | ***** | 0.70 | 0.43 | 0.60 |
| | Area | <0.001 | ***** | 0.29 | 0.74 |
| Estonia | Number | <0.001 | 0.02 | ***** | 0.38 |
| | Area | <0.001 | <0.001 | 0.01 | ***** |

+Synchrony coefficient

| | | Latvia | | Estonia | |
|---|---|---|---|---|---|
| | | Number | Area | Number | Area |
| Latvia | Number | ***** | 0.82 | 0.80 | 0.77 |
| | Area | | ***** | 0.64 | 0.67 |
| Estonia | Number | | | ***** | 0.78 |
| | Area | | | | ***** |

# 4 Discussion

The synchrony of the chronologies of AF and NF (Table 1) implied that common large-scale factors have forced variation in forest fire activity in Latvia and Estonia, yet the lower correlation between the chronologies suggested that influence of these factors on AF and NF differed. This apparently resulted in region-specific variation patterns of fire activity, as displayed by the correlations among chronologies (Table 1), that has been related to topography and climatic conditions as well as atmospheric circulation (Drobyshev et al. 2012). Still, some systematic bias particularly in fire area data might have been introduced due to political reasons. In the Soviet Union, the area of fires was the measure of efficiency of forest management system, hence the data might have been underestimated yet this might have differed among the Soviet Republics (Saliņš 1999).

As hypothesized, teleconnection between SST and the chronologies of AF and NF in Latvia and Estonia (Fig. 2) were observed, supporting linkage between fire activity and conditions in the Atlantic via alterations in atmospheric circulations (Colman and Davey 1999; Drobyshev et al. 2016). This was also supported by variation of AMO (Fig. 1). Teleconnections between North Atlantic SST and fire activity in northern Sweden (above 60°N) has been related to inflow of cool and dry arctic air masses in summer, which increase fire activity (Drobyshev et al. 2016). In our study, similar, yet less pronounced pattern of correlations between North Atlantic SST and NF in Estonia was observed (Fig. 2). This might be related to of N–S gradient of large-scale atmospheric circulations (Drobyshev et al. 2016) and regional landscape specifics (Hellberg et al. 2004). However, this teleconnection was not observed in Latvia (Fig. 2), probably due to more southern location (around 57°N) (Drobyshev et al. 2016), explaining divergence of particularly NF variation patterns (Fig. 1).

Positive correlations between Baltic Sea SST and AF in both countries and NF in Latvia (Fig. 2), might be related to regional atmospheric-sea interactions (Stramska and Bialogrodzka 2015). In summer in Baltic Sea region, meridional weather pattern prevails (Keevallik et al. 1999)

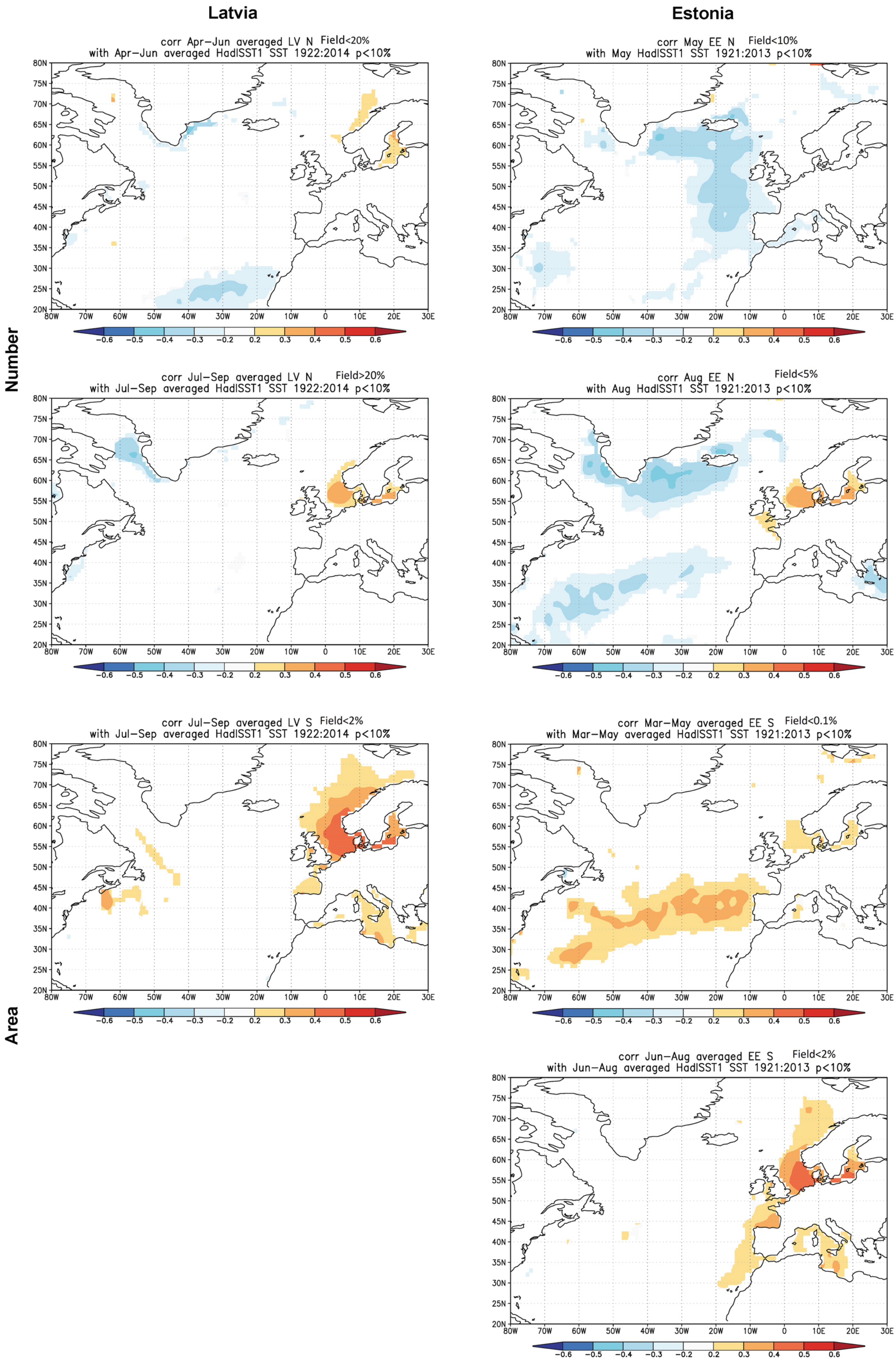


**Fig. 2.** Correlation between the sea surface temperature and chronologies of number and area of forest fires in Latvia and Estonia during the periods of 1922–2014 and 1921–2013, respectively. Only the months showing the highest correlations with the chronologies are plotted. Field significance are plotted. Correlations significant at p-value < 0.10 are marked with colour.

and, in combination with high pressure systems, promotes establishment of dry and fire-prone weather conditions (Jaagus et al. 2010; Sutton and Hodson 2005). Effect of this atmospheric circulation is supported by teleconnections with SST in Mediterranean and North Seas (Fig. 2) related to large-scale oceanic-atmospheric interactions (Ionita et al. 2017; Schubert et al. 2016). Increased SST along the coastline of Europe reduce meridional gradient of temperatures, resulting northward shifts of storm track, thus enhancing creation of large-scale drought periods in Europe (Feudale and Shukla 2010). Co-occurrence of synchronous precipitation-evaporation and SST patterns between Mediterranean, North and Baltic Seas have been also observed by Zveryaev and Allan (2010) and Ionita et al. (2017).

## 5 Conclusions

Diverse mechanisms appeared to influence forest fire activity in Latvia and Estonia. The linkage with the North Atlantic SST, which affects inflow of cool and dry air from Arctic (Drobyshev et al. 2016), might be used to predict number of ignitions in Estonia, while magnitude (area) of forest fires was more connected to the meridional atmospheric circulation and occurrence of warm high pressure systems. These systems, apparently, were the main determinants of fire activity in Latvia; and, although not clearly causal, such teleconnection might be applied to predict NF and particularly AF. Although, many uncertainties about the mechanisms of North Atlantic SST and European climate persists (Ionita et al. 2017), further research at finer-scale is needed to reveal nonstationary relationships between SST and other regional climatic variables (Ionita et al. 2017; Schubert et al. 2016).

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# Trends and patterns in annually burned forest areas and fire weather across the European boreal zone in the 20th and early 21st centuries

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ABSTRACT

Fire remains the main natural disturbance factor in the European boreal zone (EBZ), which exhibits strong gradients in climate conditions, modern and historical patterns of forest use, and the modern human infrastructure density. Understanding climatic forcing on fire activity is important for projecting effects of climate change on multiple ecosystem services over this region. Here we analysed available records of annually burned areas (ABA) in 16 administrative regions of EBZ (countries or sub-country units) and fire weather variability to test for their spatio-temporal patterns over 1901-2017. To define sub-regions of EBZ with similar fire activity we compiled 30-60 year long ABA chronologies and clustered them in Euclidian space. We then reconstructed 100-year long ABA chronologies for each cluster, using its member with the highest correlation between observational fire record and climatological fire weather proxy (MDC, monthly drought code). The 100-year chronologies helped obtain chronologies of large fire years (LFY), i.e. years with the ABA being above 10% of the long-term distribution. The climatic forcing of these events was tested in superposed epoch analysis with 500 hPa pressure fields. Finally, we tested trends in (a) synchrony of LFY's across clusters, (b) MDC values over the EBZ, and (c) spatial variability in July MDC over the EBZ geographic domain over 1901-2017.

EBZ exhibits large variability in forest fire activity with the fire cycles varying from $\sim 10^4$ (Scandinavia) to $3*10^2$ years (Russian republic of Komi). Clustering of administrative units in respect to their ABA suggested the presence of homogenous groups of units along W-E and S-N gradients. LFYs in each of the cluster was associated with the development of the high pressure cell over the regions in question in July, indicating climatic forcing of LFYs. However, contingency analysis indicated no long-term trend in the synchrony of LFYs observed simultaneously in several administrative units.

We observed a trend towards higher values of MDC for the months of April and May in the western section of EBZ (April) and southern-eastern sections of the Baltic sea region and North sections of EBZ in Russia (May). Trends in MDC during the summer months were largely absent. Geographical pattern of July MDC values, analyzed through principal component analysis over the entire EBZ, indicated the presence of a dipole, i.e. alternative behaviour, of the July MDC values over the Scandinavian peninsular and the eastern section of the EBZ. Comparison between results obtained on the complete (1901-2017) and more recent data (1950-2017) indicate that the strength of this dipole increased. The observed pattern would be indicative of a tendency towards the loss of synchrony in EBZ-wide fire activity in the future, which would make the region-wide LFYs less likely.

## INTRODUCTION

Forest fires have been the main natural disturbance force in the European boreal zone (EBZ) over the Holocene (Pitkanen & Huttunen 1999; Carcaillet et al. 2007; Greisman & Gaillard 2009; Ohlson et al. 2011; Clear et al. 2014). Since the 19th century, the EBZ has been experiencing increasingly a pronounced west-east gradient in fire activity. In its western sections the fires have been largely suppressed since late 19th century with the modern fire cycle reaching 10-20k years (Drobyshev et al. 2012). In contrast, eastern fringes of EBZ show the fire cycle of about 300 years (Drobyshev et al. 2004), i.e. the levels reconstructed prior to the onset of intensive forest use across Fennoscandia (Niklasson & Granström 2000). Variability in climate conditions, modern and historical patterns of forest use, and the overall forest accessibility for forest industry are likely the main drivers of this gradient. Although there is a general consensus on the importance and the mechanisms of human impact on geographical variability across EBZ (Granström & Niklasson 2008), the role of climate in shaping this and future geographical gradients in fire activity remains poorly understood. Indeed, a vast majority of the studies looking at climate-fire interactions in the boreal zone has been done in Fennoscandia ((Drobyshev et al. 2016; Aakala et al. 2018) and references inside), a region experiencing a much stronger influence of North Atlantic climate as compared to more easterly located sections of EBZ. The increase in climate continentality towards easterly section of EBZ is be of particular interest in understanding the response of forest fire regimes to climate variability as previous studies have pointed to higher sensitivity of more continental boreal forests to historic climate changes (Drobyshev et al. 2014; Drobyshev et al. 2017).

Climatic forcing on fire activity affects multiple ecosystem services provided by boreal forests (Gauthier et al. 2015). Recent years with large amount of burned area in the parts of the EBZ where fire suppression has been effective in suppressing the forest fires (like in Sweden in 2018) and the heavy reliance of all regional economies in this part of the world on forest resources both call for a systematic analysis of the modern patterns in fire activity and trends in its climate predictors over the EBZ. Here we provide a synthesis of the observational records of the annual burned areas resolved at the scale of EBZ large administrative regions to discuss spatio-temporal patterns in fire activity, its association with climatic fire proxies, and the synchrony of occurrence of years with large forest area burned (later referred to as large fire years, LFYs). We put forward two hypotheses: (H1) over the 20th century there was a general or region-specific trend towards increasing fire activity in EBZ; and (H2) over the 20th century there is a trend towards higher synchrony of LFYs across the EBZ. To test these hypotheses, we used cluster analyses to group the EBZ regions into clusters with temporally synchronous annual fire activity. To widen the time horizon of the analyses we reconstructed 100-year long chronologies of annually burned forest areas (ABAs) for members of the clusters with the highest correlation between observational fire record and climatological proxy of fire weather. Finally, we analysed association of LFYs with indices of atmospheric circulation to deduce the large scale climatological controls of fire activity for each EBZ fire activity cluster.

METHODS

*The region*

EBZ is the area of relatively low tree canopy diversity with limited variability in the canopy structures across its W-E extend. Scots pine (*Pinus sylvestis* L.), Norway spruce (Picea abies (L.) H. Karst) dominate the mid- and late successional stages with a marginal increase in Siberian larch (*Larix sibirica* Lebed.), while downy birch (*Betula pubescens* Ehrh.) and aspen (*Populus tremula* L.) prevail in the early successional forests. Despite low canopy diversity, variability in the types and abundances of forest fuels is high due to mosaic of forest patches with contrasting growing conditions and times in the last disturbance. Mesic and compositionally diverse forests with varying proportion of coniferous and deciduous species prevail in this biome. Xeric forests, typically with abundant Scots pine and *Cladonia* spp. lichen on the forest floor are common across EBZ with increased occurrence in its northern and eastern sections. Mires and hydric sites with abundant yet typically wet fuels are common in the EBZ although they rarely dominate at the regional scale.

*Data sources*

In this study we operated with the fire and climate data resolved at the scale of large administrative units, ranging in size from $45 \cdot 10^3$ $km^2$ (Estonia) to 417 $\cdot 10^3$ $km^2$ (Russian Komi republic) (Fig. 1). In the case of Sweden (450 $\cdot 10^3$ $km^2$) the country was divided into Southern and Northern sections, based on the earlier analyses of its modern fire activity (Drobyshev et al. 2012).

Figure 1. The geographical scope of the study with the regions providing fire data.

Compilation of the modern fire records presented two main challenges: different temporal resolution of available datasets (e.g. daily in Sweden and annual for the majority of the administrative units analysed), and varying lengths of the records. We elected to conduct the analyses on the annual scale to maximize their temporal coverage and to focus on the climate-fire linkages extending over the whole fire season. We used two sources of data on annually burned forest areas (ABA): official forest fire statistics maintained by respective state authorities and the dataset on monthly burned areas from the Global Fire Emission Database (GFED) resolved at 0.25 degrees (Giglio et al. 2013). Official fire statistics for Russia administrative regions was not available since 2012 and GFED was used to extend these records to 2016. In bridging the official and GFED data we tested for the correlation between official and satellite-based records over the overlapping period (1997-2012). For several Russian administrative units, we observed non-significant correlation between official data and GFED-based record. Two possible contributors to low correlation values were the quality of the forest statistics which has been previously reported to underestimate the levels of fire activity (Soja et al. 2004) and the inclusion in the GFED estimates all land area (i.e. both forest and non-forest lands).

*Climate data*

To represent local fire climate we calculated monthly drought codes (MDC) for the territory of each administrative unit by aggregating MDCs for the grid cells with their geographical centres located within the respective units. MDC is the monthly version of the Drought Code, which is a component of the Canadian Forest Fire Weather Index (Girardin & Wotton 2009). DC was originally developed to capture moisture content of deep layers of the forest floor (Turner 1972). The numerical value of MDC reflects a water holding capacity of 100 mm. Previous studies revealed a strong connection between MDC and regional fire activity across the boreal zone of Northern Hemisphere (Girardin et al. 2009; Drobyshev et al. 2012). MDC calculation used monthly precipitation total, minimum and maximum monthly temperatures from the CRU TS v. 4.02, (Harris et al. 2014).

*Statistical methods*

We ran principal component analysis (PCA) on the centred and normalized MDC chronologies of the best predictors of regional ABA and constructed data the distance matrix based on the Euclidean distances, using functions *prcomp* and *dist* of the R package *stats*, respectively (R Development Core Team 2018). We applied hierarchical clustering to identify groups of administrative regions with similar fire weather behaviour over the period 1901-2017, using the R function *hclust*.

*Selection of the "best" cluster members*

Acknowledging variability in efficiency of fire suppression, maximum length of ABA chronologies and data quality within the same cluster we elected to select a single administrative unit as "the best" representative of each cluster for subsequent analyses. The primary criterion for selection was the strongest correlation of ABA with the MDC predictors within the cluster in question, and the secondary criterion was the longest length of the ABA chronology. Adopting this approach allowed us to partially remove spatial correlation across regions and obtain a subset dataset of the initial data with supposedly highest data quality. The ABA record of selected administrative units was extended over the whole 20th century using its linear relationship with one or a group of MDC variables (see next section).

*Reconstruction of fire activity*

To identify the most skilful predictor of the regional ABA we ran response function analyses with the full range of combinations of the monthly, mean bi-monthly and seasonal MDCs and assessed unique contributions of MDC variables into ABA dynamics for each regions. Response function analysis is a combination of (a) principal component analysis, used to generate a reduced number of orthogonal predictors (principal components, PCs) from highly autocorrelated set of climate variables, and (b) regression analysis, which parameterizes the relationship between PC and the predictand, in this case - ABA chronology. For this step we used function *dcc* with the stationary bootstrapping option of the R package *treeclim* (Zang & Biondi 2015). Identified set of variables was used to reconstruction the ABA outside the period covered by the observational record. To this end we divided the observational ABA record into equal calibration and verification subsets and assessed the quality of reconstruction by a combination of three statistics: reduction of error (RE), coefficient of efficiency (CE), and the Durban-Watson statistic (DW) (Cook et al. 1994) (Table 1). We considered reconstruction skilful with CE above zero. We calculated the reconstruction statistics calculated with the function *skills* in the R package *treeclim* (Zang & Biondi 2015).

