Research paper

Potential of ecological modelling and smart-drainage development for mitigating adverse effects of future global change-type droughts for the Estonian forest sector

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Abstract. Global change-type droughts will become more frequent in the future and threaten forest ecosystems around the globe. A large proportion of the Estonian forest sector is currently subject to artificial drainage, which could probably lead to negative feedbacks when water supply falls short because of high temperatures and low precipitation during future drought periods. In this short article, we propose a novel research perspective that could make use of already gathered data resources, such as remote sensing, climate data, tree-ring research, soil information and hydrological modelling. We conclude that, when applied in concert, such an assembled dataset has the potential to contribute to mitigation of negative climate change consequences for the Estonian forest sector. In particular, smart-drainage systems are currently a rare phenomenon in forestry, although their implementation into existing drainage systems could help maintain the critical soil water content during periods of drought, while properly fulfilling their main task of removing excess water during wet phases. We discuss this new research perspective in light of the current frame conditions of the Estonian forest sector and resolve some current lacks in knowledge and data resources which could help improve the concept in the future.

Key words: drought, forestry, adaptation, smart drainage, Estonia.

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Introduction

Drought is currently one of the most intensively discussed topics in forest sciences and ecology, since the devastating 2018 global change-type drought has shown

how vulnerable European forests are against unprecedented water-shortage and excessively high temperatures (Buras *et al.*, 2019; Toreti *et al.*, 2019). The term *global change-type drought* (Breshears *et al.*, 2009) indicates that future drought periods will

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be largely driven by increasing temperatures as well as by increasing vapor pressure deficits (Eamus *et al.*, 2013) caused by climate change. Such droughts will have the potential to turn forest ecosystems temporarily into large carbon sources and cause unprecedented tree mortality at regional and global scale (Brecka *et al.*, 2018; Hartmann *et al.*, 2018; DeSoto *et al.*, 2020). However, like in many other countries situated in the boreal North, land use in Estonia is largely dependent on artificial drainage in order to make agricultural production and silviculture possible. Drainage of peatlands and bogs for forestry began in the first half of the 19th century and reached its peak after the Second World War (Salm *et al.*, 2009). The main purpose of artificial draining is to increase yield in moist sites which are otherwise non-suitable for wood production and difficult to access for highly mechanized forest harvesting operations. Consequently, the drainage systems influence also surrounding areas. While a lot of efforts have been undertaken in the recent past to restore a substantial amount of peatlands and bogs back to their natural hydrological regimes, there are still large managed forest areas which are highly dependent on such drainage systems in order to make wood production possible. As an example, the area of drained forest land in Estonian state forests is 500,095 ha (~50%) which contribute to the increase in wood increment by half a million cubic metres per year (RMK Annual Report, 2018). However, almost all of these drainage systems are largely non-adjustable so that the soil water reserve cannot not be retained during periods of drought when evapotranspiration exceeds precipitation. In particular, Norway spruce (*Picea abies* (L.) H. Karst.) with its shallow rooting system reacts markedly sensitively to soil water depletion, which could lead to negative effects under the current drainage practice if droughts become more frequent in the future (Lévesque *et al.*, 2013; Nadezhdina *et al.*, 2014).

Assessment of risk, drought probability, and available datasets in Estonia

The very first step in deciding where a smart-drainage system (SDS) will be needed is to assess locations where droughts are likely to cause harm and damage to forest stands in the near and far future. Consequently, forest operational areas and stands which are currently exposed to drainage and which are characterized by high vulnerability against drought can be selected in advance for initial research and case studies.

The risk or vulnerability of forest stands against drought stress is, however, a function with many different variables. The future probability or frequency of drought will most strongly determine the vulnerability of a stand, but is unfortunately also the most uncertain quantity to predict. Projecting drought occurrence in the future is a difficult task due to the fact that stochasticity plays a significant role (Hao *et al.*, 2018) and because temperature alone is not driving drought occurrence (Eamus *et al.*, 2013). Although recent studies proposed a slight increase in precipitation for the boreal North and therefore a lower probability of future drought occurrence (Stagge *et al.*, 2017), it is still unclear whether the projected precipitation surplus will be available during the vegetation period when stands demand moisture the most, or simply occur outside of the vegetation period. In the latter case, it is more likely that the precipitation surplus will result in higher runoff without any notable benefits for forest vegetation. Based on long-term observations spanning the period of 1950–2015, Spinoni *et al.* (2017) demonstrated that the probability of winter droughts in Estonia and Latvia will indeed decrease, while spring, summer, and autumn droughts show a significant tendency towards higher frequencies.

Data from the Copernicus European Drought Observatory (EDO) provides evidence that large parts of Estonia, as many other northern European countries, have

Figure 1. Soil moisture anomaly in Estonia in 2017–2019.

