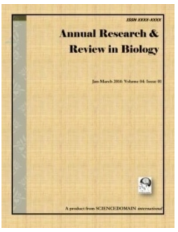

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Climatic Influences on Basal Area Increment of Forests in a Mountainous Landscape

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Authors' contributions

This work was carried out in collaboration between all authors. Author JSSH collected data, designed the study and wrote some sections of manuscript, whereas author MPG performed the statistical analysis and managed the analyses of the study. All authors read and approved the final manuscript.

Original Research Article

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ABSTRACT

Aims: The aim of this work is to assess the influence of temperature (*T*) and precipitation (*P*) on Basal Area Increment (*BAI)* of *Pinus cooperi* in a mixed conifer forest ecosystem. We hypothesize that the sensitivity of annual tree growth to climate variables will increase with increasing elevation.
Study Design: The study area is located in "Las Rusias" mountain, in northwest Mexico. The sample design consisted of selection of three sites with different elevations: Low (*L*), Mid (*M*) and High (*H*), of representative stands of *Pinus cooperi*.
Place and Duration of Study: The field work was carried out in October 2011, whilst processing data was done at Lab in December 2011.
Methodology: Increment cores were collected from 3-10 trees at each site along the elevational gradient. Increment cores were extracted for each tree of *Pinus cooperi* at 1.3 m height using increment borers of 5 mm. Increment cores were processed using standard dendrochronological techniques. In order to determine the climatic response of the *BAI* chronology, *BAI* data was associated with climate records (1946-2010) from the nearby weather station.
Results: The bootstrapped procedure conducted between the *BAI* and climatic variables showed significant correlations for the study area. All correlation coefficient values ranged

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from -0.5 to 0.42 ($p<0.05$). The Pearson´s coefficients indicated that *BAI* has been driven largely by (*P*) and (*T*) along the gradient.

The relationships between *BAI* and *P* showed similar trends for the three elevations. *P. cooperi BAI* was positively correlated with precipitation during the previous winter.

Conclusion: The results showed that the hypothesis that sensitivity to rainfall and temperature will vary along the elevation gradient appears reasonable. These findings could be used to suggest strategies for forest management, however some stand dynamics factors should be considered as well.

Keywords: Tree-rings; Pinus cooperi; elevations; tree growth–climate relationships.

1. INTRODUCTION

A recent study showed that if climate modifications persist, forest limits will contract or trees will shift to cooler sites and establish at higher elevations [1]. In this context, physiological and growth responses to climate along elevational gradients may provide a useful indicator to understand the mechanisms of adaptation of tree species to climate change [2]. Previous studies carried out on elevational gradients have reported that susceptibility to drought of conifer forests varies between elevations and species [3,4].

Dendrochronological techniques constitute a useful tool to analyze annual radial growth of trees. Dendrochronology provides tools to establish a relationship between tree growth and dynamic climate variables over time. The ring widths usually are standardized by fitting an exponential curve to remove individual growth related to stem size and age, dominance status, and other factors, while retaining patterns and trends that are in common among trees into a single chronology [5]. In Northern Mexico, most studies of radial growth-climate relationships have been carried out using the standardized ring index [6,7]. Although this is a reasonable approach for describing the response of growth to climatic variation, it is not effective for comparing absolute growth; this is especially true for standardizations relative to mean growth of the chronology.

Absolute values of stand growth, in terms of basal area increment (*BAI*) would improve the understanding of the role of climate on radial growth. *BAI* is a common measurement that has been used to project forest yield and determine appropriate silvicultural prescriptions in forest management. In ecological and management applications, *BAI* is useful because it reveals the changes in biomass accumulation rates along bioclimatic gradients. Using this approach, it is possible to identify sites with greater potential for timber production and to analyze the effects of elevation on basal area increment.

Within the perspective of sustainable forest development, it is crucial to better understand the responses of coniferous species to climate variability, in order to predict potential biogeographical changes in forest composition and structure [8].

In the state of Durango in northern Mexico, *Pinus cooperi* is widely distributed in temperate mixed conifer forests and is critical to economic development in the region [9]. Therefore, it is important to understand its potential productivity by measuring and determining the impact of climate change on *BAI*.

The aim of this work is to assess the influence of temperature and precipitation on *BAI* of *Pinus cooperi* in a mixed conifer forest ecosystem. We hypothesize that the sensitivity of annual tree growth to climate variables will increase with increasing elevation.

2. MATERIALS AND METHODS

2.1 Study Area and Field Sampling

The study area is located in "Las Rusias" mountain, in the Sierra Madre Occidental in northwest Durango, Mexico. The vegetation is mixed forest with a dominant overstory of *Pinus cooperi, Pinus duranguensis*, *Pinus arizonica*, *Pinus ayacahuite*, *Arbutus xalepensis* and several species of *Quercus* [9].