Table 1. Reconstruction skill of monthly drought code (MDC) variables in respect to the annual amount of burned areas for the administrative regions included in the study. A.CE and B.CE represent values of coefficient of efficiency, indicating the reconstruction skill with split calibration-verification scheme (A - early verification & late reconstruction, B - the opposite). $R^2$ indicates amount of variability explained by MDC in linear regression with the amount of annually burned areas. Cluster identify refers to cluster IDs on Fig. 2.

| Country | Cluster identity | A.CE | B.CE | $R^2$ |
|---|---|---|---|---|
| Sweden North | 4 | 0.336 | 0.331 | 0.369 |
| Swede South | 4 | 0.145 | 0.163 | 0.224 |
| Norway | 4 | 0.048 | 0.06 | 0.035 |
| Finland | 3 | 0.114 | 0.029 | 0.104 |
| Lithuania | 1 | 0.349 | -0.559 | 0.391 |
| Latvia | 1 | -0.35 | 0.013 | 0.13 |
| Estonia | 1 | 0.031 | 0.162 | 0.169 |
| Belorussia | 1 | 0.309 | 0.41 | 0.584 |
| St Petersburg | 3 | -0.449 | 0.263 | 0.55 |
| Karelia | 3 | 0.169 | 0.592 | 0.571 |
| Archangelsk | 2 | 0.177 | 0.065 | 0.281 |
| Komi | 2 | 0.229 | 0.135 | 0.216 |
| Murmansk | 2 | 0.579 | 0.333 | 0.572 |
| Pskov | 1 | 0.32 | -0.109 | 0.487 |
| Tver | 5 | 0.468 | 0.297 | 0.746 |
| Novgorod | 5 | 0.403 | -0.082 | 0.695 |
| Vologda | 5 | 0.1 | 0.002 | 0.27 |

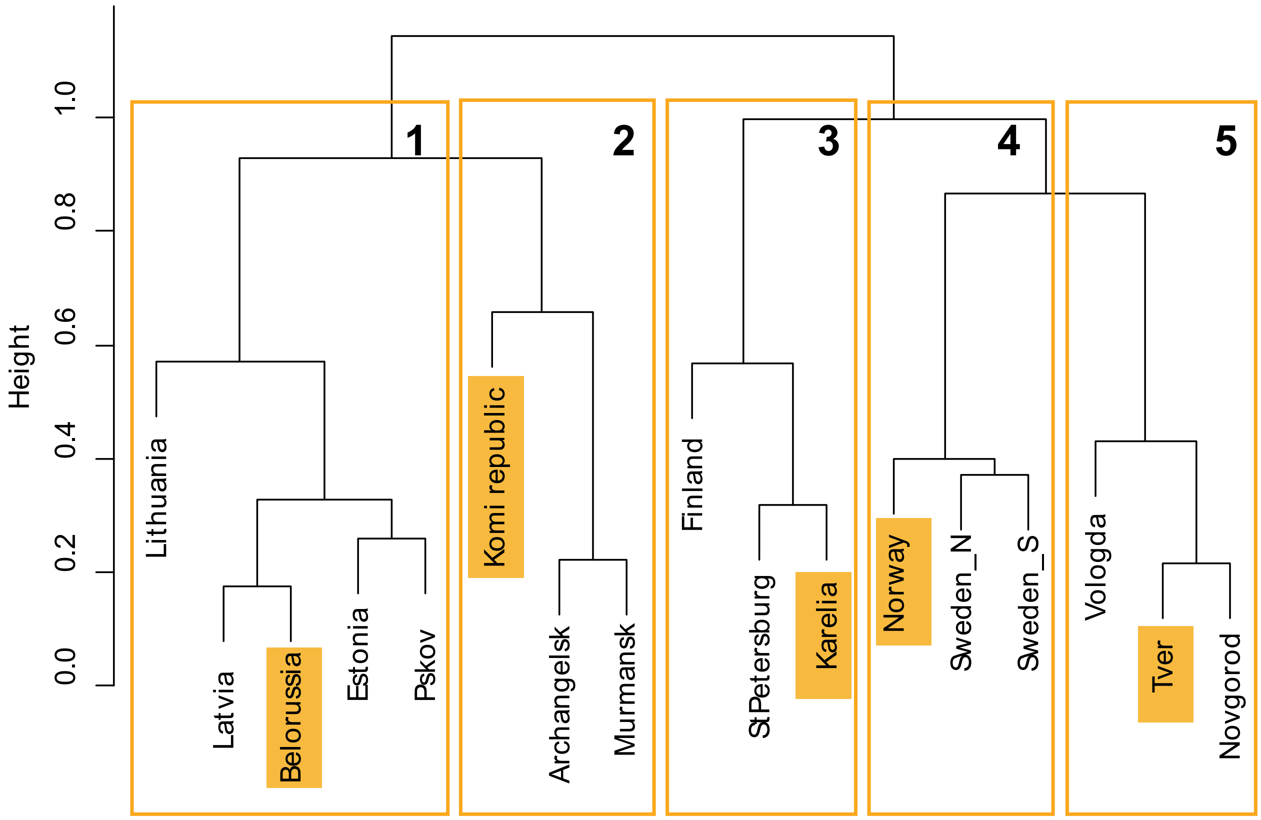


Figure 2. Clustering of the composite (i.e. composed of both observational and reconstructed data), chronologies of the region-specific amounts of burned forest area. Calculations were done on the PCA-transformed data and used the first five PCs.

*Contingency analyses*

To test for the changes in synchrony in the occurrence of LFY over the 20th century (H3) we used contingency analysis. This analysis was done on the composite (observational + reconstructed) LFY chronology for the "best" representative of each cluster, i.e. administrative region whose record had the highest correlation with MDC predictors among members of respective cluster.

We assessed the theoretically expected frequencies of LFYs observed simultaneously in different clusters we calculated joint probabilities of fire occurrence for LFY with up to the maximum number of clusters exhibiting a LFY in the same year. We assumed the binominal distribution of the LFYs:

$$p(X) = \frac{N!}{X!(N-X)} p^x q^{N-X} \quad ,$$

where $N$ was the total number of clusters in analysis; $X$ – the number of clusters with LFY in a single year; $p$ – the probability of LFY in a cluster, and $q$ – inverse of this probability. The differences between expected and observed frequencies were estimated with the Chi-square test (Sokal & Rolf 1995). Since Chi-test does not provide the means to assess the statistical significance of the occurrence of a single combination of joint LFYs we bootstrapped the dataset 1000 times to obtain the distribution of LFY occurrences in a particular year and estimated the frequency of the observed number of clusters with LFY under the assumption of a random process. We considered that year as significantly departing from that assumption if its sum of cluster-specific LFY occurrences exceeded 0.9 probability in the bootstrapped distribution.

*Trends in fire weather*

We used MDC chronologies to test for century long trends in fire weather. First, to test for the temporal trends in fire weather conditions we regressed, cell-wise, monthly MDC chronologies for the period April through September against time for the entire EBZ over 1901-2017. We used principal component analysis to study the geographical variability in the behaviour of July MDC, a common predictor of the ABA in sub-regions of EBZ, over the complete (1901-2017) and the recent (1950-2017) periods, mapping the loadings of the principal components over the study region.

*Superimposed epoch analysis*

We evaluated association of LFYs in the selected administrative units with 500 hPa pressure fields, using the Hadley Centre Sea Level Pressure dataset (HadSLP2) (Allan & Ansell 2006). Superimposed epoch analysis (composite analysis) was used to study the geographic pattern of pressure anomalies associated with LFYs with statistical significance estimated through bootstrapping of the long-term (1901 through 2016) distribution of pressure mean values respective months.

## RESULTS AND DISCCUSION

Over 20th and 21st centuries EBZ exhibited large variability in forest fire activity with the fire cycles varying from ~$10^4$ (Scandinavia) to $3*10^2$ years (Russian republic of Komi). Clustering of administrative units in respect to their ABA suggested the presence of homogenous groups of units along S-N and W-E gradients (Fig. 2). We identified five clusters with the most western cluster containing Baltic states, Belorussia and the Russian region of Pskov, and the most eastern cluster - Russian regions of Arkhangelsk and Murmansk as well as the Republic of Komi. Although our clustering exercise was aimed primarily at reducing the number of chronologies for subsequent analyses, it is worth mentioning that in case of all clusters it suggested grouping of neighbouring regions, pointing to the existence of sub-regional patterns of fire activity.

LFYs in each of the cluster was associated with the development of the high pressure cells over the regions in question in July, indicating climatic forcing of LFYs (Fig. 3). The pattern indicates importance of North Atlantic Oscillation (NAO, (Hurrell & VanLoon 1997), which is of critical importance for summer climate in Northern Europe. NAO affects the position of the storm tracks in the region, which in turn influence precipitation, cloudiness, and radiation and their variation in time and space (Bengtsson et al. 2006). Although NAO is generally considered to be a winter season phenomenon, the similar mechanism operates also during the summer months in the Northern Hemisphere, influencing regional forest fire hazard. The region with positive and sustained 500 hPa pressure anomalies is generally precipitation-free, which makes the forest fuels dry, increasing the fire hazard.

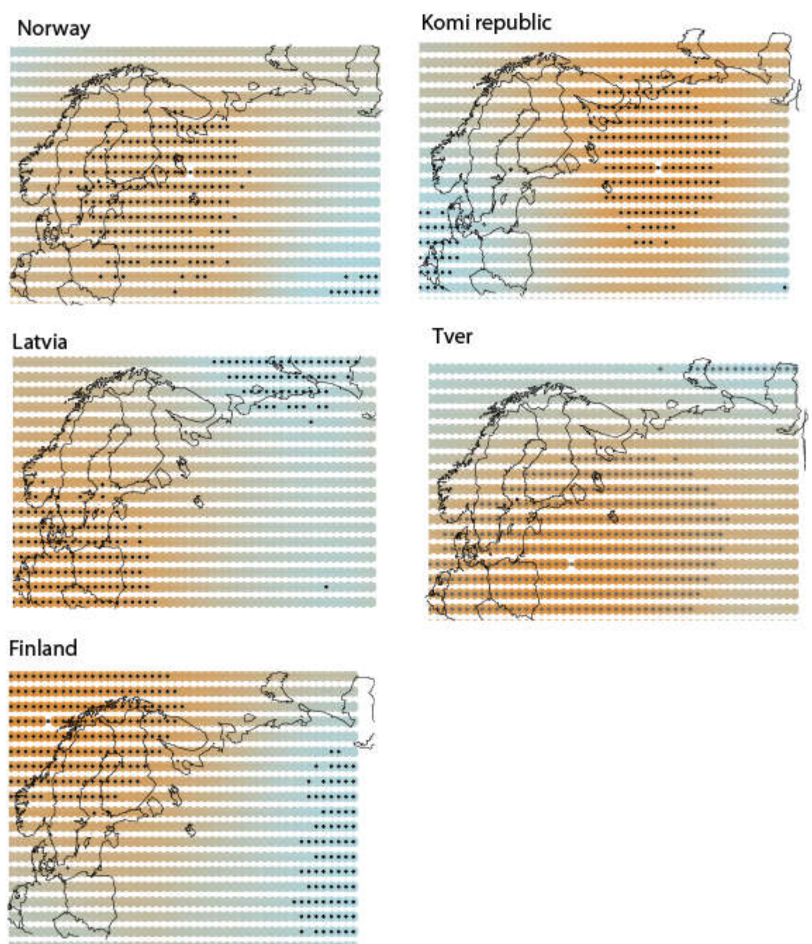


Figure 3. Superimposed epoch analysis (composite analysis) of July SLP during the five large fire years (LFY) in the cluster member with the longest observational chronology. Significant departures are indicated with black dot.

Contingency analysis indicated no long-term trend in the synchrony of LFYs observed simultaneously in several administrative units (Fig. 4), although we observed decadal variability in the synchrony levels. The general lack of trend indicated that the evolution of climate over the EBZ did not lead to an increase in the geographical extend of positive pressure anomalies during the warmer season.

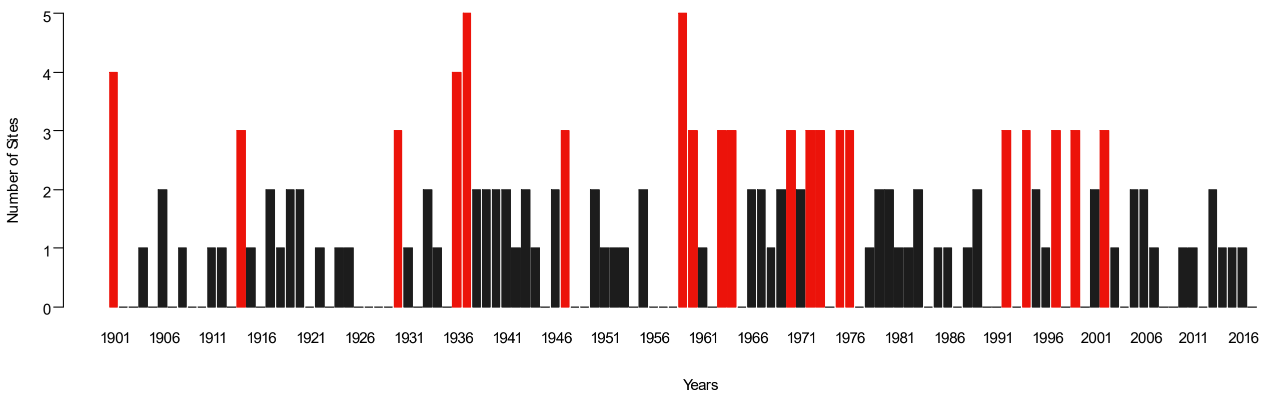


Figure 4. Contingency analysis of large fire years (LFY) occurrences. Results are obtained on the two 58-year long frames and at 0.95 confidence level. Red colour indicates years where in four years (1901, 1936, 1937, 1959) the number of regions with reconstructed LFY were above three.

The overall pattern in drought conditions, as approximated by MDC, suggested the most of the changes in fire weather happening during the start and the end of the fire season. We documented a trend towards higher values of MDC for the months of April and May in the western section of EBZ (April) and southern-eastern sections of the Baltic sea region and North sections of EBZ in Russia (May) (Fig. 5). Increase in the forest fire hazard during early part of the fire season is well in agreement with the observation of the increase in the early season fires in many countries of the region. Mid-season fire weather showed however no upward long-term trend over the majority of EBZ. In fact, sections of Scandinavian peninsular appeared to show a decreasing MDC trends, specifically - on the northern tip of Scandinavian peninsular during the month of August. Upward trend in MDC values was also observed at the end of the fire season (month of September) in the south-western section of the study area. Trends in MDC during the summer months were largely absent, which would likely indicate the lack of climatically-driven trend in fire severity. The actual dynamics of relative proportions of stand-replacing vs. surface fires would be then largely controlled by non-climatic factors, such as amount, distribution and type of forest fuels. All of them are influenced by the modern forest management, particularly - in the western section of the study area.

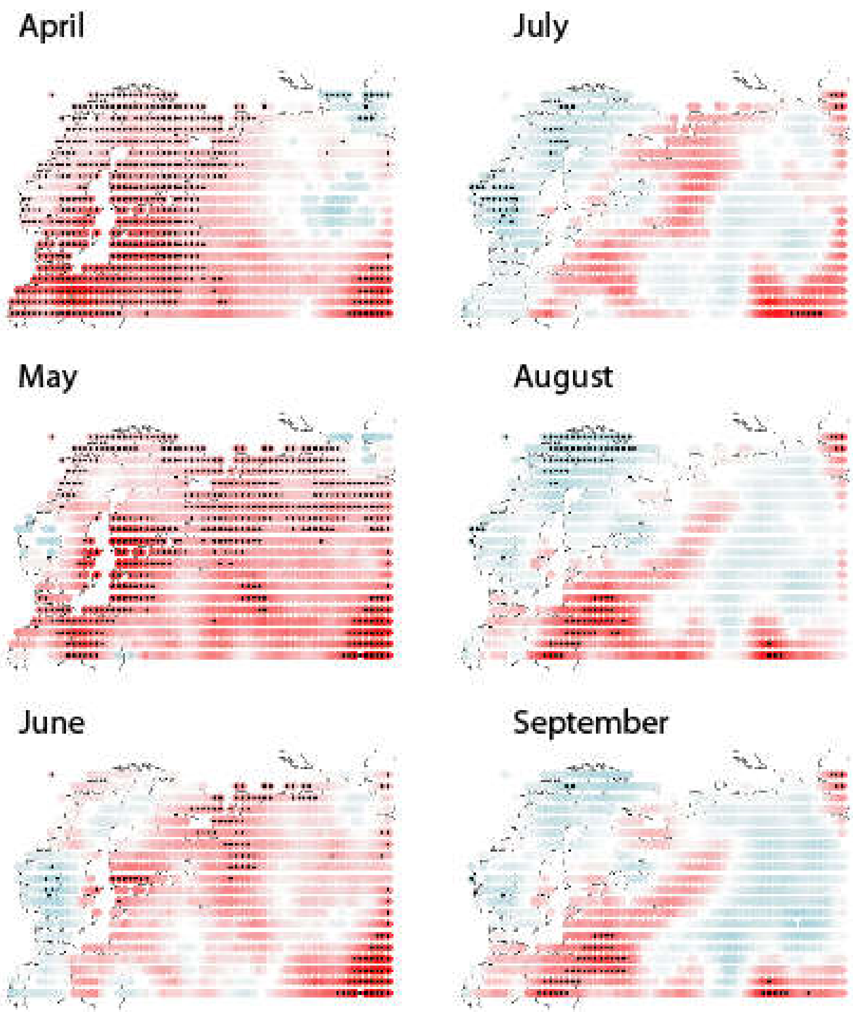


Figure 5. Trends in MDC over the 20th and the early 21st century. Significant departures are indicated with black dot.

