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Integrated effect of environmental changes on forest ecosystems in Lithuania: Strategies for adaptation to and mitigation of the main threats of global climate change

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Abstract

Field-measured forest productivity and its time series are crucial to understanding the impact of climate change on the main tree species increment and stand productivity in general. In this study, the causative relationships between environmental factors, such as O3 fluxes and tree ring width formation, including stem sap flow intensity, in the prevalent Lithuanian tree species (*Picea abies* (L.) *Karst*, *Pinus sylvestris* L., *Betula pendula*, and *Betula pubescens*) growing under different nutritional and moisture conditions in northeastern Lithuania were examined. We hope that this information will help us assess a trees capacity to adapt to and mitigate recent global clima te changes. Continuous monitoring of the tree stem increment from annual to hourly scales was crucial for this study. The obtained data revealed that Norway spruce trees are appropriately adapted to current climatic conditions in temperate forests. Even during a drought episode, spruce stem increment exceeded the increment of the rest of the studied tree species; therefore, they had the highest water use efficiency compared to the rest of the tree species in the study. O3 fluxed through the stomata at an hourly scale, stimulating the stem shrinking process more intensively than inhibiting the swelling process, but only for pine and birch trees. Spruce trees demonstrated the highest sensitivity to O3 because O3 significantly affected the stem swelling process. Pine trees were less sensitive to O3 damage, and birch trees were the least affected. Reduced tree growth intensity and the weak relationship between birch tree radial increment and the main meteorological parameters indicate that birch trees have the lowest adaptive capacity to recent environmental changes of the tree species in this study.

Key words: stem increment; sapflow intensity; meteorology; PAR; ozone flux

Introduction

Researchers have studied the growth of forests under changing environmental conditions during recent decades. Tree-ring width and its formation are appropriate indicators of changes in environmental conditions and are a proxy for ecosystem health. Climate change, with a 3 - 6°C increase in air temperature over 100 years, may affect forest sustainability and adaptive capacity to unfavorable environmental conditions such as drought, frost, and heat as well as the acidic compounds in air pollution (Augustaitis et al., 2007a, 2010), tropospheric ozone (Serengyl et al, 2011, Sicard et al., 2016), and resistance to pest damage (Augustaitis, 2007). Notwithstanding, this change in meteorology is the main factor responsible for increasing tree-growth intensity in the dominant European hemi-boreal forest tree species (Augustaitis et al., 2018). Continuous monitoring of the stem sap flow intensity and tree ring formation throughout the year is crucial for understanding tree reactions to changes in environmental conditions. This investigation used sap flow equipment and automatic dendrometers DRL-26 (Augustaitis 2021). Therefore, the present study examined the causative relationships between environmental factors and tree ring width formation of the dominant Lithuanian tree species. We found that their water use efficiency (WUE) is the main parameter for a trees capacity to adapt to and mitigate the recent changes in the global climate.

Environmental conditions in northeastern Lithuania

Long-term analysis of meteorological data for a gradient from coastal to eastern inner Lithuania revealed an increase in annual air temperature and precipitation and rising variation in monthly patterns from 1981-2020 compared to 1950-1980 (Augustaitis et al., 2010, 2021). In northeastern Lithuania at the Aukštaitija Integrated Monitoring Station (IMS), global environmental changes are mainly expressed by increasing sun activity (i.e., total radiation 0.8 w/m^2 per year and FAR radiation 1.66 w/m^2 per year). The increase in solar radiation results in significant changes in air temperature and humidity but also forest ecosystem sustainability. Different from changes in solar radiation, ozone concentrations at the Aukštaitija IMS are decreasing by 0.15 µg/m^3 per year. These changes could contribute to better tree crown conditions and higher productivity.

From 1994 to 2020 the mean annual air temperature also increased by 0.037°C per year and reached 8.2°C in 2020, making it the warmest year in the whole investigation period. The most significant temperature

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increases were recorded in September, November, and December. During this period, precipitation increased by 4.4 mm per year and reached about 800 mm. Despite this increase in precipitation, surface stream runoff decreased approximately at the same level due to a higher evapotranspiration rate, which destroyed the water balance in this ecosystem. These meteorological events had to have had a significant effect on biological and geochemical processes taking place at the monitored forest sites.

A dataset for air acidic compounds concentrations and their deposition revealed a significant decrease in the pollutant load before 2000, especially Sulphur compounds, due to decreased emissions in Europe, including Lithuania. Implementation of international legislation to reduce transboundary air pollution also resulted in decreased N compounds in soil, ground and surface waters. These environmental events had to significantly affect biological and geochemical processes taking place in forest ecosystems.

Effect of environmental factors on tree conditions

Data on tree crown conditions between 1993-2020 revealed that after an initial period (1993-1999), when defoliation levels were the highest, the condition of the monitored trees improved in the studied forest sites. This process continued from 2012-2015 (i.e., crown defoliation of birch trees decreased from 22.7% to 14.5%). This improvement in crown conditions was statistically significant ($p<0.05$). Decrease in mean defoliation of Norway spruce and Scots pine crowns was close to a level of significance, i.e., defoliation decreased from 24.5% to 22.3% and from 16.8% to 15.8%, respectively. The year 2020 was the best for tree crown conditions in the studied forest sites. The mean value of defoliation in all monitored trees decreased by 19.4%.