Soil moisture anomaly (SMA) in three consecutive years for the months June (upper panel), July (mid panel), and August (lower panel) for Estonia as obtained from the European Drought Observatory (EDO) under <https://edo.jrc.ec.europa.eu>. Briefly, soil moisture is calculated on a 5 km² raster over Europe and based on a hydrological rainfall-runoff model, including daily meteorological observations (de Roo *et al.*, 2000; Cammalleri *et al.*, 2020). Subsequently, soil moisture values are transformed into standardized values by comparison to a long-term reference period (i.e. 1995 until the last full-year observation). Negative values (brown colours) indicate a soil moisture deficit and positive values (blue colours) a soil moisture surplus. From the figure below it can be seen that soil moisture conditions in 2017 were well balanced, while in 2018 and 2019 soils reached a severe (light brown) and partly extreme (dark brown) drying status. Like many northern European countries, the entire Estonia was hit by the millennial drought in 2018, while in 2019 mainly the north-eastern part was affected. Such consecutive drought occurrences can boost tree dieback and vulnerability against pathogens, such as the bark beetle, in particular if they appear at higher frequency in the future (see, for instance, Williams *et al.*, 2010; Williams *et al.*, 2013).

already been suffering from the most recent extreme and severe soil moisture deficit in 2018 and even in the following year, although the area subjected to moisture deficit was smaller in 2019 (Figure 1). According to Toreti *et al.* (2019), such exceptional drought periods and their legacy effects for trees could theoretically become a common occurrence in as early as 2043, which implies that adaptive forest management is running out of time already.

Besides drought frequency and severity, species composition, stand density, forest management, and soil type also largely determine the vulnerability of forest stands against drought stress (e.g. Choat *et al.*, 2012; D'Amato *et al.*, 2013; Bottero *et al.*, 2017). Norway spruce and Scots pine (*Pinus sylvestris* L.) are currently experiencing an unprecedented dieback in large parts of Central Europe (Bigler *et al.*, 2006; Senf *et al.*, 2018) mainly due to drought and a subsequent biotic agent attack by bark beetles such as *Ips typographus* (L.) (Netherer *et al.*, 2015), suggesting that boreal stands harbouring large proportions of these species could be particularly vulnerable in the future. Moreover, northern conifer provenances were recently shown to be much more vulnerable against drought compared to central and southern populations (Isaac-Renton *et al.*, 2018), which could even exacerbate drought consequences in the boreal realm. However, further research is needed in order to test whether this hypothesis holds true for European conifers, as well.

Altogether, already available datasets with high spatial and temporal resolution can be utilized for identifying stands and forest operational areas which will be more vulnerable to drought than others and which are currently exposed to drainage. Such datasets can, for example, include high resolution climate data as already provided for temperature and precipitation at the national and European level (e.g. Haylock *et al.*, 2008; Jaagus *et al.*, 2014). In particular, recent advances in precipitation observation based on a dual-polari-

zation weather radar (Voormansik *et al.*, 2020) have overcome limitations of traditional rain gauges networks and constitute a promising source of high-resolution precipitation data for ecological modelling. Soil information can now be obtained for the entire Estonia from the geoportal of the Estonian land board; the 1:10,000 map covers an area of 43,000 km² (<https://geoportaal.maaamet.ee/eng/Spatial-Data/Estonian-Soil-Map-p316.html>).

The vulnerability scoring of stands can either be solely based on climate (present/future), vegetation, and soil information or, alternatively, on the growth response of stands where relative growth change after droughts is retrospectively analysed. Such approaches would require reliable and accurate assessment of growth measures, such as above-ground biomass and can, for instance, incorporate spatially and temporally high-resolution remote sensing data, such as airborne laser scanning (Simonson *et al.*, 2016), which is already available for the entire Estonia with high spatial resolution. However, predicting above-ground biomass using airborne LiDAR data is not an easy task and therefore careful evaluation against data from long-term monitoring plots, forest national inventory data, and tree-ring networks is necessary and strongly advisable (Simonson *et al.*, 2016). Response variables such as a validated change in above-ground biomass can then be modelled as a function of climate, species proportion, forest management, soil parameters, and many more, depending on how much spatial and temporal information is at hand. Besides traditional modelling techniques in ecology, the random forest algorithm (Breimann, 2001) and boosted regression trees (Elith *et al.*, 2008) have proven particularly suitable for handling big ecological datasets consisting of a variety of numerical and categorical variables (e.g. De'ath, 2007; Cutler *et al.*, 2007). When provided with estimates of future climate change (e.g. temperature from different representative concentra-

tion pathway (RCP) scenarios or hypothetical drought frequencies), such models can be able to identify target areas with high vulnerability (e.g. Simonson *et al.*, 2016).

Smart-drainage systems in forestry: current prospects and future challenges

Once target areas with high drought vulnerability are identified, they can be intersected with spatial information on current drainage in order to localize stands in which installation of smart-drainage systems as complementation to the already existing system will be reasonable. The term *smart drainage* (also often referred to as *controlled drainage* or *controlled water table management*) is used to describe any kind of system in which the drainage outlet is modified in a way that water can be either retained during periods without rainfall and high evapotranspiration or quickly released when precipitation exceeds evapotranspiration in order to avoid extreme water tables (Skaggs *et al.*, 2016). While already commonly applied in agricultural systems for purposes of improved water supply and quality (e.g. Ayars *et al.*, 2006), the idea of using smart-drainage systems (SDS) in forestry as a mitigation tool has been so far only rarely reported (but see Amatya *et al.*, 1996 for an example).