Geographical pattern of July MDC values, analyzed through principal component analysis over the entire EBZ, indicated the presence of a dipole, i.e. the opposite behaviour, of the July MDC values over the Scandinavian peninsular and the eastern section of the EBZ. This patterns probably explains generally moderate levels of synchrony in forest fire activity over EBZ (Fig. 4): while fire-prone conditions occur over the Scandinavian peninsular, wet conditions dominate over the areas in vicinity of western slopes of Ural Mountains. The mechanistic explanation of this pattern is unclear although we speculate that the jigsaw pattern of jet stream, controlling the intrusions of cold and dry Arctic air into the EBZ from the Arctic region, may be at play here.

Comparison between results obtained on the complete (1901–2017) and more recent data (1950–2017) indicate that the strength of this dipole increased (Fig. 6). The observed pattern would be indicative of a tendency towards the loss of synchrony in fire activity across EBZ in the future, which would make the region-wide LFYs less likely. Similar to our speculation above, we propose that amplification of jet stream's jigsaw pattern acts towards increasing differences in fire weather among sub-regions of EBZ during the fire season.

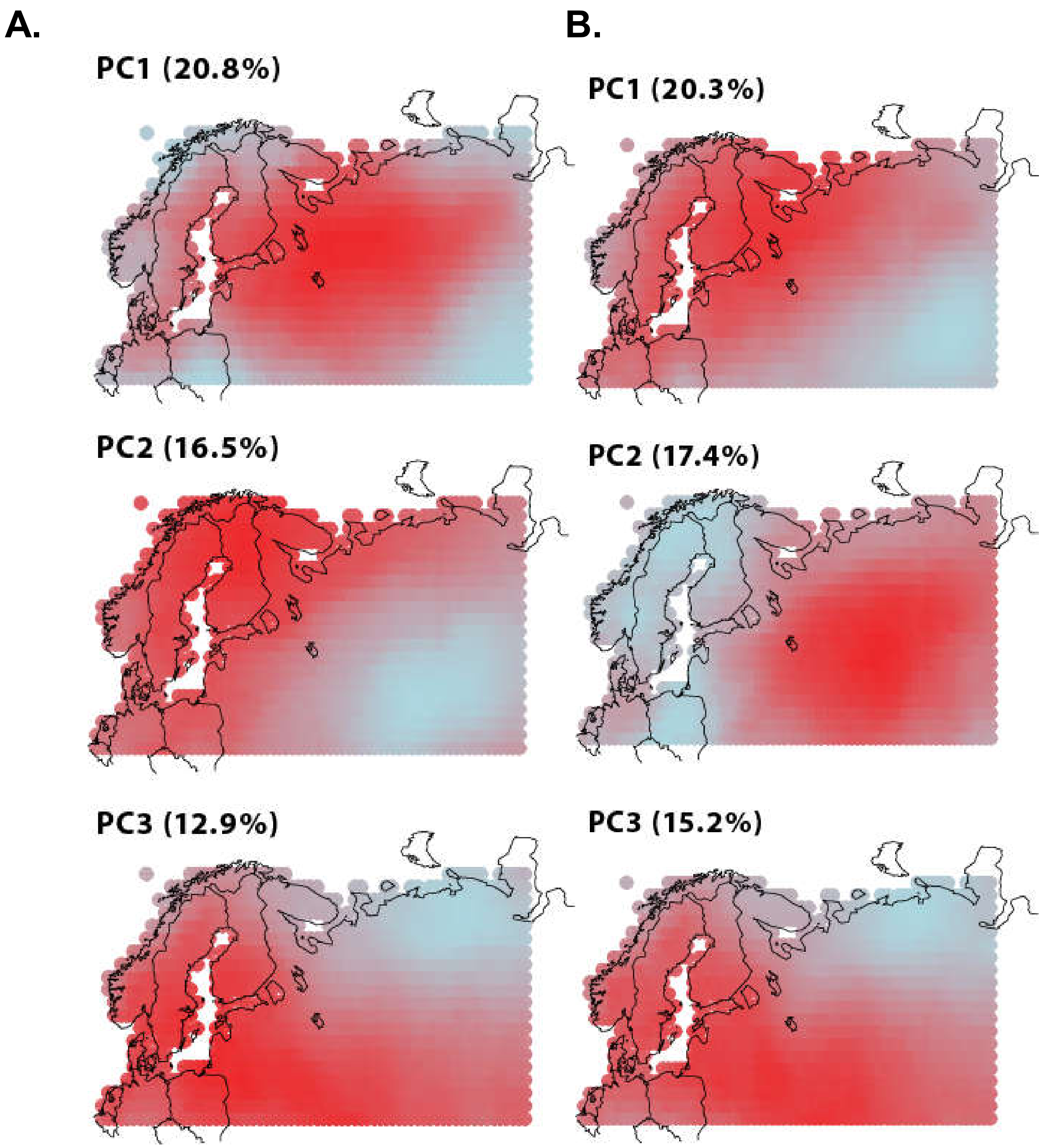


Figure 6. Loadings of the first three PCs of July MDC over the study region over 1901-2017 (A) and over 1950-2017 (B).

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# A mixture of human and climatic effects shapes the 250-year long fire history of a semi-natural pine dominated landscape of Northern Latvia

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ABSTRACT

Fire has been shown to shape successional pathways and dynamics of forest vegetation. However, its role in European hemiboreal forests remains poorly understood. Here we provide the first annually resolved reconstruction of fire history from the Eastern Baltic Sea region, developed in the pine-dominated landscape of Slitere National Park (SNP), northwestern Latvia, over the last 250 years. Our results suggest that forest fires have been a common disturbance factor in the studied landscape. In total, we dated 62 single fire years, with the mean-point scale fire return interval of 46 years and the length of the fire cycle ranging from 45 to 80 years. We identified periods of high (1750–1950) and low (1960–2000) fire activity, with the corresponding lengths of fire cycles being 45–68 and 58–80 years, respectively. Although both long-term (century and decade-long) and annual dynamics of fire activity in SNP was closely linked to socio-political changes in Latvia, fire activity in SNP was also affected by climate, as indicated by the close positive association of years with increased area burned and positive SST anomalies in the Baltic and North Seas. Future management of SNP should make fire an important element of natural forest dynamics and consider using prescribed fires of various spatial extent and severity.

## 1. Introduction

Forest fires have been an integral part of the natural disturbance regime in the European boreal (Granström, 2001; Drobyshev et al., 2014), hemi-boreal (Olsson et al., 2010), temperate (Zin et al., 2015) and meditteranen forests (Fulé et al., 2008; Christopoulou et al., 2013). Fires drive forest ecosystem dynamics (Granström, 2001; Bowman et al., 2009) and define the contribution of boreal forests to biogeochemical cycles through their control of C storage and the release of aerosols. This is particularly true for Scots pine (*Pinus sylvestris* L.), which has adapted to survive low- to moderate severity fires and successfully regenerate after them (Keeley, 2012; Zin et al., 2015). Scots pine dominated forests are widespread across European boreal and hemiboreal forest zones (Angelstam and Kuuluvainen, 2004; Niklasson et al., 2010b). Fires there have been shown to heavily influence tree cohort dynamics (Angelstam and Kuuluvainen, 2004; Kuuluvainen and Aakala, 2011), vegetation succession and biodiversity patterns (Niklasson and Drakenberg, 2001; Granström, 2001).

Fire regime is a result of abiotic and biotic factors operating at multiple spatial and temporal scales. Synoptic climatic patterns exercise the main control over regional fire regimes in boreal forests (Fauria and Johnson, 2008; Drobyshev et al., 2016). On the scale of single landscapes or watersheds, the fire regime is influenced by complex interactions among climate, topography (Hellberg et al., 2004; Drobyshev et al., 2008), fuels (Zin et al., 2015) and anthropogenic factors (Groven and Niklasson, 2005), all of which vary considerably across geographical gradients (Groven and Niklasson, 2005; Niklasson et al., 2010b; Drobyshev et al., 2016).

The majority of dendrochronological fire reconstructions in Europe have been carried out in Scots pine-dominated stands in the northern part of the subcontinent (Niklasson and Granström, 2000; Niklasson and Drakenberg, 2001; Drobyshev et al., 2014). In contrast, the knowledge of historical forest fire regimes of the European hemiboreal forest is limited. In the eastern Baltic Sea region, the long and intensive land-use history and the lack of intact natural forests in this region are the primary reasons for this pattern (Brumelis et al., 2005; Terauds

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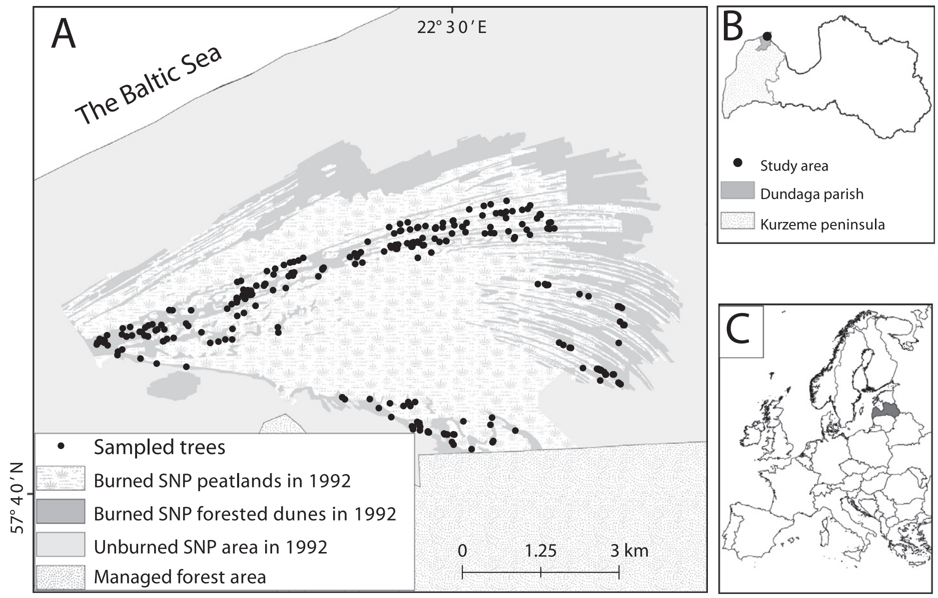


**Fig. 1.** Location of the fire history reconstruction area in Slitere National Park. A: locations of sampled trees and burned area in 1992 fire; B – the study site location within Latvia; C – location of Latvia in Europe.

et al., 2011). The only study of annually-resolved fire histories from this region has been focused on the Bialowieza Forest in Poland and Belarus (Niklasson et al., 2010b; Zin et al., 2015).

Slitere National Park (SNP), located in coastal lowland in the northern part of Kurzeme peninsula (Fig. 1B), is a rare example of the pine-dominated forests in the southern Baltic Sea region, which has preserved evidence of fire driven cohort dynamics and, therefore, provides an opportunity to get insight into past disturbance histories of that region (Brumelis et al., 2005). Pine-dominated forests grow on sandy dune ridges, which are parts of the SNP landscape, encompassing a mosaic of mostly treeless transitional wetlands and mires. The landscape has been formed in the coastal zone of the Baltic Sea during the regression of the Littorina Sea about 7500–4000 BP (Kalnina et al., 2015). The sandy dune ridges stretch parallel to the Baltic Sea coastline. The largest of the dunes extend 15 km in length and up to 50 m in width. The poor soil nutrient conditions and a large proportion of wetlands have hindered expansion of slash-and-burn agriculture in this area in the past (Dumpe, 1999). Challenging topography has also restricted access to the area by the timber industry during the 18th and 19th centuries (Slitere protection plan, 2010). Fire-scarred trees growing on sandy dune ridges in SNP and the presence of well-defined pine cohorts, point to fire activity as an important driver of vegetation dynamics (Brumelis et al., 2005). SNP is one of the few areas in the Baltic states with availability of old fire-scarred wood, which provides an opportunity to explore the historical range of spatio-temporal variability of the fire regime in this part of the European hemiboreal zone.

We provide a 250-year long reconstruction of the forest fire regime, based on the dating of fire-scarred trees of Scots pine, and evaluate the climatic and human forcing on the fire regime over this period. Considering the low levels of past management activities and the strong influence of westerlies on the regional climate (Dravniece, 2003), we hypothesized that the historical fire regime was strongly influenced by large-scale patterns of atmospheric circulations. To test this hypothesis, we evaluated the relationships between the SNP forest fire regime and North Atlantic sea surface temperatures (SST), which have been shown to be closely linked to weather states at a sub-continental scale (Sutton and Hodson, 2005) and forest fire activity in Northern Scandinavia (Drobyshev et al., 2016). Since the fire legacies shape fuel load and distribution, both of which are related to fire severity (Schimmel and Granström, 1997), we also hypothesized that parts of SNP with more frequent fires, would have a lower fire severity, i.e. a stand-replacing fire being less common. To this end, we assessed the relationship between fire frequency and the severity of the last large fire in 1992 in SNP. Our study provides baseline information on the role of fires in the SNP landscape and contributes towards the development of nature-based management guidelines for European hemi-boreal forests. To the best of our knowledge, the current study presents the first spatially explicit fire history reconstruction in the Baltic States.

## 2. Methods

### 2.1. Study area

The inter-dune peatland complex of Slitere National Park (SNP) is situated in the hemiboreal forest zone (Ahti et al., 1968) in the northwestern part of Latvia (57°68′–57°70′ N, 22°46′–22°52′ E) (Fig. 1). Climate conditions are mild and strongly influenced by westerlies which bring moist maritime air masses from the Baltic Sea and Atlantic Ocean (Dravniece, 2003; Avotniece et al., 2017). The long-term (1961–2010) mean annual temperature is +6.4 °C, with February being the coldest month (mean temperature −2.8 °C) and July – the warmest (+16.5 °C). The mean annual precipitation is 606 mm. The length of the vegetation period when the mean diurnal temperature exceeds > 5 °C, is up to 190 days (Avotniece et al., 2017).

The studied pine stands grow on nutrient-poor, sandy dunes in the *Cladinoso-callunosa* and *Vacciniosa* forests (Bušs, 1976). The ground vegetation is dominated by ericaceous dwarf shrubs (*Calluna vulgaris* L., *Vaccinium myrtillus* L., *Vaccinium vitis-idaea* L., *Empetrum nigrum* L.). *Dicranum* spp. and *Cladonia* spp. prevail on drier sites (Seile and Rēriha, 1983). Dry and forested sites occupy 33%, while peatlands and wetlands occur on 66% of the study area. The peat formation process started in ridge depressions 5000 years ago (Pakalne and Kalniņa, 2005). The peatlands were formed following the overgrowing of ridge depressions by peat. Bazi mire is the largest raised bog of coastal type in the SNP, dominated by *Sphagnum-Eriophorum vaginatum* communities. Smaller inter-dune mires are mainly of fen or transitional types (Pakalne and Kalniņa, 2005). In the beginning of the 19th century, the Bazi mire was drained. Although the ditches were never renovated, a few of them are still partially functioning, modulating the natural hydrological regime of Bazi mire (Slitere protection plan, 2010).

The close proximity to the Baltic Sea and local geomorphological characteristics has shaped the patterns of human activities in the area of SNP. The fishery has been the main occupation for local communities, whereas large-scale agriculture has not been developed, due to unsuitable soil conditions and challenging topography. Some of the inter-dune depressions was used as meadows or pastures for small-scale cattle farming until the 1920s. Areas south of Bazi mire were still used as pastures at the beginning of the 20th century (Abaja, 2011). In July 1992, a large fire occurred within SNP, burning 3000 ha, of which 1022 were forested (Fig. 1). Archives have preserved dates of two earlier large fires in this region, which took place in 1834 (Sloka, 1930) and 1905 (Wätjen, 1994).

### 2.2. Field data collection

We inventoried the area of 2000 ha within the SNP (Fig. 1A), including both forested and peatland parts of the landscape. We systematically surveyed all forested inland dunes for fire-scarred material. The relatively small study area allowed us to make a comprehensive inventory of the scared wood. We sampled only deadwood (stumps, snags, logs), since SNP regulations prohibited us from collecting partial cross sections from living fire-scarred pines. We collected full or partial cross-sections of deadwood, following the procedure described by Arno and Sneck (1977) and McBride (1983). Out of 350 deadwood samples collected, we dated 287 trees (82%), including 44 deadwood samples with no fire scars. Wood decay was the primary reason for our failure to date remaining samples.

### 2.3. Sample preparation and fire-scar dating

Wood samples were glued, mounted on boards and sanded with up to 400 grit sandpaper to obtain clear view of the annual tree-rings and fire scars. We scanned samples at 1200–2400 dpi resolution and measured ring widths, using Cybis AB CooRecorder/CDendro 7.7 program package (Larsson, 2013). We used a combination of local pointer years and a newly developed pine chronology to cross-date deadwood samples. The cross-dating accuracy was verified by the *t*-test value, which was calculated using the CDendro program. We assigned the calendar year and, when possible, the fire season to each past fire, as indicated by the scar position within the annual rings. Fire scars located within the earlywood were classified into three groups, based on the earlywood development phase at the time of scar formation including: early earlywood, middle earlywood, late earlywood fires. Similarly, we classified latewood fire scars as early latewood, middle latewood, and late latewood scars. Scars which occurried between the latewood and earlywood formation periods were regarded as indicators of dormant-season fires (Baisan and Swetnam, 1990).

### 2.4. Reconstruction of burned area and fire cycle

To reconstruct the spatial extent of area burned, we used a regular spatial grid, which encompassed the whole study area. The grid cell was considered as recording for a year, i.e. providing information about fire activity, when that cell contributed with at least one sample which had a ring representing the year in question (with or without a fire scar). A grid cell was considered as non-recording in a year, when no samples from that cell covered the year in question. The grid cell was considered as burned in a year, when at least one sample within that cell had fire scar recorded the year in question. For spatial reconstruction, we used only fire scars. This might lead to the underestimation of past fire activity in SNP, since not all fires scar trees (Swetnam et al., 1999; Piha et al., 2013). The total area burned in a fire year was equivalent to the area of burned cells in the year in question. We used four different grid-cell sizes ($100 \times 100\,m^2$, $300 \times 300\,m^2$, $500 \times 500\,m^2$ and $700 \times 700\,m^2$). The use of different cell sizes in spatial reconstruction analysis, allowed us to assess the sensitivity of the algorithm to variation in grid cell sizes. To assess the accuracy of the spatial reconstruction and to identify the optimal size of the grid cells to be used in historical analyses, we compared the total area burned, as estimated by our protocol with the actual area of 1992 fire, available through direct observations (Peterhofs, 2005).