Photo 1. A view of monitoring of environmental conditions (PM_{10}, $PM_{2.5}$, O_3, NOx CO_2 etc, with student dormitory and laboratory.

Air concentrations of Sulphur species and ammonium and their deposition, were the main drivers in the changes in mean defoliation of Scots pine trees in Lithuania. Meteorological factors stimulated the recovery of pine tree crown condition, while the effects of ozone concentrations were nearly insignificant.

Outbreaks of *Ips typographus*, which occur after episodes of droughts mainly in mature and over mature stands, could be a new threat to spruce trees.

Variation in stem basal area in relation to meteorology

Norway spruce trees demonstrated the most significant increase in annual basal area increment (BAI), followed by Scots pine trees. In contrast, silver birch and downy birch trees demonstrated stable or decreasing rates, respectively in the BAI in the period studied in northeastern Lithuania.

Photo 2. Monitoring of litter fall and through-flow water in a forest in the experimental site.

Meteorology was a key factor in the variations in stem basal area. In September and July, significant increases in air temperature increased the BAI of the coniferous tree species in the study. Only heat and drought in June limited spruce growth intensity at Aukštaitija IMS. A higher moisture regime increased the sensitivity of Scots pine and Norway spruce trees to the drought effect in the vegetative stage.

Neither silver nor downy birch trees in premature and mature age stands can be characterized as tree species tolerant to drought and heat stress. More abundant precipitation during the vegetative stage and at the beginning of autumn resulted in intensive birch tree growth, whereas a reduction in the growth rate of silver birch trees was mainly attributed to the effect of heat in July, August, and September. The reduction in birch tree leaf span could be the critical factor in reduced tree productivity in general.

Vegetation nitrate deposition, a fertilizing compound, stimulated BAI formation of the pine tree stem, while ammonium compounds reduced it on diurnal and annual scales. The negative ozone effect on pine growth intensity was significant only on mineral soil forest sites (FS). Higher moisture regimes significantly increased the tolerance of pine trees to the negative effect of air concentrations of acidic compounds.

Our data revealed that Norway spruce trees are better adapted to current climatic conditions in hemi-boreal forests than Scots pine and birch trees (Augustaitis et al., 2018). Even during a drought episode, spruce stem increment exceeded the rest of the tree species studied. Scots pine seems to be the most sensitive species to seasonal environmental changes. Silver and downy birch tree reactions showed the lowest sensitivity to unfavorable or favorable environmental factors affecting tree growth intensity. These are the reasons the growth intensity of birch trees has been gradually decreasing recently.

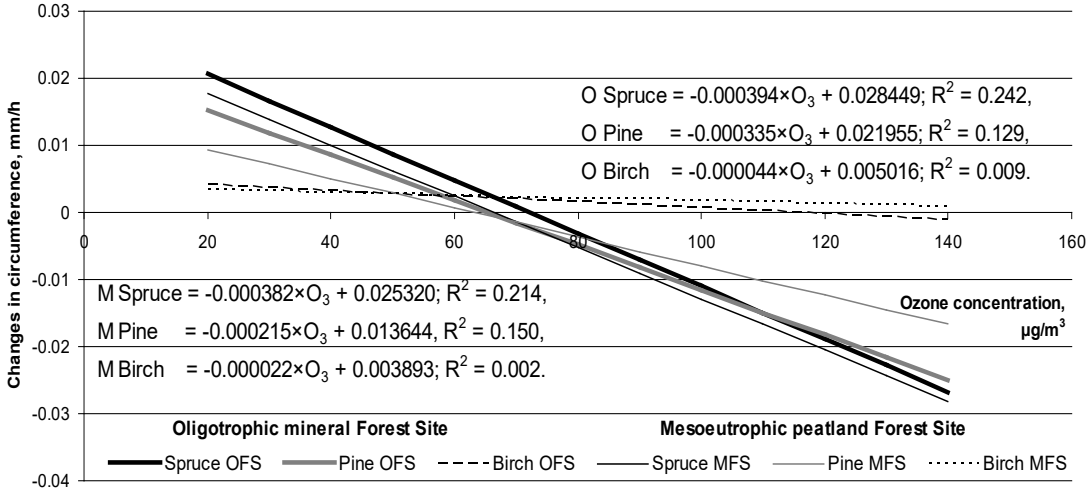

Figure 1. Relationship between surface ozone concentrations and hourly variation in stem circumference of the prevailing in Lithuania tree species under different growth condition.

Effect of O_3 flux on tree increment on an hourly scale

Stem shrinking/contraction during the day due to transpiration and swelling/expansion during the night due to rehydration are significantly related to meteorology, solar activity, and O_3 flux intensity (Augustaitis et al., 2021). These variations were negatively associated with current time-temperature but positively with precipitation and relative humidity. O_3 fluxing through the stomata stimulated the shrinking process more intensively than inhibiting the swelling process, but only for pine and birch trees. Spruce trees demonstrated the highest sensitivity to O_3 impact due to its significant effect on the stem swelling process. While pine trees were less sensitive to O_3, and birch trees were the least affected. Overly wet conditions on measoeutrophic organic FS increased the significance of the O_3 effect on tree increments of the tree species in the study.