Smart-drainage systems comprise currently manual, semi-automatic, and fully automatic control systems (Fouss *et al.*, 2007). While manual systems can be easily and affordably built by installing weirs at the drain outlet that can be manually adjusted depending on whether the system should run in the drainage or sub-irrigation mode, such systems will be most likely unsuitable for the Estonian forest sector, since their reaction time is slow and they would require regular personal visits and manipulation. Hence, semi-automated and automated systems with feedback field-sensors can be a suitable alternative given that they are capable of accurate minimum and

maximum water table adjustments under quickly alternating weather conditions (Fouss *et al.*, 2007). Such forest SDS systems make use of weather radar-based local precipitation estimates provided as reanalysis data or as real-time monthly measurements. As the final step, we propose that once target areas with high drought vulnerability are identified, establishing long-term field study and monitoring sites is strongly required in order to validate the proposed smart-drainage system under various scenarios. When coupled with state-of-the-art computer simulation models such as DRAINMOD (Skaggs, 1980), reliable estimates of feasibility and cost-effectiveness can be obtained without the need for decades of monitoring.

Conclusions and outlook

We proposed here a multi-disciplinary and applied research concept which could help mitigate negative climate change consequences for the Estonian forest sector in the very near future, in particular, adverse effects caused by global change-type droughts. The concept will make use of various data resources which are partly already available at national level with very high spatial and temporal resolution such as airborne LiDAR data, temperature and precipitation maps, soil data, national forest inventory data, tree-ring networks, and forest management information (Figure 2). However, we are also aware of some drawbacks and problems that need to be addressed in advance. As such, the use of growth or productivity proxies derived from LiDAR data as a response variable for drought vulnerability assessment is highly dependent on the achieved accuracy. Since annual or short-term periodical changes (e.g. 3–5-year intervals) in growth will be required for modelling, standard errors need to be in a reasonable range in order to overcome critical signal-to-noise ratios. Therefore, sufficient validation data

Figure 2. Project workflow with proposed and already available datasets that could be included.

A possible project workflow with already available datasets is demonstrated in the figure below: Temporal and spatial resolution of the datasets are described in detail in the “Explanation” panel. However, the different resolutions will make rescaling and resampling necessary. Once datasets are compiled and rescaled, the vulnerability assessment can be performed. Option 1 would offer a simple and less laborious possibility to assess vulnerability over a huge area without the need for statistical modelling, but it would also be less accurate and solely based on arbitrarily chosen thresholds. In contrast, option 2 is more laborious, more accurate, and would specifically allow for forecasting vulnerability into the future, when high-resolution future climate data is available on a gridded base. Projections (i.e. forecasts) can be compared between optimistic and pessimistic climatic scenarios, such as given in the representative concentration pathways RCP2.6 and RCP8.5. Both of these scenarios make different assumptions about future emission trajectories and comparing vulnerabilities under consideration of one or the other scenario will be a valuable task when combined with a cost-benefit analysis and projected yield loss. However, the accuracy of results obtained by applying option 2 will strongly depend on the response variable which will be used for modelling. While airborne laser scan (LiDAR) is able to provide massive data on tree height in a relatively short time, estimates for biomass or volume still need to be modelled under consideration of species-specific and location-specific allometric functions. Since modelling needs to be performed on relative growth measures (e.g. biomass change from one year to the next) rather than with absolute values, the accuracy of the obtained response variable will be crucial in order to overcome signal-to-noise ratios caused by measurement and/or transformation errors.

Finally, when vulnerable areas are identified they can be intersected with the current drainage information obtained from GIS-based information systems. This will help rapidly identify stands and management areas in which transformation of the current drainage system into a smart-drainage system can be realized. As a general note: since installation and maintenance of such smart-drainage systems will be costly, we presume that productive stands or those with high conservation priority should be preferred for case studies in order to achieve economic feasibility of such a system modification.

are needed and probably also alternative response variables which can be assessed with higher accuracy and fewer model assumptions. The available datasets have different spatial and temporal resolution; thus, resampling will be necessary in order to include them in one and the same mod-

el. Especially, LiDAR data for Estonia and soil data from the Estonian soil map come at much higher spatial resolution compared to most of the other data, and resampling could result in the loss of important information and introduce bias. Finally, financial considerations and cost-efficiency

for installation of smart-drainage systems need to be considered, since implementing such systems will require considerable investments. Therefore, sensitivity analyses of the current and future forest growth and yield models by including different hypothetical drought scenarios need to be carried out in order to justify the proposed mitigation strategy. By proposing the integrated smart-drainage system concept for forestry we strongly encourage other colleagues from related disciplines to contribute with their knowledge, data or simply remarks to design SDS implementations for mitigation of global change-type droughts in the forest sector.

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