Extending our reconstruction back in time resulted in a decline of replication, i.e. decline in the number of recording grid cells which, in turn, led to a decrease in the fire detection probability. To adjust for the time-related decrease in detection probability, we assumed that the proportion of non-recording grid cells which burned, was equal to the proportion of burned recording grid cells in that year. We adjusted burned areas for fire years, for which at least 30% of all grid cells were recording the year in question. Using this procedure, we extended the reconstruction of the burned area and the fire cycle (FC) from 1750 to 2014. FC is a period (in years) needed to burn the area equal to the total study area (Van Wagner, 1978). FC confidence limits were estimated through a bootstrap method.

We calculated FC separately for forested areas (sandy dunes) and for the whole study area, including both forested dunes and wetlands. Peatlands and mires do burn, particularly following a prolonged period of drought (Hellberg et al., 2004), although they commonly did not yield samples to evaluate the frequency of such events, which introduces uncertainty in FC estimates. To account for that uncertainy, we provided two versions of FC estimates, based on forested area only within grid cells and, altrenatively, on the total area of the grid cells (Fig. S1).

To calculate point-scale fire return interval (FRI), we estimated the number of years between two successive fire scars recorded by a single tree. The FRI mean and standard deviation were calculated for the entire study period.

### 2.5. Identification of fire regime shifts

We assessed regime shifts in FC by using a sequential *t*-test algorithm (Rodionov, 2004). This method has been used earlier to assess regime shifts in marine ecosystems (Rodionov, 2015), climate (Jaagus et al., 2016) and forest fire activity (Taylor et al., 2016; Drobyshev et al., 2016). We identified shifts as statistically significant changes in the cumulative sum of normalized deviations of the mean value between the “current” and “new” regime, moving along a time axis in an incremental fashion. The thresholds indicative of changes in the regimes are set by (a) cut-off length, which is the minimal interval of constant regime magnitude, (b) significance level and (c) the Hubert’s weight function, which handles outliers as deviations from the expected mean value of a “new” normalized regime. We used the cut-off length of 10 years, significance level of $p = 0.1$ and 1 as the Hubert weight parameter. For each defined FC epoch, we calculated the fire frequency and survivorship function, representing the probability for a cell to burn at a certain age, i.e. the time since the last fire in that cell (Fig. S3).

### 2.6. Analysis of fire history effect on fire severity

Availability of data on fire impact in 1992 allowed us to assess the role of historical fire activity on fire severity during a large fire event. We used a post-fire age class of stand as a measure of 1992 fire severity. High-severity stand-replacing fires kill most of the canopy trees and are usually followed by major tree regeneration waves (Agee, 1993; Zin et al., 2015). Low to moderate-severity fires cause partial (if any) mortality of the main canopy and initiate development of multiple-aged pine stands (Östlund et al., 1997; Kuuluvainen et al., 2002). We considered stand age, as recorded by the 1996 forest inventory (Dundagas virsmežniecība, 1996), as a binary proxy of 1992 fire severity. Forest inventory data provided information about the mean age of the dominant tree species in each stand. Stands with a mean age of “0″ (according to inventory records) were considered as patches where stand-replacing fires took place. A stand with all other age classes was regarded as a stand with a non-stand replacing fire. We expected a negative correlation between the 1992 fire severity, as expressed by 1996 stand age data, and dendrochronologically reconstructed fire frequency expressed as the mean number of years between fires within the respective grid cell. To test this hypothesis, we used a generalized least squares model with a spatial correlation structure (Zuur et al., 2009) from R package nlme (Pinheiro et al., 2018). We tested four spatial correlation structures – exponential, Gaussian, linear, rational quadratics and spherical. The best fitting model was chosen based on the lowest AIC value.

### 2.7. Climate influence on fire activity

We used superimposed epoch analysis (SEA) to assess the relationships between fire activity in SNP and SST dynamics in the subpolar North Atlantic. SEA is a method used in analyses of event-based and non-normally distributed time series data, where the significance of departures of continuous chronology during event years, is tested through bootstrapping. In the analysis, we correlated fire data with SST in the subpolar North Atlantic (40–70°N; 60°W–40°E) averaged over the May-September period. The climate of that region is dominated by large-scale weather systems controlling climate in northwest Europe (Sutton and Hodson, 2005; Moffa-Sánchez and Hall, 2017). For the analysis, we selected fire years with reconstructed burned area exceeding 1 km$^2$, which corresponded to ~30% of the studied area (Fig. S2). Previous studies have shown that the climatic forcing upon fire activity increases, with the size of the fire episodes (Drobyshev et al., 2015). The significance of anomalies in SST was verified by a two-sided Student *t*-test. Field significance, which illustrates the strength of anomalies, was calculated for each composite map (Wilks, 2006). In the analysis, we used SST data set starting in 1870 that was provided by Met Office Hadley Centre (Rayner et al., 2003). The analysis was carried out using KNMI Climate Explorer (Trouet and van Oldenborgh, 2013).

## 3. Results

### 3.1. Reconstruction of the burned areas

We dated 329 fire scars and identified 62 single fire years, of which 27 were recorded by more than one tree (Fig. S2). The mean number of tree rings per sample was 122 (minimum 30, maximum 327) and only one sample had more than 300 tree rings. The earliest fire scar was dated to 1558 and the latest fire occurred in 1992. The number of recoding trees per fire year varied between 1 (1558) and 180 (1890). During 1558–1750, we dated 11 single fire years (1558, 1585, 1646, 1664, 1678, 1689, 1710, 1713, 1721, 1734, 1746) using a sample of 16 trees. For this period, we did not reconstruct the burned area, due to the low sampling coverage.

For the whole study period (1558–1992), the mean point-scale FRI was 46 and the standard deviation was ± 33.5 years. The shortest point-tree FRI was six years, recorded by a single tree, which was scared during 1791 and 1797 fires. The seasonal distribution of fires revealed the dominance of early season fires. In the 1750–1992 period, 51 fire events were recorded, of which 33 (65%) formed scars in earlywood and 18 (28%) in the latewood.

For the 1750 to 2000 period, the burned area was reconstructed for the whole study area and for its forested areas. Over this period, 51 single fire years were recorded. The amount of burned area slowly increased between the 1750s and the early 1800s. It then increased sharply during 1800–1850 period (Fig. 2). The total burned area varied considerably, depending on the defined grid cell size and ranged for the whole study area from 5.1 km$^2$ (100 × 100 m$^2$) to 114.4 km$^2$ (700 × 700 m$^2$) and for the forested portion of the area – from 1.6 km$^2$ (100 × 100 m$^2$) to 33.3 km$^2$ (700 × 700 m$^2$).

The reconstructed total forested area burned during the 1992 fire, ranged from 0.2 km$^2$ to 3.5 km$^2$, depending on the grid cell size (Fig. 3). These estimates were below the value obtained through direct observations by 16% (the grids with cell size of 500 × 500 m$^2$) to 94% (the grid of 100 × 100 m$^2$), while the grid of 700 × 700 m$^2$ overestimated the actual burned area by 16%. For the analyses of fire cycle and survival analysis, we used two cell grid sizes, 500 × 500 m$^2$ and 700 × 700 m$^2$.

### 3.2. Dynamics of the fire cycle and the effect of past fires on fire severity

Over the 1750–2000 period, we assessed the regime shifts separately for the forested and the whole study area, using two different grid-cell sizes (500 × 500 m$^2$ and 700 × 700 m$^2$). The shifts in fire regime were identified in the 1950s, by both grids based on forested areas (p-value = 0.1) and the whole grid area (p-value = 0.2) (Fig. 4). The earlier epoch (1750–2000) had shorter FC than the last epoch (1960–2000) (Table 1). By analysing the whole area, we obtained generally shorter FC than by using forested areas, irrespectively of the grid size. However, the differences in FC length between the whole grid areas and forested areas for the same epoch did not differ substantially. The largest difference was 14 years for the later epoch (1960–2000) using a 500 × 500 m$^2$ grid, while the smallest difference was five years for the earlier epoch (1750–1950) using a 700 × 700 m$^2$ grid.

Fire frequency showed a large variation across the studied landscape, ranging between 22 and 197 years for the 500 × 500 m$^2$ cells and between 20 and 180 years for the 700 × 700 m$^2$ cells (Fig. 5). The spatial pattern of fire frequency was similar in both analyses, only exception being the southern part of the study area where larger grid size was associated with shorter intervals.

During the 1992 fire, the highest fire severity was observed in the northeastern and eastern side of the study area, while the lower fire severity was found in the western and southern parts (Fig. 6). The model with exponential spatial correlation structures provided the best fit of the empirical data, according to its AIC value. We used that model to evaluate association between 1992 burn severity and fire frequency at the grid cell scale. Past fire intervals did not have a significant effect on the spatial severity pattern of the 1992 fire either using the 500 × 500 m$^2$ grid (estimate = −0.04; t-value = −1.08; p-value = 0.28) or the 700 × 700 m$^2$ grid (estimate = −0.007; t-value = −0.16; p-value = 0.86). Similar results were obtained using spatial survival analysis, which is presented in the Supplementary Material (Fig. S3).

### 3.3. Climate influence on fire activity

Superimposed epoch analysis operated with four large fire years: 1905, 1914, 1921, and 1992 (Fig. S2). Fire activity in SNP was linked to SST in the North Atlantic, Baltic and North Seas (Fig. 7). The fires in SNP were associated with positive SST anomalies in the Baltic Sea from May to July. Similar associations were also observed in the North Sea in May and July. The large fires were also associated with negative SST anomalies in the Central North Atlantic region (50–60°N, 20–30°W) in May and northern North Atlantic region (40–60°N, 30–50°W) in June and July. The fires were positively associated with SST anomalies in the Grand Banks region (40–50°N, 50–40°W) in June.

## 4. Discussion

For the past 250 years, the forest fire has been a common disturbance agent in the Scots pine dominated forests of Slitere National Park (SNP). Long-term changes in the fire cycle revealed strong synchrony with changes in socio-political settings in Latvia and suggested strong human forcing upon fire regime. In particular, a dramatic decline in fire activity in the middle of 20th century followed a shift in the land use patterns of the region which was not synchronized with dynamics of climatic proxies of fire hazard. However, a positive correlation between annual fire record with summer SSTs in the Baltic and North Seas

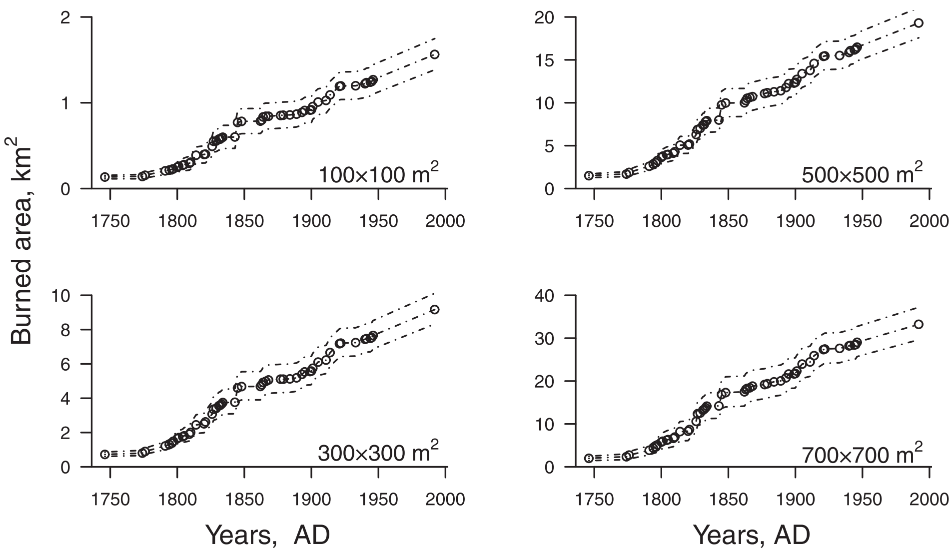


**Fig. 2.** Cumulative sum of forested area burned (km$^2$) at the grid-cell size 100 × 100 m$^2$, 300 × 300 m$^2$, 500 × 500 m$^2$, 700 × 700 m$^2$ in Slitere National Park. The broken lines represent 10th and 90th percentiles of the respective mean distribution. Fire events are marked as empty circles. Note the difference in the y-axis scales.

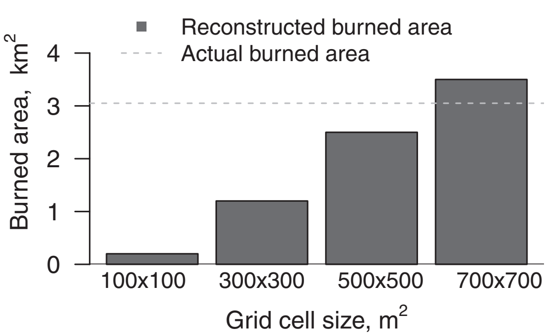


**Fig. 3.** Observed and reconstructed burned forest area the 1992 fire, using the grid cells of several sizes in Slitere National Park. The horizontal dashed line represents the actual burned area during the 1992 fire, as estimated through the forest inventory.

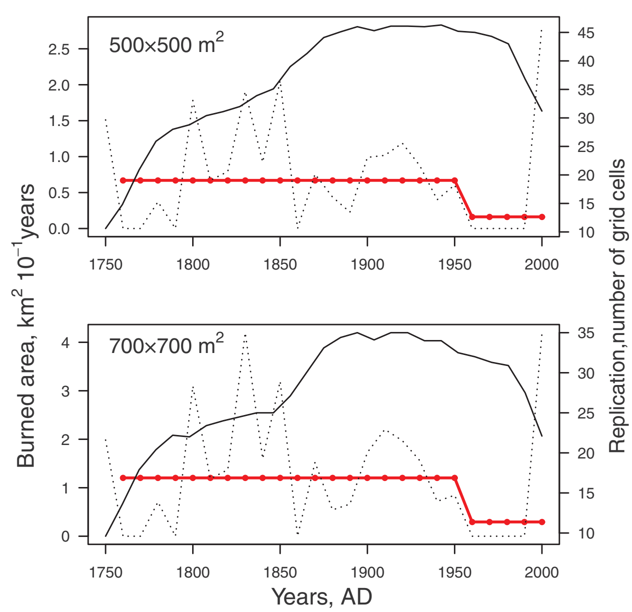


**Fig. 4.** Shifts in FC of Slitere National Park, calculated using fire prone areas only and for two grid cell sizes over 1750–2000. The dashed lines represent burned area in km$^2$ per decade. The red line represents periods with a specific fire cycle (i.e. fire epochs in respect to the dynamics of fire cycle), as identified by the Rodionov shift detection method. The solid black line represents sample depth, i.e. the number of recording grid cells. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

implied a degree of climate forcing upon fire activity in SNP at the annual scale. Despite a human-related decline in fire during the 20th century, the major fire event of 1992 has helped to maintain the fire-driven stand dynamics in SNP to the present day.

To the best of our knowledge, this is the first spatially explicit dendrochronological fire history reconstruction in hemiboreal forests in the eastern Baltic Sea region, which generally lacks large, semi-natural forests with a potential for fire scar-based analyses. In this context, fire history reconstruction of Slitere National Park is of immediate value for understanding the dynamics and developing conservation policies for Scots pine dominated forests in the Baltic region and, in a broader perspective, the European hemiboreal forests.

### *4.1. Dynamics of fire return interval and fire cycle in SNP*

Over the period from 1558 to 2014, the mean point-scale interval in SNP was 46 years, slightly longer than that observed in the Bialowieza forest (35 years) over generally the same time period (Zin et al., 2015). The shortest point-scale fire interval, in SNP (6 years) was longer than that recorded in southern Sweden in Norra Kvills Park (5 years) (Niklasson and Drakenberg, 2001) and Białowieza forest (2 years) (Zin et al., 2015). The lower limit of fire return interval at the point scale, is controlled by the rate of fuel build-up, which varies along gradients in climate and fuel properties (Schimmel and Granström, 1997). In the pine forests of SNP, the dominating component of the shrub layer is *Calluna vulgaris* (Seile and Rēriha, 1983), which recovers after five to six years following a fire (Marozas et al., 2007). This estimate coincides well with the minimum fire return interval of six years observed in this study. In contrast, the ground vegetation in Białowieza is dominated by grasses (Zin et al., 2015), likely speeding up fuel recovery and reducing the minimum fire return interval. Relatively slow fuel recovery might explain why the year 1834, with an exceptionally large fire in the northwestern part of the Kurzeme peninsula (Fig. 1) (Sloka, 1930; Cimermanis, 1998), was missing in our fire record (only one tree in our dataset had a scar dated to that year), despite the fact that aproximatetly 70% of all grid cells were recording during the1830s. The previous large fire in SNP was recorded just eight years earlier, in 1826

**Table 1**
Fire cycles of FC epochs, as identified by the regime shift analysis, with corresponding confidence intervals for fire prone areas and the whole area of Slitere National Park.

| | Grid size ($m^2$) | Epoch (from-to) | Fire Cycle | Lower bound (5% quantile) | Upper limit (95% quantile) |
|---|---|---|---|---|---|
| Fire prone area | 500 × 500 | 1750–1950 | 68 | 52.5 | 93.4 |
| | | 1960–2000 | 80 | 39.6 | inf |
| | 700 × 700 | 1750–1950 | 50 | 38.8 | 67.5 |
| | | 1960–2000 | 69 | 34.5 | inf |
| Whole study area | 500 × 500 | 1750–1950 | 60 | 46.0 | 84.0 |
| | | 1960–2000 | 66 | 22.1 | inf |
| | 700 × 700 | 1750–1950 | 45 | 34.1 | 62.5 |
| | | 1960–2000 | 58 | 19.4 | inf |

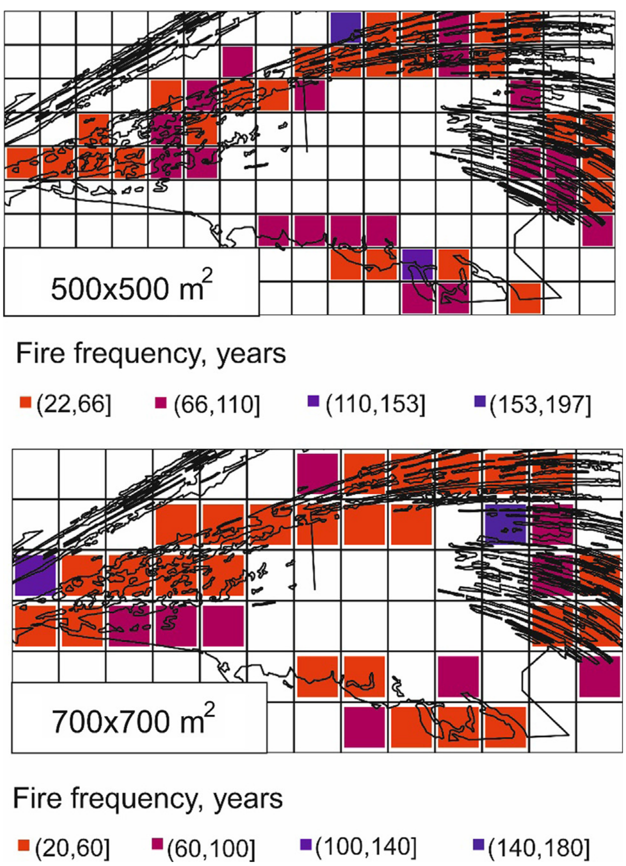


**Fig. 5.** Fire frequency for each recording grid-cell in Slitere National Park for the grids with the cell size of 500 × 500 and 700 × 700 $m^2$. Red colour indicates a shorter fire frequency while blue colour indicates a longer fire frequency. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and might have removed fuels to support the 1834 event.