Special attention was paid to the problem of the O_3 threshold. Trees exceeding this threshold should suffer increment losses. The O3-flux concept (Emberson et al., 2007; Matyssek et al., 2007), based on the accumulated stomatal O_3 flux above the detoxification threshold Y over the growing season (phytotoxic ozone dose, [PODY]), is believed to be crucial for understanding O_3's effects on forests. However, during the IUFRO conferences, PODY is frequently put forth as a new European legislative standard, but validation of the Y threshold under field conditions is still missing (Sicard et al., 2016). The data on fluctuation of stem circumference in relation to surface ozone on an hourly scale revealed that ozone concentration had the most significant effect on spruce tree growth. Its concentration explained the 25% variation in the fluctuation of stem circumferences. O_3's effect on pine growth was a slightly lower but remained statistically significant, explaining the 15% fluctuation in stem circumferences. A significant effect of O_3 on tree ring formation of coniferous trees was detected at both forest sites. Nevertheless, the most interesting fact was that lines, which express this relationship, cross the abscissa line at 65-70 µg m^{-3} concentration level (Fig. 1). The 65-70 µg m^{-3} concentration level is close to or above the level on the Accumulated Ozone over Threshold (AOT) index for trees growing in Central and Southern European forests during April – September, (80 µg m^{-3}), and slightly lower (70 µg m^{-3}) for more Nordic or Eastern European forests (Karlsson et al., 2002, 2006). Whether or not this ozone concentration can be presented as PODY for the new European legislative standard for hemi-boreal coniferous forests is a question for deeper discussion in the future.

Birch tree stem circumference was the only variation not related to changes in ozone concentration on this time scale. Therefore, the statement that birch trees are highly resistant to O_3 effects is arguable because no significant reactions (positive or negative) to other environmental factors, mainly meteorology, were detected. Based on this assumption, we concluded that trees that did not demonstrate any (positive or negative) reactions to environmental changes should be seen as not having the capacity to adapt to existing environmental conditions. Maintaining sustainable succession is problematic, especially when their annual growth gradually decreases. Our hypothesis that the coniferous species are more adaptive to recent climate changes and their capacity to mitigate the threats of global changes is higher than that of deciduous tree species was confirmed by the hourly scale of variation in stem circumference.

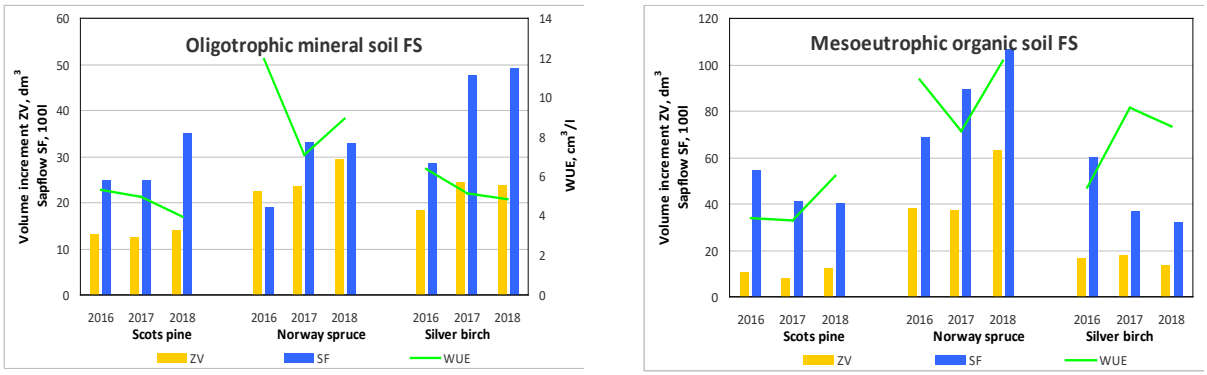

Figure 2. Water use efficiency (WUE) of the considered tree species and their stem volume increment (ZV) and sapflow intensity (SF) during 2016-2018.

Water use efficiency

Water use efficiency shows how much timber is produced per liter of water. An increase in this value indicates an increase in WUE. This parameter differed significantly among the tree species in this study. Meteorological conditions were also a key factor significantly impacting the value of WUE.

The WUE of Norway spruce was the highest, especially in 2016, the driest year for natural moisture on oligotrophic mineral soil FS. This high WUE value indicates their proper adaptation to current meteorological conditions in a hemi-boreal forest.

Conclusion

Scots pine trees' more intensive tree ring formation in relation to recent environmental changes indicates their high resilience and adaptation to local conditions. Norway spruce remains the important tree species for future silviculture. Reduced tree growth intensity and weak relationships with meteorological parameters indicate that spruce has the lowest adaptive capacity to environmental changes, limiting its ability to mitigate climate change.

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