Abstract

Forest ecosystems are an essential part of the global carbon cycle and constitute a large fraction of the storage of terrestrial carbon. However, climate change may induce shifts in temperature and precipitation. These changes in temperature and precipitation have pronounced consequences for forest growth and carbon sequestration potential. This study addressed the comparative analysis of foliage biomass in the deciduous genus *Larix* spp. and the evergreen subgenus *Pinus* spp. in gradients of annual precipitation and winter temperature. The database for modeling involved 400 and 2,110 sample plots for Larch and Pine, respectively. Pine had reduced foliage biomass in dry conditions; however, an increase in foliage biomass was observed in moist conditions. On the contrary, regardless of conditions, *Larix* accumulated more foliage biomass. Interestingly, precipitation (100mm) increased Pine tree foliage biomass in warm regions. This positive trend of precipitation was observed for Larch in warm regions. We argue that these responses are related to the differences in physiology. In winter, Larch carries out only respiration. We discuss that these responses are due to the different status of tree needles in these two species. Understanding tree genera responses to rising temperature and shifts in precipitation regimes will enable us to improve predictions of the carbon storage potential in Eurasian forests.

Key words: *Pinus*; *Larix*; Biomass; Eurasia; Equations.

Introduction

Numerous studies have demonstrated the inevitable effect of climate change in recent decades. Such studies have addressed the possible negative impacts on vegetation and human health (Behrensmeier, 2006; Lenton et al., 2019; Malhi et al., 2020). Indeed, climate change is a severe environmental problem and affects biological and non-biological systems worldwide (Malhi et al., 2020). Forest ecosystems constitute an integral component of the global carbon cycle as they store significant amounts of carbon above- and belowground (Ripple et al., 2019). Eurasian forests, and particularly boreal forests, play a vital role in the global sequestration and storage of C forests (Usoltsev, 2007). Eurasian forests account for 70% of total C storage in forests (Myneni et al., 2001). Eurasia constitutes 36.2% of the global terrestrial area, harbors high plant biodiversity, and provides vital ecosystem services (Addison & Greiner, 2016; Zhou et al., 2017). In particular, 5,283 species are native to the Eurasia region (Hu & Li, 2015). It clearly demonstrates the significance of Eurasian forests.

Scientific data suggests that Eurasia has experienced an increase in temperature (Serreze et al., 2000), and high temperature indeed depicted a negative impact on the Eurasian forests. For instance, a significant shift in tree lines has been attributed to high temperature, and reduced cone and seed production were reported in *Larix sibirica* and *Pinus sylvestris* in Eurasia (Kharuk et al., 2007). This shows the importance of changing temperature patterns for tree species composition, phenology, and forest structure in Eurasia (Kharuk et al., 2007).

Forest landscape model (FLM), simulations of forest cover excluding species identity composition showed that moderate increase in temperature (+3°C) resulted in high photosynthesis activity; however, less biomass was observed. Interestingly, an increase of 6°C reduced biomass production and photosynthesis. On the contrary, increasing precipitation tends to increase photosynthesis and biomass (Gustafson et al., 2017). While using a biomass data set of more than 6,200 forest plots from 61 countries across a mean annual temperature gradient of, i.e., 40°C, it was found that average annual temperature better predicts tree biomass allocation to plant organs than soil moisture (Reich et al., 2014). Notably, the study by Reich et al., (2014) showed that the proportion of belowground part (roots) increases whereas the proportion of foliage decreases towards colder climates. This result supports the hypotheses about forest tree adaptability to survive against temperature (Reich et al., 2014). At the level of forest
Foliage efficiency is one of the crucial parameters to understand forest production. It is defined as the net primary production value per unit mass of foliage (Usoltsev et al., 2018). The foliage efficiency of any given tree genera varies due to several factors. Among them, temperature and precipitation determine the foliage efficiency. Besides these climatic factors, morphology and tree ages are taken into consideration to predict the foliage biomass of any given tree species (Usoltsev et al., 2018).

Liebig’s Law of the minimum has been applied to forest ecosystems (Molchanov, 1971; Stine, 2019). According to this law, “resistance limit for any organism may be regarded as limiting factors (Bobrov, 1978). For instance, temperature and precipitation could determine biomass in tree species. It is essential to mention that low biomass values were reported due to decreasing temperature and precipitation (Stine, 2019).