Past fires likely removed considerable amounts of deadwood, as suggested by the rare presence of old deadwood (only one sample had more than 300 rings). As a result, the reconstructed period of burned areas was rather short (250 years), as compared to northern Sweden and south-central Norway, where well-replicated fire records often go back to 14th and 15th centuries (Niklasson and Granström, 2000; Drobyshev et al., 2014; Rolstad et al., 2017).

In the earlier epoch (1750–1950), a wide adoption of slash-and-burn agriculture in Latvia likely promoted forest fire activity (Dumpe, 1999). Slash-and-burn agriculture has been one of the main reasons for forest

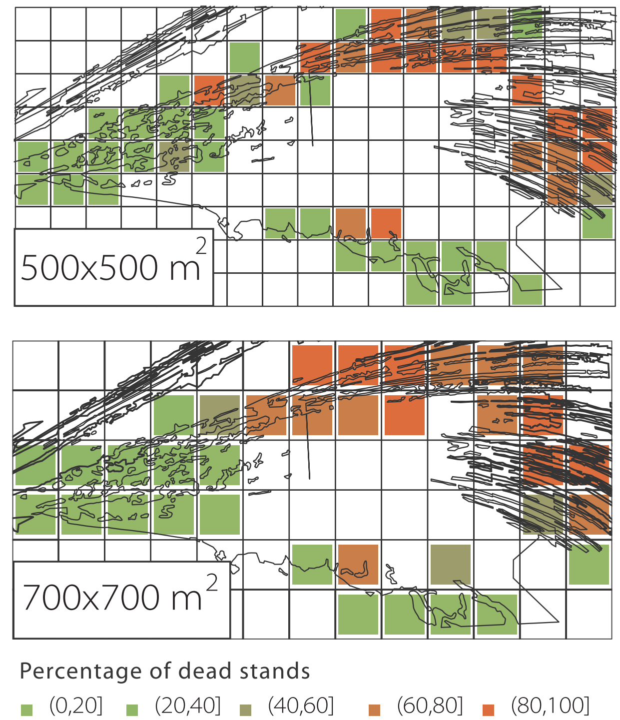


**Fig. 6.** A map of the 1992 fire severity in Slitere National Park for the grids with the cell size of 500 × 500 and 700 × 700 $m^2$. Colours indicate an area of dead forested areas within a grid cell. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

destruction over recent centuries. Forest burnings have illegal since the early 17th century. However, due to the unstable political situation and poor state governance, fire remained a common forest disturbance factor, until the middle of 19th century (Strods, 1999). Similar trends have been observed in Fennoscandia and Bialowieza, where an increase in fire activity during the 17th century and its subsequent decline in the18th and 19th centuries have been linked to the human use of fire to improve grazing conditions and/or tar production. Both of these activities have declined due to the increasing economic value of timber and the introduction of fire suppression policies (Niklasson and Granström, 2000; Niklasson et al., 2010a; Rolstad et al., 2017).

The shift from high to literally non-existent fire activity (with the exception of the large fire year of 1992) occurred in the middle of 20th century (Fig. 4). These dynamics are a likely result of a drastic change in the land-use, employment and agriculture systems in Latvia, which took place during the Soviet Union period (Hiden and Salmon, 2013). After the Second World War, the western coastline zone of the Baltic Sea was designated exclusively for military purposes. The coastal fishery was prohibited, except for the inhabitants of a few coastal villages (e.g. Sikrags, Kolka). In parallel, agricultural production experienced a transition from private to collective farming, which led to the abandonment of many remote and less productive fields and meadows, due to decline in their economic value (Ržepicka and Ziemelniece, 2017). Consequently, a considerable proportion of the local population had lost their main income source and migrated away from this region. A similar decline in fire activity has been reported in a region of Russian Karelia, near the Lake Venehjärvi, in the 1950s (Lampainen et al., 2004).

The 20th century decline in fire activity in SNP mirrored a broader trend of decreasing fire activity in Latvia (Donis et al., 2017). At the country scale, the length of FC has increased from $1.1 \times 10^3$ years at the beginning of the 20th century to $3.2 \times 10^3$ years at the beginning of the 21st century (Donis et al., 2017). Similarly, in SNP, the length of FC increased from 45 to 68 years (1750–1950) to 58–80 years (1960–2000)

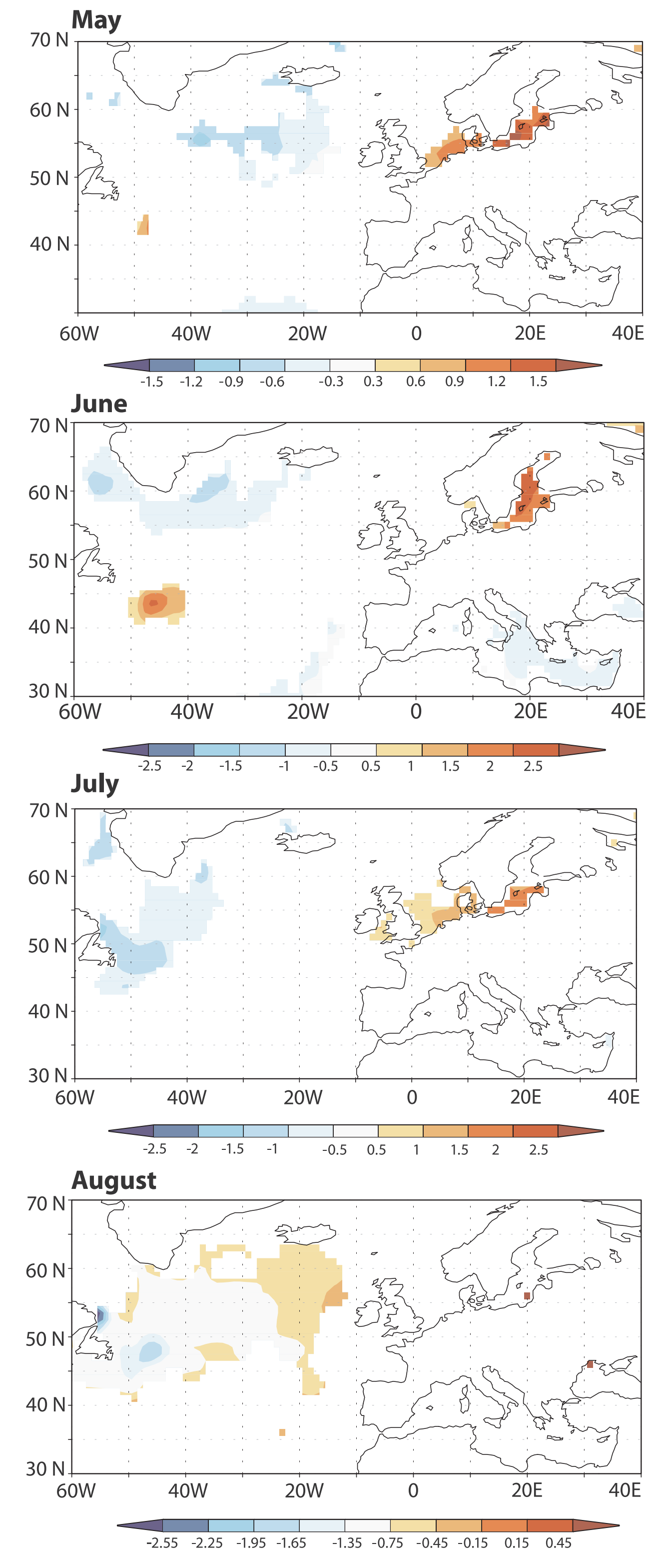


**Fig. 7.** Superimposed epoch analysis of gridded sea surface temperature in the North Atlantic from May to August during the large fire years in Slitere National Park (burned area > 1 $km^2$) over the 1870–2000 period. Colour delineations indicate SST anomalies significant at P < 0.10.

depending on the grid size and the type of area included in the calculation (fire prone section only or the entire area). Observed differences in FC length between the two periods in SNP appear minor, in comparison to Russian Karelia, where the FC increased from 75 years during the 1551–1850 period to ~400 years between1851 and 1950 (Wallenius et al., 2004). Socio-economic changes in Latvia during the 20th century has likely hindered the development of efficient forest governance and fire suppression systems (King and Mcnabb, 2015). This has made the decline in fire activity less dramatic, compared to other parts of Northern Europe and Bialowieza.

We observed high spatial variability in the frequency of fires in the SNP (Fig. 6). The highest risk of fire was observed in the northern and western parts of the study area. Several inter-dune depressions are located north and south of the study area, which were meadows until the 1920s (Abaja, 2011). We assume that the higher fire frequency might be a result of fires escaping from grassland burnings, which were a common soil fertility improvement practice, until the early 20th century (Strods, 1999; Gustiņa, 2016). Similarly, in southern Scandinavia, humans have been shown to facilitate fire activity through intentional burnings prior to the 19th century (Groven and Niklasson, 2005).

Correspondence between socio-economic changes and fire activity observed in the SNP over the centuries and decades extended to the annual scale, with the timing of a single fire which appeared to coincide with socio-political events. A 1905 fire occurred in the year of Russian revolution, when manors, including those of Baltic German landlords, were commonly destroyed by arson fire (Raun, 2006). In that year, many forest fires were recorded in Dundaga parish (Fig. 1B), which included the area of SNP at that time (Wätjen, 1994). Fires during the1940s (during 1940, 1941, 1945) might be related to warfare during the Second World War. Finally, the last fire in 1992 was a result of arson, as reported by J. Jansons, a former inspector in SNP (*personal communication*).

A large proportion of early season fires in the study area also points to human influence on fire activity. Spring and early summer forest fires are linked to field burning, which has been regularly carried out to improve soil fertility at the beginning of the vegetation period (Groven and Niklasson, 2005). In Latvia, grassland burning was a common practice until the early 20th century (Gustiņa, 2016) and fire safely regulations adopted in 1765, indicated that fire escaping from grassland burnings was a common source of forest fires (Strods, 1999). The importance of human-related ignitions during early-season fires is indirectly supported by the analysis of lightning patterns in the area. In coastal regions, lightning activity in the spring and first half of summer is low, because the Baltic Sea surface is cold and upward moving airflows are weak, hindering the formation of thunderstorms (Enno et al., 2013). This suggests that lightning-initiated forest fires in the coastal area at the beginning of the vegetation season were rare, if not implausible.

A climatic explanation of fire regime shifts in the middle of the 20th century appears unlikely, since this period lacks significant changes in precipitation or mean temperature, as well as in the frequency of extreme weather events (Lizuma et al., 2010; Tammets and Jaagus, 2013; Jaagus et al., 2014; Briede, 2016). However, years with fire activity in Latvia have been shown to be closely associated with atmospheric drought and high fire danger indices (Donis et al., 2017), which points to the climate as an important factor influencing fire activity in the study region. Exceptional conditions have been also recorded in 1826 and 1914, which are two large fire years in SNP. The summer of 1826 has been reported as being extremely hot and dry, with many large forest and peatland fires being common in Latvia (Ebenhards, 2016). July 1914 has been recorded as one of the warmest months in the country during the 20th and 21st centuries (Briede, 2016). The last large fire event in SNP in 1992 occurred after a prolonged drought period (21 days without rain, Latvijas vides, 1992). This was a prominent fire year in all three Baltic countries (Schmuck et al., 2015), exemplifying the effect of climatic forcing on regional fire activity (Drobyshev et al., 2014; Aakala et al., 2017).

### *4.2. Relationship between fire severity and historical fire occurrence*

A substantial spatial variability of the 1992 burn severity (Fig. 6) was not correlated to the fire frequency at the grid cell level. Low correlation between posterior mean spatial frailties and 1992 burn severity (Suppl. section A) supported the notion of a more complex relationship between disturbance legacies and burn severity. A study from northern Sweden has suggested that the lack of suitable surface fuels can limit fire spread up to 20 years following the previous fire (Schimmel and Granström, 1997). The 1992 fire occurred in SNP after an almost 50-year period with no fires. We speculate that the recovery of ground fuels over this period removed the potential effect of past fire frequency on fuel amounts. The shortest point-scale estimates of fire return interval suggested that fuel build-up in SNP is closely linked to the shrub layer composition, which can sustain fire spread for six years following the previous fire.

### *4.3. Relationships of fire regime and SST*

We observed a positive relationship between fire activity in SNP and the average SST in the Baltic Sea and North Sea during June and July (Fig. 7). The Baltic Sea is a relatively shallow, semi-enclosed brackish sea, with limited water exchange with the Atlantic Ocean. Consequently, the Baltic Sea SST is strongly influenced by regional air–sea interactions, especially in the summer (Stramska and Bialogrodzka, 2015; Høyer and Karagali, 2016; Jakobson et al., 2017). There is a strong correlation between mean air temperature and the Baltic SST (Stramska and Bialogrodzka, 2015). The positive correlation between fire activity and mean monthly SST of the Baltic and the North Seas likely reflects dependence of both processes on the presence of a high-pressure cell developing during the summer time and leading to the drying of the forest fuels and warming up of the SST (Høyer and Karagali, 2016). The weather pattern in the Baltic Sea region is strongly influenced by westerlies in the autumn and winter. However, in the summer their strength weakens, and the meridional circulation systems become increasingly more important (Jaagus et al., 2010; Helama et al., 2018). High pressure systems and meridional circulation with northerly airflow have been linked to dry weather conditions in the Baltic Sea region (Jaagus et al., 2010; Klavins and Rodinov, 2010) that dry fuels and increase the forest fire hazard (Donis et al., 2017). High pressure systems are also related to atmospheric blocking episodes, which can last from few days up to few weeks and have been suggested as one of the main factors affecting precipitation distribution in Europe during summer (Ionita et al., 2015). In areas of the direct influence of atmospheric blocking, precipitation amounts can decrease more than two times (Sousa et al., 2017). Our results indicate that both fire activity in SNP and the SST of the Baltic and the North Seas are strongly influenced by the position and persistence of high-pressure systems in Northern Europe during the summer.

We also observed a significant, yet spatially varying, negative association between SNP fire activity and the North Atlantic SST (Fig. 7), indicating a similar teleconnectivity pattern observed in an earlier study of Northern Scandinavian fire activity (Drobyshev et al., 2016). The cooling of the western North Atlantic has been suggested as moving westerly wind tracks into more southerly positions, ultimately making Northern Europe drier during the summer season. The less strong spatial pattern observed in this study is likely due to the fact that this analysis was based on a single site, rather than a region-wide synthesis (Drobyshev et al., 2016).

### *4.4. Management implications*

A knowledge of the SNP fire history is valuable in a larger geographical context, since it helps to define the long-term goals of nature-based management guidelines in the hemiboreal zone in Europe. In SNP, frequent fires were the dominating disturbance feature over the past 250 years, shaping stand dynamics, structure and species distribution. Strong human influence on past fire regime suggests, however, that the estimates of historical fire cycles and fire return intervals over that period cannot be viewed as a reference representing natural (human-free) variability in disturbance extend and frequency.

Future management of SNP may consider using prescribed burnings with their frequency, spatial extent and severity, depending on the set goals of the nature protection policy. Prescribed surface burns can be a valuable management tools to promote pine regeneration (Kuuluvainen and Rouvinen, 2000; Marozas et al., 2007). Encroachment of spruce currently occurs in more mesic section of SNP, which escaped the 1992 fire (Brumelis et al., 2005). This pattern implies that a prolonged absence of fire leads to changes in forest species composition towards more shade-dominant vegetation, as observed in Fennoscandia and Belowieza (Niklasson and Drakenberg, 2001; Niklasson et al., 2010a, 2010b; Zin et al., 2015). Without fire intervention, long-term pine stands can probably dominate only on dry and nutrient-poor soils, where spruce establishment is obstructed by unsuitable soil conditions (Sutinen et al., 2005; Wallenius et al., 2010). Prescribed burns can also be important to create fresh deadwood, which is an important habitat for fugal (Olsson and Jonsson, 2010) and saproxylic beetles (Hyvärinen et al., 2006).

Potential trade-offs associated with prescribed burns include the loss of valuable pre-fire existing deadwood (Eriksson et al., 2013) and a loss of threatened epiphytic lichens species (Hämäläinen et al., 2014). Careful consideration of these trade-offs is definitely warranted, – particularly due to a limited knowledge of the long-term effects of conservation burns on stand structure and their successional trajectories (Eales et al., 2018).

In addition to their ecological importance, prescribed fires can help minimize the risk of uncontrolled large-scale fire spread, by reducing the amount and continuity of fuels (Angelstam and Kuuluvainen, 2004; Drobyshev et al., 2008). Implementing these conservation and fire risk reduction tools, will require communication among different stakeholders, government and nature protection organisations as well as the engagement of local communities (Eales et al., 2018).

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## Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foreco.2019.03.020.

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# HEIGHT-GROWTH DYNAMICS OF SCOTS PINE (*PINUS SYLVESTRIS* L.) IN BURNED AND CLEARCUT AREAS IN HEMIBOREAL FORESTS, LATVIA

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The aim of this study was to compare medium-term growth dynamics of Scots pine (*Pinus sylvestris* L.) in areas after forest fire and clearcut in different forest types to improve the understanding of post-fire growth of trees in hemiboreal forest zone. The data were collected at four Scots pine dominated forest stands located in northern and central parts of Latvia (56°45´ - 57°40´N; 22°32´-24°98´E) burned or clearcut in 1992, 2004 and 2006; forest types *Vacciniosa, Vacciniosa mel* and *Myrtillosa mel*. In each study site 100m$^2$ and 25 m$^2$ circular plots were placed systematically and height increment of Scots pine were measured. The average height of Scots pine at the age of 8 years was 167±54.2 cm *Vacciniosa* and 230±90.3 cm *Myrtillosa mel*. At the age of 10 years 184+71.1 cm *Vacciniosa mel*, and at the age of 22 years 360±214.1 cm *Vacciniosa*. Our results demonstrated that 8 years after the forest fire mean height of Scots pine was significantly lower in burned areas in comparison to clearcut, but there were no significant differences in mean height of trees 10 and 19 years after forest fire. It indicates, that impact of forest fire on tree growth diminishes over time and in forest types on more fertile soil its effect is more limited than on poor soil. Tree height was notably more variable in all the burned areas in comparison to the control areas.

*Keywords*: forest fire, forest type, height increment.
*Parole chiave*: incendi boschivi, tipo di foresta, altezza incremento.

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## 1. Introduction

Latvia is located in hemiboreal forest zone and its forests cover, according to National forest inventory is 52%. During last decade forestland has been expanding gradually due to afforestation of less fertile and abandoned agriculture land. In 2013 forest sector generated around 6% of country's GDP according to Ministry of Agriculture statistics. There are different kinds of natural disturbances in hemiboreal forests, like forest fires, windthrows, insects and disease outbreaks which are essential elements of ecosystem dynamics. In order to improve post-disturbance silviculture practices it is important to understand how to mitigate negative and use positive effects of these disturbances.

Historically forest fires have been a component of the forest ecosystem dynamics, but at least for the last 3 millenniums main cause of them is human activity. Nowadays forest fire occurrence in hemiboreal forest zone in Europe has declined due to the effective forest fire protection systems.

The number of forest fires varies every year. In last 24 years the total forest area burned per year in Latvia vary from 90 ha in year 2012 to 8412 ha in 1992, on average every year in Latvia fire affects 1083 ha of forest land according to Latvian State Forest statistics. In year 2013 93% of all forest fires were human caused. Moreover notably more fires occur around urban areas, for example, 22% of all forest fires in 2013 occurred close to capital city Riga (Leisavnieks, 2013). Similar situation has been observed across northwest Europe: the majority of forest fires is caused by humans and located in vicinity of cities (Hille and den Ouden, 2004). According to the climate-change scenarios, a rise of the mean temperature 2.5 °C in the territory of Latvia until the end of the century is expected, meanwhile the increase of rainfall will be minimal, causing prolonged periods of drought (Aigars *et al*., 2009). This situation will inevitably lead to increase in frequency of years with very high fire risk (calculated based on Nesterov index and Canadian Forest Fire Weather Index) as well as in days per year with very high fire risk. Very high fire risk indicates both high flammability of organic material (litter, duff etc.) as well as high temperatures during the fire, thus increasing fire likelihood of forest fire to initiate as well as its severity. In future in Latvia higher forest fire risk are mainly expected in forest types on poor and dry soils where the dominant tree species mostly is Scots pine. Scots pine is categorized to withstand moderate severity fire (Granströem, 2001). It is important to understand post-disturbance stand development dynamics in order to find most suitable stand regeneration methods in future.

Therefore aim of this study was to compare medium-term growth dynamics of Scots pine (*Pinus sylvestris* L.) in areas after forest fire and clearcut in different forest types.

## 2. Materials and methods

*2.1 The study area*

The study area is located in northern and central parts of Latvia (56°45´- 57°40´N, 22°32´-24°98´E). The average annual temperature in territory of Latvia is +5.9 °C, on average July is the warmest month with the average temperature is +17.0 °C, the coldest months of the year are January and February with the average temperature from – 4.6 to – 4.7 °C. The mean amount of precipitation annually is 667 mm. The months with the most of precipitation on average 78 mm are July and August. The months with the lowest amount of precipitation on average 33 mm are February and March according to Latvian Environment, Geology and Meteorology Centre statistics**.**

*2.2 Data sampling and data analysis*

The data were collected in four Scots pine (*Pinus sylvestris* L.) dominated forest stands in summer and autumn in 2014. In all sites has been recorded high severity- stand replacing forest fire, followed by salvage clearcutting. Sites were regenerated by planting in year 1992 (Slitere, *Vacciniosa* forest type), 2004 (Ugale, *Vacciniosa mel*. forest type) and 2006 (Jaunjelgava and Dalbe, *Vacciniosa* and *Myrtillosa mel*. respectively). Clearcut area of the same year and forest type, regenerated by Scots pine, located close to the respective site were chosen as comparison.

At each study site 100 $m^2$ and 25 $m^2$ circular plots were placed systematically and height increment of Scots pine, Silver birch (*Bentula pendula* Roth.), Norway spruce (*Picea abies* L.) and Trembling aspen (*Populus tremuloides*) was measured. Student's T-test was used to assess significant differences between areas after forest fire (further in text referred as burned) and control areas.

## 3. Results

The average height of Scots pine at the age of 8 years was 167±54.2 cm (mean±SD) in *Vacciniosa* forest type and 230.4±90.3 cm in *Myrtillosa mel* forest type. At both sites mean height of Scots pine was significantly higher ($p$=0.001) in the control areas than in the burned areas (Tab. 1). The difference between burned and control areas was from 25 to 36 cm, higher height difference were found in forest type on poorest soil (*Vacciniosa*). At these sites also the Scots pine height increment of the last 3 years demonstrated similar tendency i.e. gradual increase of height difference between burned and control areas (Fig.1. A, B). At age of 10 years in *Vacciniosa mel* forest type no significant ($p$>0.1, $\alpha$=0.05) height differences between control and burned areas was observed, however, it is a results of changes during last years, since at the age 7 years pines were significantly higher in the burned areas than in control (Fig. 1 C).

At the age of 19 years in *Vacciniosa* forest type no significant height differences between burned and control areas ($p$=0.76, $\alpha$=0.05) was observed (Fig. 2). Moreover there was no significant height differences between burned and control areas in the last two years.

Scots pine height was clearly more variable in all the burned areas compared to control areas. At burned areas variation coefficient ranged from 32-59%, but in control areas from 29-50 % respectively (Tab. 2).

The highest Scots pine height variability observed in *Vacciniosa* forest type at age of 19 years in burned area was 59% but in control –50%. The most even distributed height of Scots pine is observed in *Vacciniosa* forest type at age of 8 years in burned areas 32 % but in control areas 29%. Density of Scots pines was notably and significantly higher in burned areas in comparison to clearcuded in both sites in *Vacciniosa* forest type and lower in *Vacciniosa mel.* forest type; density of other tree species (birch, aspen, spruce) was significantly higher in clearcuted sites only in tow oldest areas (Ugale and Slitere). Plot-mean level correlation between density of other tree species and density Scots pine varied widely, but was not significant in any of the sites (Tab. 2).

## 4. Discussion

Number of studies has analyzed post-fire regeneration and short-term growth trends. For example, positive effect of forest fire on Scots pine regeneration is reported by Hille and den Ouden (2004): they found that Scots pine recruitment in *Oxalio-Myrtillo-Cultopinetum sylvestris* forest sites was more successful and height significantly higher after medium severity fires than after soil scarification in clearcut areas in Germany. Similarly, in Lithuania regeneration of Scots pine in first 4 years after low intensity fire in *Vaccinium* forest type was more successful than in control areas, although height increment wasn't measured in this study (Marozas *et al*., 2007). However, there is very limited number of studies covering medium-term impact of forest fire on tree growth that is the object of our study. Our results demonstrate that after the fire growth of Scots pine is significantly slower at age of 8 years in *Vacciniosa* and *Myrtillosa mel* forest types, but at age of 10 and 19 years no significant mean height differences were observed at burned and clearcut areas in *Vacciniosa mel* and *Vacciniosa* forest types. In Canada study results shows that in black spruce stand height differences between burned and clearcut area disappear at age 50 years on sandy loam soils (Ruel *et al*., 2004). Negative effect of forest fire on tree growth, decreasing over time, is linked to its impact on soil. During high severity forest fire large part of organic matter is consumed, soil characteristics i.e. porosity and structure are degraded (Certini, 2005) and root system and mycorrhizas are damaged (Hille, 2006). Also significant loses from forest floor of K and N have been observed at young stands after forest fire, while no significant loss of soil nutrients were observed after clearcut harvesting (Simard *et al*., 2001). The higher height difference between burned and control areas was found in *Vacciniosa* forest type at age of 8 years. On average in non-disturbed *Vacciniosa* (poor sandy soil) forest floor humus layer is 5 cm thick, while in *Myrtillosa mel* (sandy loam soil) humus layer is around 20 cm. It could explain the higher absolute and relative tree height differences between burned and clearcut areas observed in Vacciniosa in comparison to

*Myrtillosa mel.*: effect of forest fire on thinner humus layer could be more degrading and soil nutrient leakage is more intense from sandy soils than from sandy loam soils. In *Vacciniosa mel* forest type with relative thick humus layer (20 cm on average) all organic material may not be consumed also during high intensity forest fire and could therefore explain, why no significant height differences are observed for Scots pine at the age of 10 years between burned and clearcut areas in this forest type. Negative effect of forest fire on soil (total mass of organic carbon, extractable Ca, P and pH), lasting longer than the age of trees of in our study (for 21 years) was found in boreal forest zone (Simard *et al*., 2001). Sooner disappearing impact of forest fire in our study could be explained by differences of climatic conditions (as the nutrient cycling and accumulation of organic matter is faster in hemiboreal or nemoral, than in boreal zone) or forest type. Scots pine and other tree species density in our study varied significantly between treatments and sites; moreover we did not find significant correlation between Scots pine density and other tree species densities. Tree densities at commercial stands are mainly influenced by timing and intensity of thinning (not known in our study sites) therefore we cannot attribute observed differences to influence of forest fire. Stand-development following fire disturbance primarily depends on the fire severity and the scale of damage to the ecosystem (Hille, 2006). Scots pine height variation was higher at burned sites compared to control areas. Similar results have been observed by Taylor *et al*. (2013) in boreal forests and these differences can be explained by different spatial heterogeneity of forest fire severity which is affected by stand composition and fuel load (Kafka *et al*., 2001) weather conditions and topography (Taylor *et al*., 2013).

This heterogeneity affects humidity, soil moisture and temperature, crucial for early development stages of trees (Hille and den Ouden, 2004) as well as nutrient availability, important to boost tree growth. Patches of lower fore intensity might even have had a positive influence on availability of soil minerals and eliminate plant competition (Certini, 2005), therefore boosting growth of particular trees.

Therefore further studies shall include soil- analysis to improve the understanding of the causes of observed Scots pine height differences and cover higher number of sites and sample plots to address the impact of heterogenity and better reveal the medium-term impact of forest fire.

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Table 1. Tree height in stands after forest fire and clearcut.

| *Site Forest type* | *Treatment* | *Mean height of Scots pine (cm)* | *SD (cm)* | *Mean height of birch, aspen, spruce tree species (cm)* | *SD (cm)* |
|---|---|---|---|---|---|
| Jaunjelgava *Vacciniosa* | Burned | 167 | 54.2 | 147 | 83.3 |
| | Control | 202 | 57.9 | 165 | 151.6 |
| Dalbe *Myrtillosa mel* | Burned | 230 | 90.3 | 146 | 64.2 |
| | Control | 254 | 85.9 | 125 | 52.1 |
| Ugale *Vacciniosa mel* | Burned | 184 | 71.1 | 78 | 44.8 |
| | Control | 192 | 69.4 | 117 | 64.9 |
| Slitere *Vacciniosa* | Burned | 360 | 214.1 | 75 | 53.8 |
| | Control | 356 | 179.1 | 119 | 71.9 |

SD - standard deviation
*differences between burned and clearcuted sites statistically significant

Table 2. Variation of Scots pine height at burned and control sites.

| *Sites* | *Treatment* | *Coefficient of variation* | *Scots pine ha$^{-1}$* | *Birch, aspen, spruce trees ha$^{-1}$* | *Correlation* |
|---|---|---|---|---|---|
| Jaunjelgava *Vacciniosa* | Burned | 32% | 2829* | 2800 | 0.10 |
| | Control | 29% | 3815 | 5070 | 0.21 |
| Dalbe *Myrtillosa mel* | Burned | 39% | 3174 | 3076 | -0.06 |
| | Control | 34% | 2995 | 2633 | -0.16 |
| Ugale *Vacciniosa mel* | Burned | 39% | 2820* | 565* | -0.34 |
| | Control | 36% | 2008 | 3602 | -0.29 |
| Slitere *Vacciniosa* | Burned | 59% | 1918* | 1362* | 0.09 |
| | Control | 50% | 4457 | 6811 | 0.64 |

Correlation-plot mean correlation between density of Scots pine and density of other tree species

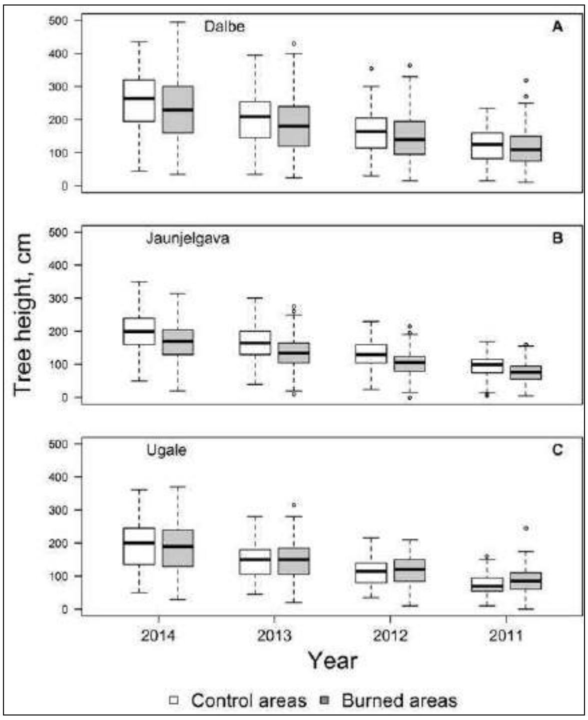


Figure 1. Average height of Scots pine at the age of 5 to 8 years in *Myrtillosa mel* (A) and *Vacciniosa* (B) forest type and at age of 7 to 10 years in *Vacciniosa mel* (C) forest type.

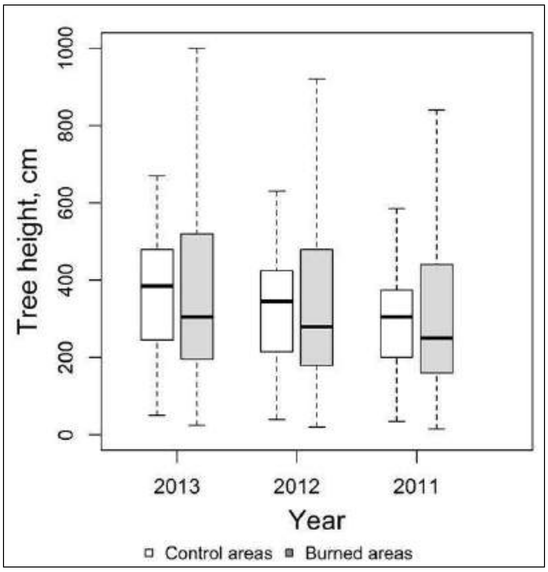


Figure 2. Average height of Scots pine at the age of 17 to 19 years in *Vacciniosa* forest type.

**RIASSUNTO**

**La dinamica della crescita in altezza del pino silvestre (*Pinus sylvestris* L.) nelle aree bruciate e in quelle disboscate a taglio raso delle foreste emiboreali, Lettonia**

L'obiettivo di questo studio era quello di comparare la dinamica di rigenerazione e crescita di lungo periodo del pino silvestre (*Pinus sylvestris* L.) nelle aree bruciate e in quelle disboscate a taglio raso per migliorare la comprensione delle conseguenze a lungo termine dell'incendio boschivo nella zona delle foreste emiboreali.
I dati sono stati raccolti in quattro soprassuoli forestali dominati da pino silvestre situati nelle parti settentrionali e centrali della Lettonia (56°45′ - 57°40′N; 22°32′-24°98′E), bruciati o disboscati a taglio raso nel 1992, 2004 e 2006; tipi forestali: *Vacciniosa, Vacciniosa mel* e *Myrtillosa mel*.
In ogni area di studio sono stati localizzati in modo sistematico i plot circolari di 100 m$^2$ e di 25 m$^2$ ed è

stata misurata la crescita in altezza del pino silvestre. Il test T è stato usato per stimare differenze significative tra le aree bruciate e quelle di controllo. L'altezza media del pino silvestre all'età di 8 anni era 167±54.2 cm (media ± DS) – *Vacciniosa* e 230±90.3 cm – *Myrtillosa mel*. All'età di 10 anni: 184+71.1 cm – *Vacciniosa mel*, e all'età di 22 anni: 360±214.1 cm – *Vacciniosa*. I nostri risultati hanno dimostrato che 8 anni dopo l'incendio boschivo l'altezza media del pino silvestre era significativamente più bassa nelle aree bruciate rispetto a quelle disboscate a taglio raso. Comunque 10 e 19 anni dopo l'incendio boschivo non abbiamo constatato differenze significative dell'altezza media del pino silvestre tra le aree bruciate e quelle di controllo. Ciò potrebbe indicare che l'importanza delle conseguenze dell'incendio col passare del tempo sta cambiando. Inoltre l'altezza dell'albero era notevolmente più variabile in tutte le aree bruciate che nelle aree di controllo.

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# Effect of salvage logging and forest type on the post-fire regeneration of Scots pine in hemiboreal forests

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## ABSTRACT

In post-disturbance areas, salvage logging is a common management practice that can negatively affect ecosystem services and alter successional pathways of natural regeneration. In this study, we aim to investigate the effects of salvage logging in post-fire areas on the regeneration and height of Scots pine (*Pinus sylvestris* L.) on dry-poor, wet-poor, and peat soils. We used the Poisson generalised linear mixed-effects model and linear mixed-effect model to assess the effects of salvage logging on the abundance and height of Scots pine. In all forest types in post-fire areas, Scots pine and birch (*Betula pendula* Roth and *Betula pubescens* Ehrh.) were the most common tree species, accounting for 70% to 100% of the total regeneration abundance. Salvage logging resulted in significantly higher abundance of Scots pine only on mesic-peat soil. Mean height of Scots pine was significantly lower in stands with larger abundance of remnant living trees. In our study, we did not find conclusive evidence of negative effects of salvage logging on the abundance and height of Scots pine.