In our study, we focus on the Larix spp. (deciduous) and Pinus spp. (evergreen) as the primary biomass forming dominant tree species that contribute significantly to C storage in Eurasia (Kharuk et al., 2007; Pfadenhauer & Klotzli, 2020). Species of the genus Larix are dominant in Northern Eurasia due to continuous permafrost, low annual precipitation, thin snow cover, early-summer drought, and cold winter temperatures (Tchebakova et al., 2005; Herzschuh, 2019). At present, 15-19 species of the genus Larix are documented for the Northern Hemisphere, including 13-14 main species along Northern Eurasia and three hybrid species. Apparently, only the Larix genus, among other forest-forming species, is represented by a variety of species, i.e. L. decidua Mill., L. sukaczewii N. Dyl., L. sibirica Ledeb., L. czezanovskii Turcz., L. gmelinii Rupr., and L. cajanderi Mayr (Borisov, 1967).

We assessed foliage biomass response against temperature and precipitation. Our results will improve our understanding of tree genera responses to changing temperature and precipitation regimes. In addition to this, the present result may aid in predicting the C storage potential of Eurasian forests.

Materials and Methods

We selected and processed pure stands harvest data from the previous database to study the impact of temperature and precipitation on Larix and Pinus in Eurasia. Our forest biomass data consisted of four hundred and 2,110 samples for Larix and Pinus, respectively. Larix spp. is presented by eight species, and a majority of Pinus species are dominated by Pinus sylvestris L. (Sokolov et al., 1977; Bobrov, 1978). As we can see in Figure 1, the distribution of these genera is uniform within the habitats on the territory of Eurasia.

Availability of schematic maps of rainfall distribution and average January temperatures for the period from 1996 to 2006 on the territory of Eurasia allowed us to combine the harvest data and the available coordinates of the experimental sites (World Weather Maps, 2007). This temperature, precipitation, and biomass data were subjected to correlation and regression analysis. We show a fragment of a numerical matrix (Table 1) for the explanatory purpose. We preferred the average temperature of January since it changes in the planetary biota most intensively than the average annual one (Morley et al., 2017). The seasonality of solar radiation changes allowed us to select one of two different levels of average temperatures – winter or summer. The seasonality of rainfall in most of the territory of Eurasia is not expressed to the same extent; therefore, we selected the average annual data.

Fig. 1. Position of Larix (left) and Pinus (right) harvest data.
The biomass of tree species is dependent on morphology and tree age (Usoltsev, 2007). To model the changes in biomass of species in specific in relative challenging. Nonetheless, the logarithmic transformation of equations may overcome this challenging task (Baskerville, 1972; Stahl et al., 2012). We used a system of equations, as suggested previously (Moore, 1917). After transformation, we got 50 M and 40 M for Larix and Pinus. Notation of variables in equations is described in Table 1. First, the structure of the main equation is assumed.

$$
\ln P_f = f(\ln A, \ln V, \ln N, (\ln A)(\ln N), \ln(Tm+M), \ln PRm, [\ln(Tm+M)];(\ln PRm))
$$

(1)

It is important to mention that we can only incorporate or insert tree age. But they can be obtained by calculating using our database. This idea is implemented by calculating two related equations:

$$
\ln N = f(\ln A, \ln (Tm+M), \ln PRm, [\ln(Tm+M)];(\ln PRm))
$$

(2)

$$
\ln V = f(\ln A, \ln N, (\ln A)(\ln N), \ln(Tm+M), \ln PRm, [\ln(Tm+M)];(\ln PRm))
$$

(3)

Correlation and regression analyses were carried out in Statgraphics (Statgraphics, 1988).