KEYWORDS: Scots pine, natural regeneration, salvage logging, fire disturbance

## INTRODUCTION

In Europe, forest fires have been an integral part of Scots pine (*Pinus sylvestris* L.) dominated forests, altering successional pathways and stand dynamics (Granström 2001; Bowman et al. 2009). The majority of forest fires in European temperate, hemiboreal, and boreal forests have low- to moderate-severity (Gromtsev 2002; Wallenius et al. 2002; Zin et al. 2015;), causing partial mortality of the canopy layer (Östlund et al. 1997; Kuuluvainen et al. 2002). In post-fire areas, biological legacies (remnant living/dead trees) are a vital part of forest ecosystem resilience, as they facilitate ecological recovery (Seidl et al. 2014; Jõgiste et al. 2017). In post-fire areas, living remnant trees provide seeds and create a favourable microclimate for seedling establishment (Vanha-Majamaa et al. 1996; Moser et al. 2010), but can compete with regenerating trees for light and nutrient resources, causing a negative effect on their abundance and height growth (Kuuluvainen et al. 1993; Parro et al. 2015). Dead retained trees can reduce evaporation (Moser et al., 2010) and create suitable microsites for regeneration (Vanha-Majamaa et al. 1996; Kuuluvainen and Kalmari 2003).

Salvage logging (SL) is a silvicultural practice when damaged trees are removed from disturbed forest areas. The key motivation of SL may vary from case to case depending on the disturbance type and forest protection regime, but there are several reasons for its use: economic reasons, pest control, safety issues, fuel reduction, and restoration (Nieuwenhuis and Fitzpatrick 2002; Fraver et al. 2011; Havašová et al. 2017; Bodaghi et al. 2018; Kärhä et al. 2018; Müller et al. 2019). Moreover, SL in post-disturbance areas creates interactions between effects of two consecutive disturbances in a short period, which can have negative ecological effects (Thorn et al. 2017; Leverkus et al. 2018). In addition, SL alters the ground microtopography (Waldron et al. 2013), nutrient cycling (Smith et al. 2012), and successional pathways of natural regeneration (Beghin et al. 2010). Studies have shown that SL can have a negative effect on water quality (Smith et al. 2012), soil (Page-Dumroese et al. 2006; García-Orenes et al. 2017; Malvar et al. 2017;), natural regeneration (Beghin et al. 2010; Boucher et al. 2014; Parro et al. 2015), and biodiversity (Thorn et al. 2017; Leverkus et al. 2018). Similarly, SL can negatively affect ecosystem services (Lindenmayer and Noss 2006) and increases carbon dioxide ($CO_2$) emissions (Serrano-Ortiz et al. 2011).

In dry areas, forest fires occur more frequently than on wet or peat soils; however, after prolonged periods of drought, many waterlogged areas dry out and become fire-prone environments (Granström 2001; Hellberg et al. 2004; Gustafsson et al. 2019). In Northern Europe, the effects of fire have been studied in poor and dry growth conditions (Lampainen et al. 2004; Castro et al. 2004; Parro et al. 2015), but information on natural regeneration after fire on wet and peat soils is limited. Therefore, the aim of the study was to assess the influence of post-fire management type (no intervention and SL) on natural generation of Scots pine and other tree species in five different forest types (*Cladinoso-callunosa*, *Vacciniosa*, *Vaccinoso-sphagnosa*, *Sphagnosa*, and *Caricoso-phragmitosa*). Considering the negative effects of SL on soil compaction and erosion (García-Orenes et al. 2017; Malvar et al. 2017) and the regeneration of Scots pine on poor and dry soils (*Vaccinium uliginosum*, *Calluna* sites types) and entisols in the Alps (Beghin et al. 2010; Parro et al. 2015), we hypothesised that abundance and height of Scots pine would be lower on all types of soil after SL, in comparison with regeneration in non-intervention areas.

## METHODS

### *Study Area*

The study area is located in Slītere National Park (SNP) in the north-western part of Latvia in the hemiboreal forest zone (Ahti et al. 1968) (Fig.1). The landscape of SNP is a unique inter-dune peatland complex of the coastal area of the Baltic Sea, which began to form from 7500–4000 BP when the sea level decreased (Kalnina et al. 2015). The sandy dunes stretch parallel to the coastline of the Baltic Sea, and the largest of the sandy dunes reaches up to 15 km in length and 50 m in width. The sandy dunes are predominantly covered by Scots pine-dominated forests (Seile and Reriha 1983). Old forest inventory plans from the 1970s show that the studied landscape was mainly dominated by pine (more than 90% of the stands). Over the last 5000 years, peat has accumulated in depressions between sandy dune ridges, creating transitional mires and raised bogs (Pakalne and Kalnina 2005). On sandy dune ridges, the ground vegetation layer is dominated by ericaceous dwarf shrubs (*Calluna vulgaris* L.), but in drier sites, lichens (*Cladonia* spp.) or mosses (*Dicranum* spp.) dominate (Seile and Reriha 1983).

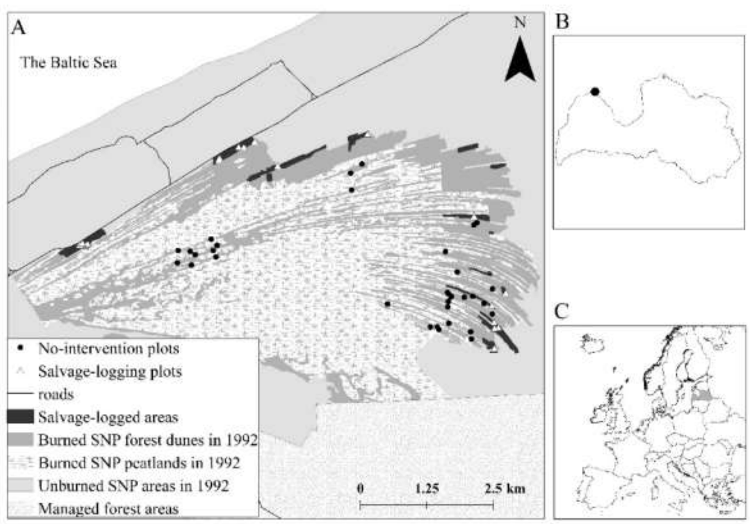


Figure 1. A -location of sample plots in Slītere National Park. Each sample plot character shows a forest compartment where 10 sample plots were placed.

Over the last 250 years, fire has been a common disturbance in pine-dominated forests in SNP, with a relatively short fire cycle of 45 to 80 years, which has been strongly influenced by the socio-political situation in this region (Kitenberga et al. 2019). Presumably, the high frequency of forest fires in the past has maintained the dominance of pine in this landscape (Brumelis et al. 2005; Kitenberga et al. 2019).

The last large fire in the SNP area occurred at the beginning of July in 1992 after a prolonged period of drought, when a total of 3100 ha burned, of which 1032 ha were forested (Donis 1995). The fire severity was high in the northern and eastern sides of the burned area, where tree mortality in the canopy layer reached 80% to 100%, compared to 0% to 40% on the western and southern sides (Kitenberga et al. 2019). The largest part of the burned area (~95%) remained without any silvicultural management due to the nature protection status of SNP. Economic reasons were the main motivation for SL in a part of the stands, which was conducted in autumn of 1992. Several places with a mean size of 3.7 ha, ranging from 0.2 to 10 ha were salvage logged in burned areas nearby roads (Fig. 1). In the two largest SL areas (approximately 10 ha), 5 to 10 retention trees were left per hectare. The shape of the SL areas was largely determined by the topography of the sandy dunes; hence, the majority of SL areas were rather long (200 to 1500 m) and narrow (width 20 to 160 m) (Fig. 1). The trees were cut using chainsaws, and logging slash was retained. The logs were skidded using rubber-tyre tractors, which could pull one to two logs at the same time.

Two studies with the aim to investigate the natural regeneration pattern were previously conducted in the 1992 burned areas of SNP, respectively two years (Donis 1995) and seven years following the fire (Zadina et al. 2014). The sampling plot coordinates of these two studies have not been preserved, prohibiting the opportunity to carry out repeated measurements.
The climate conditions in the study area are strongly influenced by the Baltic Sea. The long-term (1960–2010) mean annual air temperature is +6.4°C. The coldest month is February (mean temperature is -2.9°C), and the warmest months are July and August (+16.5°C and +16.2°C, respectively). The mean precipitation is 606 mm. Length of the vegetation period (diurnal temperature exceeds 5°C ) is approximately 194 days (Avotniece et al. 2017).

*Sampling Design*

In the area affected by the 1992 fire, we randomly selected non-intervention areas in the pool of stands having basal area of undamaged trees < 6 $m^2$ $ha^{-1}$. We similarly selected SL areas. For both management types, we placed sampling plots along the longest axis of the selected areas. The studied plots included five forest site types (Bušs 1976): (1) dry and poor mineral soil *Cladionoso-callunosa* (*CCT*), (2) dry and less poor mineral soil *Vacciniosa* (*VT*), (3) wet and poor mineral soil *Vaccinoso-sphagnosa* (*VST*), (4) poor peat *Sphagnosa* (*ST*), and (5) medium-fertility peat *Caricoso-phragmitosa* (*CPT*) (Table 1). The size of the sampling plots was 25 $m^2$ ($r$ = 2.82 m). The sampling was performed in the summer of 2014. In total, we placed 196 plots in SL and 323 plots in non-intervention areas (Fig. 1, Table 2). In sampling plots, all trees (height > 30 cm) were identified by tree species, and the height was measured using a survey-grade rod. Large living trees within a 10-m radius from the outer margin of the sampling plot were identified.

Table 1. Description of forest site types according to the Latvian forest classification (Bušs 1976). Notes: * I: highest bonity site index (the most productive sites); V: lowest site index (the poorest sites)

| Forest site types | Soil composition | Soil moisture regime | Dominant tree species | Site index* (bonity class) | Dominant ground vegetation |
|---|---|---|---|---|---|
| *Cladinoso-callunosa* (CCT) | poor podzol quartz sand | dry | Scots pine | IV-V | *Calluna vulgaris*; *Vaccinium vitis-idaea*; *Cladina spp*; |
| *Vacciniosa* (VT) | poor podzol quartz sand | dry | Scots pine | III | *Vaccinium vitis-idaea; Vaccinium myrtillus; Calluna vulgaris; Pleurozium schreberi* |
| *Vaccinoso-sphagnosa* (VST) | poor podzol quartz sand | seasonally saturated with water | Scots pine | IV | *Sphagnum; Vaccinium vitis-idaea; Vaccinium uliginosum; Vaccinium myrtillus* |
| *Sphagnosa* (ST) | poor *Eriophorum-sphagnum* peat | wet | Scots pine, rarely silver birch | V | *Sphagnum; Calluna vulgaris; Oxycoccus palustris; Eriophorum spp* |
| *Caricoso-phragmitosa* (CPT) | medium rich *Carex*-wood peat | wet | Scots pine, silver birch, and downy birch | III | *Sphagnum; Carex spp; Phragmites spp; Calamagrostis spp* |

Table 2. Number of sampling plots per management type and forest site type, and number of regenerating trees according to forest site type, management type, and species.

| Forest site type | Number of plots per soil type | | Tree species | Number of trees | |
|---|---|---|---|---|---|
| | No intervention | Salvage logging | | No intervention | Salvage logging |
| *Cladionoso-callunosa* | 109 | 40 | Scots pine | 1336 | 548 |
| | | | birch | 158 | 81 |
| | | | Norway spruce | 16 | 1 |
| *Vacciniosa* | 50 | 100 | Scots pine | 979 | 1691 |
| | | | birch | 344 | 877 |
| | | | Norway spruce | 10 | 43 |
| | | | trembling aspen | 3 | 5 |
| | | | black alder | 36 | 33 |
| | 64 | 36 | Scots pine | 1345 | 903 |

| | | | | | |
|---|---|---|---|---|---|
| *Vaccinoso-sphagnosa* | | | birch | 620 | 890 |
| | | | Norway spruce | 35 | 74 |
| | | | black alder | 4 | 43 |
| *Sphagnosa* | 70 | 10 | Scots pine | 1565 | 204 |
| | | | birch | 1260 | 432 |
| | | | Norway spruce | 6 | |
| | | | black alder | 1 | |
| *Caricoso-phragmitosa* | 30 | 10 | Scots pine | 54 | 136 |
| | | | birch | 355 | 298 |
| | | | Norway spruce | 6 | |
| | | | black alder | 157 | |

*Statistical Analysis*

To assess the effects of the stand parameters and post-fire management type on the abundance of naturally regenerating Scots pine, we employed a Poisson generalised linear mixed-effects model (GLMM). The initial GLMM model was Number of Scots pine = Forest site type + Management type + Number of remnant trees + Remnant pines + Spatial covariate + Forest site type: Management type + Forest site type:Number of remnant trees + Forest site type:Remnant pines + (1|Compartment/Sampling plot/Tree ID). We used a linear mixed-effect model (LME) to assess the effect of different variables on the mean height of Scots pine. Tree height was log-transformed to minimise the heteroscedasticity effects. The initial LME model was log(height of Scots pine) = Forest site type + Management type + Number of remnant trees + Remnant pines + Spatial covariate + Forest site type: Management type + Forest site type:Number of remnant trees + Forest site type:Remnant pines + (1|Compartment/Sampling plot). The tested interaction between the factors are identified using colon (:) in both models. Sampling plots were nested in compartments, both of which were used as random effects in the both models to account for possible correlation of observations from the same sampling unit. The observation-level random effect (Tree ID) was added to the GLMM model to cope with overdispersion (Harrison 2014). To account for spatial dependence, we added a distance-weighted spatial autocovariate as a variable in the models. After removing non-significant interaction terms, the final model was chosen using the Akaike information criterion (McGullagh and Nelder 1989). We used the Tukey HSD multiple-comparison test to assess the differences between the levels of significant factors. We used Analysis of Similarity (ANOSIM), which is non-parametric ANOVA-like analysis, to determine significant differences in species composition between natural regeneration under different post-fire managements. The significance of the differences was obtained by performing 999 permutations (Clarke 1993). All calculations were performed in R v.3.5.0 (R Core Team 2018), using the package lme4 (Bates et al. 2015) for the LME and GLMM, the package multcomp (Hothorn et al. 2008) for the Tukey multiple comparisons, the package spdep for the spatial autocovariates (Bivand et al. 2013), and the package vegan (Oksanen et al. 2019) for the ANOSIM.

## RESULTS

### *Regeneration Abundance of Scots Pine and Other Tree Species*

Scots pine and birch (*Betula pendula* Roth and *Betula pubescens* Ehrh.) were the most common tree species in all sampled forest site types and together accounted for 70% to 100% of the total abundance of regenerating tree species (Table 3). Common aspen (*Populus tremula* L.), Norway spruce (*Picea Abies* (L.) H. Karst.) and black alder (*Alnus glutinosa* (L.) Gaertn.) established in low proportion of total abundance, ranging from 0.1% to 6%, except in one non-intervention *Caricoso-phragmitosa* site where black alder constituted 27% of the natural regeneration. Scots pine was the most abundant tree species under both management types in forests on sandy soils (*Cladinoso-callunosa*, *Vacciniosa*, *Vaccinoso-sphagnosa*) (Table 2).

Table 3. Regeneration abundance per ha under the two management types in the post-fire area in Slītere National Park. SD - standard deviation

| | No-intervention | | Salvage-logging | |
|---|---|---|---|---|
| *Forest site type /* Tree species | Mean | SD | Mean | SD |
| *Cladionoso-callunosa* | | | | |
| Scots pine | 4902 | 4483 | 5480 | 4595 |
| birch | 579 | 1373 | 810 | 1168 |
| Norway spruce | 58 | 384 | 10 | 63 |
| *Vacciniosa* | | | | |
| Scots pine | 7832 | 5664 | 6764 | 4322 |
| birch | 2752 | 3721 | 3508 | 3537 |
| Norway spruce | 80 | 255 | 172 | 444 |
| black alder | 288 | 1241 | 132 | 601 |
| trembling aspen | 24 | 125 | 20 | 104 |
| *Vaccinoso-sphagnosa* | | | | |
| Scots pine | 8406 | 5236 | 10033 | 5850 |
| birch | 3875 | 4775 | 9888 | 5725 |
| Norway spruce | 218 | 821 | 822 | 1331 |
| black alder | 25 | 157 | 477 | 875 |
| *Sphagnosa* | | | | |
| Scots pine | 8942 | 5321 | 8160 | 8456 |
| birch | 7200 | 6669 | 17280 | 6015 |
| Norway spruce | 34 | 131 | 0 | 0 |
| black alder | 5 | 47 | 0 | 0 |
| *Caricoso-phragmitosa* | | | | |
| Scots pine | 720 | 745 | 5440 | 1740 |
| birch | 4733 | 4095 | 11920 | 3616 |
| Norway spruce | 80 | 244 | 0 | 0 |

| | | | | |
|---|---|---|---|---|
| black alder | 2093 | 3049 | 0 | 0 |

GLMM showed that post-fire regeneration abundance of Scots pine was significantly affected by site type, spatial covariance, and interactions between site type and management type (Table 4). The highest abundance of Scots pine was observed in SL *Vaccinoso-sphagnosa* (10033 ± 5850 standard deviation (SD)), and the lowest in non-intervention *Caricoso-phragmitosa* (720 ± 745 SD) (Table 3). When we comparted the levels of interaction factor (site type* management type) the only significant ($p < 0.05$) difference between management types was observed in the *Caricoso-phragmitosa* forest site type (Fig. 2).