**Results and Discussion**

The results of equations 1, 2, 3 are shown in Table 2. Differences in Larch and Pine biomass responses against climatic factors (temperature and precipitation) are described (Table 2). The slopes of independent variables for temperature, rainfall, and their joint impact in the foliage biomass were +3.390, +1.783, and -0.524 for Larch, -3.614, -1.684 and +0.555 for Pine, suggesting a common trend for the foliage biomass of Larch and Pine, respectively. Larch and Pine significant regressions were calculated at the probability level of 0.999. T-test results indicated +3.71, +3.29, and -3.54 for Larch foliage. On the other hand, Pine foliage values were -6.20, -5.31, and +6.03. Independent variables contribution to tree foliage biomass were highlighted in Table 3. Our biomass variable results explained 75% and 78% variations in foliage biomass of Larix and Pinus. Stem volume accounted for 39% and 47% of explained variance in Larix and Pinus respectively.
Foliage biomass of Larch and Pine showed statistically significant transcontinental trends along gradients of temperature and precipitation. 3-D graphs clearly showed a dependence of foliage biomass on temperature and precipitation (Fig. 2) with clear differences between Larch and Pine, respectively.

The central theme in forest ecology is to study foliage biomass responses against air temperature deviation by one °C and precipitation by 100 mm per year. Our constructed model answered such a question concerning Larch and Pine stands. We showed different foliage biomass responses of Larix (Fig. 2a) and Pines (Fig. 2b). The tree stands age was 100 years for both genera, i.e., Larix and Pinus.

Different eco-regions differ in temperature and precipitation. Temperature change also occurs regionally. In addition to the change in temperature, annual precipitation change occurs. In Fig. 3, we indicated an increase in precipitation by 100 mm at various territorial levels. Such an increase in precipitation was designated as 200A (300Δ) ... 800A (900Δ). Larix and Pinus foliage biomass (Δ, %) responded differently to an increase of 1°C in different eco-regions (Fig. 3). Furthermore, a decrease in foliage biomass was observed in the insufficient moist region (PRm = 300–400 mm) (Fig. 3b). On the contrary, temperature and precipitation depicted a positive impact on leaf biomass in the Larix (Fig. 3a). The percentage of increase in biomass was also reported from warm regions to cold ones (Tm = -30°C). However, negative results were obtained in warm zones (Tm = 10°C). Scientific data obtained previously in Siberia (Glebov & Litvinenko, 1976) validated our current findings. In Siberia, maximum temperature and precipitation showed positive impacts on above ground parts, i.e., stem. However, low temperature and high precipitation decreased stem biomass by 4-9%. Nonetheless, an increase in radial growth was observed in the high-temperature range at the moderate precipitation level of 600 mm (Glebov & Litvinenko, 1976). This shows the importance of temperature and precipitation in Eurasia. Recent work also highlighted the significance of temperature and precipitation to determine the biomass of tree species in Eurasia (Usoltsev et al., 2020a, 2020b). Responses of Pine trees (Fig. 2) followed the Liebig-Shelford trend because we noticed a decline in foliage biomass due to minimum precipitation. At the same time, Larch demonstrated the opposite pattern, at least in a warm climate (Tm = 0°C) with insufficient moisture (PRm = 200 to 300 mm). The explanation for such a pattern is described in the following lines. The distribution of Larches and Pines is approximately the same (Fig. 1). Since the distribution of Larches and Pines is almost similar, we argue that temperature and precipitation values are identical for these two tree species. Ultimately, model results produced almost similar results for Larches and Pines. It is worth mentioning that Pines biomass was slightly higher than Larch stands. Biomass pooled data for Larches and Pines authenticated the validity of models in our analyses. Furthermore, we did not observe any change in variables (temperature and precipitation). Foliage efficiency (FE) increased in Pine but decreased in Larch in the same zonal range. This increase and decrease trend was found in the northern belt towards subequatorial areas (Usoltsev et al., 2018). Current modeling results highlighted the physiological differences between the two species. It is evident that evergreen and deciduous species have differences in photosynthetic activity. Evergreen species can prolong the assimilation process even in winter (Wieser, 1997; Usoltsev et al., 2018).

Table 2. Model results for the effects of forest stand factors and climatic indices on foliage biomass of Larix and Pinus.

<p>| Table 2. Model results for the effects of forest stand factors and climatic indices on foliage biomass of Larix and Pinus. |
|-----------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|</p>
<table>
<thead>
<tr>
<th>ln(Y)¹⁾</th>
<th>ln(N)</th>
<th>ln(A)</th>
<th>ln(V)</th>
<th>ln(N)+ln(A)</th>
<th>ln(Tm+M)</th>
<th>ln(PRm)</th>
<th>[ln(Tm+M)+ln(PRm)]</th>
<th>adjR²⁾</th>
<th>SE³⁾</th>
</tr>
</thead>
<tbody>
<tr>
<td>Larix</td>
<td></td>
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<tr>
<td>ln(N)</td>
<td>0.9264</td>
<td>-0.9330</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.6526</td>
<td>0.8802</td>
<td>-0.3648</td>
<td>0.436</td>
</tr>
<tr>
<td>ln(V)</td>
<td>-14.4847</td>
<td>0.7836</td>
<td>-1.1206</td>
<td>0.3384</td>
<td>5.7240</td>
<td>1.6297</td>
<td>-0.6172</td>
<td>0.562</td>
<td>0.61</td>
</tr>
<tr>
<td>ln(PRm)</td>
<td>-12.5131</td>
<td>-0.1977</td>
<td>0.6214</td>
<td>0.9387</td>
<td>-0.1866</td>
<td>3.3906</td>
<td>1.7836</td>
<td>-0.5349</td>
<td>0.638</td>
</tr>
<tr>
<td>Pinus</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>ln(N)</td>
<td>2.8168</td>
<td>-1.0696</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.9165</td>
<td>0.5011</td>
<td>-0.3577</td>
<td>0.566</td>
</tr>
<tr>
<td>ln(V)</td>
<td>16.4304</td>
<td>0.7200</td>
<td>-0.7996</td>
<td>0.2065</td>
<td>-3.3579</td>
<td>-2.5007</td>
<td>0.6225</td>
<td>0.472</td>
<td>0.69</td>
</tr>
<tr>
<td>ln(PRm)</td>
<td>11.8492</td>
<td>-0.3495</td>
<td>0.4313</td>
<td>0.1311</td>
<td>-0.0289</td>
<td>-3.6140</td>
<td>-1.6842</td>
<td>0.5555</td>
<td>0.424</td>
</tr>
</tbody>
</table>

¹⁾Dependent variables; ²⁾logarithmic retransformation; ³⁾adjR²⁾ adjusted R squared; ⁴⁾SE – standard error of the equations
Higher temperatures in the winter season induce increased physiological activities (Photosynthesis) in Pine trees (Usoltsev et al., 2018). It is one of the plausible explanations for the high foliage efficiency of Pines in northern zones. On the other hand, Larch trees had more foliage efficiency (northern temperate to subequatorial zone). Larches perform more respiration and shed leaves; therefore, Larches’ foliage efficiency is less (Usoltsev et al., 2018).

The modeling results of this study reported different foliage efficiency and biomass of Larches and Pines. But these differences in foliage efficiency and biomass coincided only in low moisture areas (PRm = 200 to 300 mm) (Fig. 2a,b); however, in areas of sufficient moisture (PRm = 800 to 900 mm), these contradictions become less pronounced. Our results represent a change in biomass patterns under assumed climatic conditions. The present findings of the study highlighted the importance of the adaptability of tree species in the Eurasia region. Due to the rise in temperature, the majority of forest tree species are unable to adapt to high temperatures, resulting in the loss of tree species (Schaphoff et al., 2016; Spathelf et al., 2018).

We carried out data analyses in 1970-1990 and used maps to predict the changes in foliage biomass of Larches and Pines in Eurasia. Our results are significant to understand the tree genera responses to climate change in Eurasia. Our work can improve predictions of how forest ecosystems will change at a continental scale under a warming climate. Ultimately, combining large datasets of forest plots with physiological data will be essential to understand better the underlying mechanisms (DeLeo et al., 2020).

Fig. 2. Larch (a) and Pine (b) foliage biomass (Pf) dependence on mean January temperature (Tm), and mean annual precipitation (PRm).

Fig. 3. Model prediction in Larch (a) Pine (b) foliage biomass.
Conclusions

Pine trees accumulated more biomass in warm regions due to increased precipitation by 100 mm. On the contrary, Larch trees had reduced foliage biomass in warm areas. Our model results of Larch and Pine species showed differential foliage biomass responses against temperature and precipitation in Eurasia.

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