Table 4. The main effects of explanatory variables and their interaction (*) on the regeneration abundance of Scots pine (Poisson generalised linear mixed-effects model).

| Explanatory Variable | Likelihood Ratio Chi-square | Degrees of Freedom | *p*-value |
|---|---|---|---|
| Forest site type | 50.5 | 4 | < 0.001 |
| Management type | 1.4 | 1 | 0.233 |
| Number of remnant trees | 1.2 | 1 | 0.267 |
| Remnant pines | 2.8 | 1 | 0.09 |
| Spatial covariate | 13.2 | 1 | < 0.001 |
| Site type * Management type | 16.3 | 4 | 0.002 |

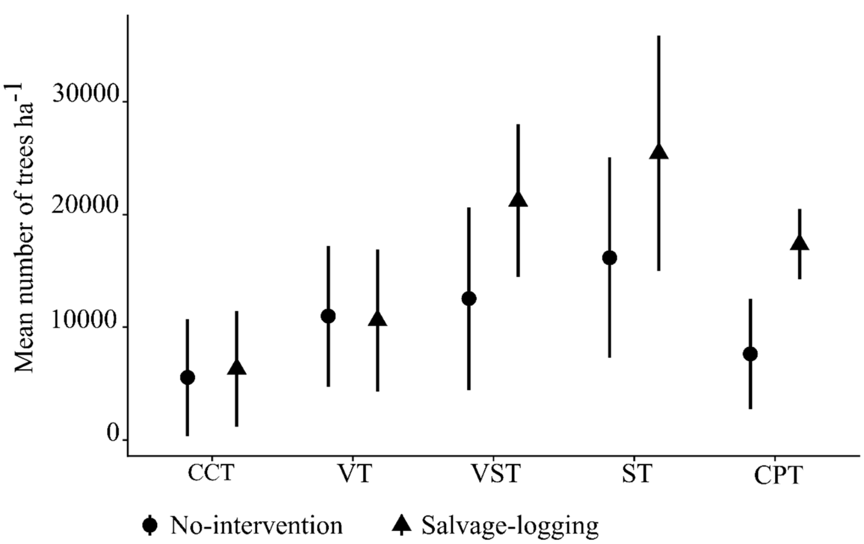


Figure 2. Total regeneration abundance per ha (and standard deviation) under the two management types in a post-fire area in Slītere National Park. Forest site types: (1) CCT: *Cladinoso-callunosa*, (2) VT: *Vacciniosa*, (3) VST: *Vaccinoso-sphagnosa*, (4) ST: *Sphagnosa*, and (5) CPT: *Caricoso-phragmitosa*.

ANOSIM showed that species composition of the naturally regenerated trees significantly differed between post-fire management types in *Vaccinoso-sphagnosa* (stat. *R* =

0.13, *sig* =0.001) and *Caricoso-phragmitosa* (stat. *R* = 0.29, *sig* = 0.006) sites. In *Vaccinoso-sphagnosa* sites, the proportion of birch and black alder was considerably higher in SL areas than in non-intervention areas. In *Caricoso-phragmitosa* sites, the proportion of Scots pine regeneration was considerably higher in SL than in non-intervention areas, while the proportion of black alder was considerably higher in non-intervention than in SL areas. For the other forest site types (*Cladinoso-callunosa*, *Vacciniosa*, and *Sphagnosa*), the differences between management types were not significant.

*Mean Height of Scots Pine and Other Tree Species*

LME showed that the mean height of Scots pine was significantly ($p < 0.05$) affected by the management type, site type, number of remnant trees, presence of remnant pines, spatial covariance, and interactions between factors (site type* number of retained trees and site type* presence of remnant pines (Table 5)). The largest mean height of Scots pine was observed in the *Vacciniosa* forest site type without remnant living pines (3.5 m), and the lowest in the *Sphagnosa* forest site type with remnant living pines (2.1 m) (Fig. 3, Table 6). When we compared the levels of interaction factor site type* presence of remnant pines, the effect of presence of old remnant pines significantly negatively affected the mean height of Scots pine only in *Cladionoso-callunosa* and *Vaccinoso-sphagnosa* site types.

Table 5. The main effects of explanatory variables and their interaction (*) on the log height of Scots pine (Linear mixed-effects model). numDF: numerator degrees of freedom; denDF: denominator degrees of freedom

| Explanatory Variable | Sum of Squares | numDF | denDF | F-value | *p*-value |
|---|---|---|---|---|---|
| Management type | 2.3 | 1 | 42.1 | 12.5 | 0.01 |
| Forest site type | 1.8 | 4 | 127.7 | 2.5 | 0.04 |
| Number of remnant trees | 4.6 | 1 | 475.0 | 25.4 | <0.001 |
| Remnant pine | 1.1 | 1 | 463.3 | 6 | 0.02 |
| Spatial covariate | 2.4 | 1 | 51.3 | 13 | <0.001 |
| Site type * Number of remnant trees | 3.1 | 4 | 465.7 | 4.3 | 0.01 |
| Site type* Remnant pine | 2.5 | 4 | 464.3 | 3.5 | 0.01 |

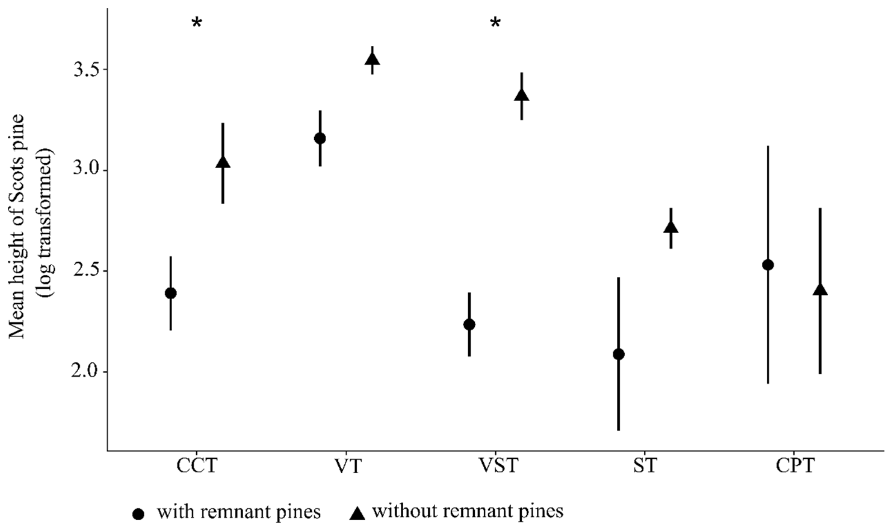


Figure 3. The mean height of Scots pine (log transformed) and 95% confidence interval with and without living remnant pines in a post-fire area in Slītere National Park. * - statistically significant ($p < 0.05$) difference between with/without remnant pines. Forest site types: (1) CCT: *Cladinoso-callunosa*, (2) VT: *Vacciniosa*, (3) VST: *Vaccinoso-sphagnosa*, (4) ST: *Sphagnosa*, and (5) CPT: *Caricoso-phragmitosa*.

Table 6. The mean height of Scots pine and other tree species under the two management types in the post-fire area in Slītere National Park. SD- standard deviation

| *Forest site types* / Tree species | No intervention | | Salvage logging | |
|---|---|---|---|---|
| | Mean | SD | Mean | SD |
| *Cladinoso-callunosa* | | | | |
| Scots pine | 1.7 | 1.4 | 3.3 | 2.2 |
| birch | 1.5 | 1.1 | 1.8 | 1.4 |
| Norway spruce | 0.7 | 0.4 | 0.3 | |
| *Vacciniosa* | | | | |
| Scots pine | 2.7 | 1.4 | 3.5 | 1.9 |
| birch | 2.2 | 18 | 2 | 1.5 |
| Norway spruce | 1.8 | 1.9 | 1.1 | 0.9 |
| trembling aspen | 1 | 0.2 | 1.3 | 0.9 |
| black alder | 2.5 | 1.9 | 1.8 | 1.4 |
| *Vaccinoso-sphagnosa* | | | | |
| Scots pine | 1.6 | 1.1 | 3.2 | 1.8 |
| birch | 1.2 | 0.8 | 1.9 | 1.3 |
| Norway spruce | 0.9 | 0.5 | 1.9 | 1.7 |
| black alder | 1.2 | 0.2 | 4.3 | 2.6 |
| *Sphagnosa* | | | | |
| Scots pine | 1.3 | 0.8 | 2.5 | 0.9 |
| birch | 1.3 | 0.7 | 2 | 1 |
| Norway spruce | 0.9 | 0.5 | | |
| black alder | 1.4 | | | |

| *Caricoso-phragmitosa* | | | | |
|---|---|---|---|---|
| Scots pine | 1 | 0.8 | 2.6 | 1.1 |
| birch | 1.3 | 0.7 | 1.6 | 0.9 |
| Norway spruce | 0.8 | 0.4 | | |
| black alder | 2.2 | 1.4 | | |

Mean height of Scots pine was significantly lower in plots with large numbers of retained trees only for the *Cladinoso-callunosa* (Linear mixed-effects model, slope -0.46, confidence interval (CI) -0.60 to -0.32) and *Caricoso-phragmitosa* (slope -0.40, CI -0.59 to -0.21) site types (Fig. 4). In the model, besides interaction effects, the main effect of management type was also significant (Table 5), in SL areas the mean height of Scots pine was significantly higher than in non-intervention areas.

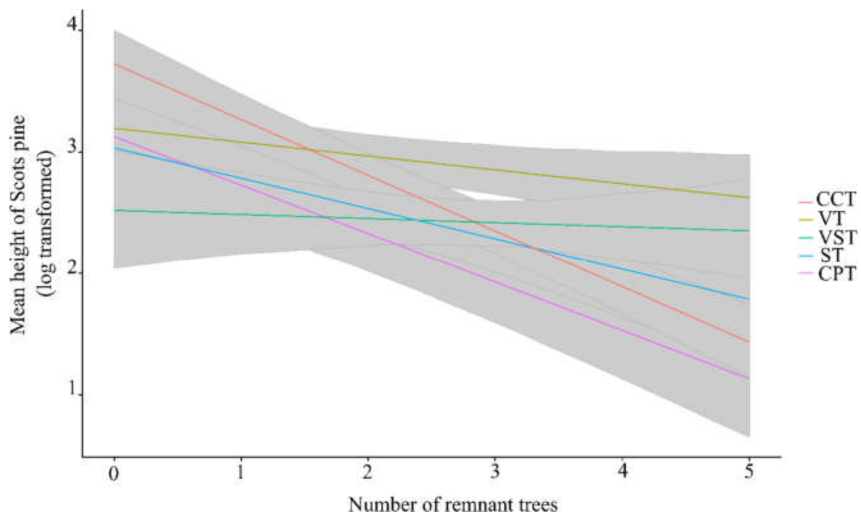


Figure 4. The relationship between the number of remnant trees and the mean height of Scots pine (log transformed) in post-fire area in Slītere National Park (±95% confidence interval (grey area)). Forest site types: (1) CCT: *Cladinoso-callunosa*, (2) VT: *Vacciniosa*, (3) VST: *Vaccinoso-sphagnosa*, (4) ST: *Sphagnosa*, and (5) CPT: *Caricoso-phragmitosa*.

In all forest types in SL areas, mean height of Scots pine exceeded height of birch, whereas in the non-intervention areas the mean height of Scots pine exceeded mean height of birch only in forest types on sandy soils (*Cladinoso-callunosa, Vacciniosa*, and *Vaccinoso-sphagnosa*). In *Sphagnosa* sites, these tree species had similar mean height.

## 4. DISCUSSION

The light-demanding tree species, Scots pine and birch, were the most common tree species in post-fire regeneration areas in our study (Table 3). Both tree species rapidly and abundantly regenerate in open areas following natural or human-made disturbances (Beghin et al. 2010; Hynynen et al. 2009; Parro et al. 2015). The establishment of light-demanding tree species in a post-fire area requires sun-lit conditions and exposed bare mineral soil following the partial or complete mortality of the canopy layer and ground vegetation (Karlsson et al. 1998; Nilsson et al. 2002; Castro et al. 2004; Hille and den Ouden 2004; Claessens et al. 2010; Kitenberga et al. 2019).

The distance from a seed source is a significant factor influencing the regeneration abundance (Vanha-Majamaa et al. 1996; Beghin et al. 2010; Vacchiano et al. 2014). Presumably, the majority of seeds in the upper soil layers were likely destroyed by fire (Vanha-Majamaa et al. 1996; Habrouk et al. 1999); hence, the regeneration of trees depended on unburned patches within the burned area or the nearest seed sources outside the burned area. Studies have shown that Scots pine can survive several low-to medium severity forest fires (Zin et al., 2015). The dispersal distance of Scots pine seeds is limited, < 60 m from the tree (Debain et al., 2007). Hence, the most probable seed sources for Scots pine were individual living remnant trees that survived the fire and the surrounding unburned pine-dominated forests. In contrast, birch seeds are light and can be easily carried long distances by wind (Eriksson et al. 2003; Hynynen et al. 2009). We observed only three living birch trees in the post-fire area, which suggests that the majority of the birch seeds came from nearby forest stands. Although birch can also regenerate naturally from coppice (Perala and Alm 1990), we did not observe such cases in our study area. The fire of 1992 occurred shortly before the seed release of birch (July-September; Suchockas 2002) and hence the birch seeds likely arrived from sources outside of the fire-affected areas.

In the studied landscape, frequent fires have shaped the dynamics of Scots pine-dominated stands over the last 250 years (Kitenberga et al. 2019) by promoting fire-resistant and eliminating fire-sensitive tree species (Brumelis et al. 2005). In particular, the abundance of Scots pine in the post-fire area might have been driven by a high proportion of Scots pine in the pre-fire forest. The direct re-growth of pre-disturbance dominant tree species has also been observed for late-successional tree species (Kramer et al. 2014; Baders et al. 2017).

The post-fire management type did not have a significant influence on the abundance of Scots pine. In contrast, Parro et al. (2015) and Beghin et al. (2010) reported delayed natural regeneration of Scots pine in SL post-fire areas compared to that in non-intervention areas. The effect of fire and SL on tree regeneration depends on various factors like the timing and techniques of SL operations (Keyser et al. 2009) and the fire characteristics (Vacchiano et al. 2014; Dzwonko et al. 2015). We assume that soil scarification created by log skidding may have created suitable microsites for tree species germination (Saursaunet et al. 2018). In our study, SL areas were narrow in shape (width 20–160 m) and surrounded by post-fire areas with living remnant trees or unburned forest, both of which could have served as seed sources (Fig. 1). In addition, in the two largest SL areas, several remnant living pine trees were left as seed trees. Possibly, the positive influence of soil scarification and nearby seed sources can explain why we did not observe effects of SL caused by soil compaction (Malvar et al. 2017) and removal of remnant trees (Seidl et al. 2014).

Salvage logging did not affect the tree species composition on poor and dry soils (*Cladinoso-callunosa* and *Vacciniosa* forest types) and poor peat soil (*Sphagnosa*). In these site types, nutrient deficiency is the main limiting factor for the natural regeneration and survival of tree species (Pretzsch and Dieler 2011; Mellert and Ewald 2014), explaining lack of effect of SL. The growth of birch, trembling aspen, and Norway spruce trees is not optimal on dry and poor sandy soils due to low fertility (Karlsson 1996; Karlsson et al. 1998; Hynynen et al. 2009; Myking et al. 2011). Scots pine, which is adapted to growth in fire-prone environments with a limited amount of available nutrients (Keeley 2012), is the most competitive tree species in these growth conditions, suggested by its large abundance and height under both management types (Table 2; 5). Similarly, on poor peat soil (*Sphagnosa*), the post-fire management did not affect the tree species composition. Scots pine is a common tree species on peat soil, but with a significantly lower growth rate than on mineral soils (Dauškane and Elferts 2011; Edvardsson et al. 2015). On peat and waterlogged mineral soils, the regeneration and growth of trees is hindered by the low availability of nutrients and high water saturation (Ohlson and Zackrisson 1992; Sundström and Hånell 1999; Repo et al. 2017). Downy birch is another tree species that has adapted to the harsh growth conditions on wet peatlands (Hynynen et al. 2009) and is the main competitor for Scots pine in these growth conditions (Table 3).

SL significantly positively affected the abundance of Scots pine only on medium rich peat soil (*Caricoso-phragmitosa*). Among the site types in non-intervention areas, the lowest abundance of Scots pine was observed in the *Caricoso-phragmitosa* site type (Fig. 2). In this forest type, the natural regeneration of Scots pine might be constrained by the strong competition from ground vegetation, especially *Polytrichum* spp., which was a common species especially on slightly burned peat soils following the 1992 burn in SNP (Donis 1995). The study that was conducted two years following the 1992 burn in SNP revealed that the spatial variation of the fire severity was highly variable on peat soils (Donis 1995). A similar pattern was observed in Poland, where the regeneration of trees was hindered by the surviving herbaceous plants on slightly burned muck-peat soil (Dzwonko et al. 2015). We suggest that the positive effect of SL on the abundance of Scots pine in this forest type could be related to soil disturbance and improved light conditions. Partial removal of ground vegetation and mineral soil mixing the with the forest floor could have created favourable conditions for germination and establishment of Scots pine (Kramer et al. 2014; Poirier et al. 2014).

The living remnant trees had a negative effect on the mean height of Scots pine (Fig. 3, 4). On the one hand, in post-disturbance areas, remnant living trees serve as a seed source and help to maintain a favourable microclimate for seedling establishment (Vanha-Majamaa et al. 1996; Lampainen et al. 2004). However, remnant living trees create competition for aboveground and belowground resources (Kuuluvainen et al. 1993; Lundqvist and Fridman 1996; Craine and Dybzinski 2013). The study conducted 7 years following the fire in SNP showed that the mean height of Scots pine was greater in SL than in non-intervention areas (Zadina et al. 2014), as observed in our study. It is likely that height growth of Scots pine in close proximity to remnant trees was hindered by shade and competition for soil nutrients. Other studies have shown that after SL, Scots pine become the dominant tree species earlier than in non-intervention areas (Parro et al., 2015), which most likely is linked to the ability of Scots pine to efficiently acclimate to changes in light conditions with morphological modifications. Under better light conditions, the potential of photosynthesis and the growth rate is promoted by increased needle length (de Chantal et al. 2003; Erefur et al. 2011). Interactions between the studied factors showed that the effect of remnant trees on the height of Scots pine differed between forest site types (Fig. 4), which might be due to differences in distances between the sampling plots and closest remnant trees.

## CONCLUSIONS

In this study, we examined the effect of salvage logging on regeneration and height growth of Scots pine. Salvage logging had an effect on the abundance of Scots pine only on mesic-peat soil (*Caricoso-phragmitosa*). We found that remnant living trees in post-fire areas have a negative effect on height of the regenerating Scots pines. In our study, we did not find conclusive evidence of the negative influence of salvage logging on abundance and height of Scots pine. Further studies need to assess effect of retention tree density on the abundance of regenerating trees.

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