The sample design consisted of selection of three sites with different elevations: Low (*L*), Mid (*M*) and High (*H*), where there were representative stands (i.e. mesic sites) of *Pinus cooperi*. We avoided injured or deformed trees, as well as those whose growth may have been influenced by competition for light or soil nutrients (Table 1). Sites had similar slopes (5–10 %) to reduce environmental variation. Homogeneity of tree size based on diameter at breast height (dbh) was the criterion for tree selection in the field. In the lab, we verified that tree ages were similar for comparative purposes.

Table 1. Geographical location of sampled *Pinus cooperi* plots

Site[1]	**Geographic coordinates**		**Elevation (masl)**	**No. of trees**	**Age mean & Sd[2] (years)**	**Dbh mean & Sd[2] (cm)**
	Longitude W (°)	**Latitude N (°)**				
H	105.534944	23.747306	2905	10	61(±3)	47(±3)
M	105.533583	23.752605	2813	7	58(±5)	50(±2)
L	105.503194	23.742139	2680	8	59(±4)	44(±4)

[1]H: High, M: Mid, L: Low. [2](Sd: Standard deviation)

Increment cores were collected from 3-10 trees at each site along the elevational gradient. Two or three increment cores were extracted for each tree of *Pinus cooperi* at 1.3 m height using increment borers of 5 mm and variable length (16 to 20 inches).

2.2 Dendrochronological Methods and Modeling Approach

Increment cores were processed using standard dendrochronological techniques to determine the exact year of formation of each growth ring [10]. In addition, *BAI* (m^2), was calculated from tree-ring width as a more accurate estimate of annual radial growth around the circumference of the tree, assuming concentric circularity. *BAI* was calculated using the ring widths of each core as follows:

$$BAI=\pi(R^2_t-R^2_{t-1}) \tag{1}$$

Where R_t is the radius (m) at coring height (dbh; inside bark) for year *t* of tree ring formation. The cores from each site were averaged to create a single basal area increment series for each site. The *BAI* measurements were then used to analyze relationships with selected climate variables.

In order to determine the climatic response of the *BAI* chronology, *BAI* data was compared with climate records from the nearby "El Salto" weather station [11] with data from 1946 to 2010. Data from the weather station indicated that most rainfall occurred during the summer period (June – August), representing 76% of the total annual precipitation, whereas 24% was recorded during the winter season (December – February). Climatic variables that were analyzed were total monthly precipitation (P) in mm, maximum monthly temperature (T_{max}), mean monthly temperature (T_{mean}), and minimum monthly temperature (T_{min}) in °C.

BAI records and climate relationships were carried out using DendroClim2002 [12]. With this software, we calculated the correlation coefficient using 1,000 replicates for each data point in a random resampling. This procedure associated the instrumental meteorological data with *BAI* variable. Furthermore, exponential regressions by nonlinear least squares were performed with the statistical software SAS/STAT® [13] in order to calculate *BAI* trends against time. Then, a *nlin* procedure was carried out to compute maximum current annual increment (BA_{CAI}) for each site along time, using the following equations:

$$BA = \beta_0 e^{\left(-\frac{\beta_1}{E}\right)} \tag{2}$$

$$BA_{CAI} = \frac{\beta_1 BA}{E^2} \tag{3}$$

Where BA is Basal Area (m^2); BA_{CAI} corresponds to maximum current annual increment of BA (m^2/year); e represents Napier's constant; E is the age of tree (years) and β_0, β_1 are the regression coefficients.

The criterion used for judging the performance of the model was based on a numerical analysis consistent in the comparison of three statistics commonly used in forest modeling: 1) the bias (E) that evaluates the deviation of the model with respect to the observed values; 2) the mean root square error (*RMSE*) that analyzes the precision of estimates; 3) the adjusted coefficient of determination R^2adj, which represents the percent of the variance explained by the model, taking into account the number of parameters in it. The expressions of these fitting statistics are summarized as follows:

$$\overline{E} = \sum_{i=1}^{n} (y_i - \hat{y}_i) / n \tag{4}$$

$$REMC = \sqrt{\sum_{i=1}^{n} \left(y_i - \hat{y}_i\right)^2 / (n-p)} \tag{5}$$

$$R^2_{\text{adj}} = 1 - (n-1) \cdot \sum_{i=1}^{n} (y_i - \hat{y}_i)^2 / (n-p) \cdot \sum_{i=1}^{n} (y_i - \bar{y}_i)^2 \tag{6}$$

This procedure provides an empirical model of tree growth based on the effects of BA_{CAI} across the elevational gradient. BA_{CAI} trees should exhibit a positive growth trend in response to an elevation increase, modulated by the respective climatic signal, while at the lower elevation *P. cooperi* should show slower growth.

3. RESULTS AND DISCUSSION

3.1 Basal Area Increment Trends

The *BAI* showed similar patterns among sites at different elevations, especially after the 1960´s, decreasing during 1960, 1971, 1974, 1980, 1989, 1991, 1996, 1999, 2003 and 2006. *BAI* showed high values across all sites in 1964, 1973, 1975, 1981, 1990, 1993, 1997, 2001, 2005, and 2007 (Fig. 1).

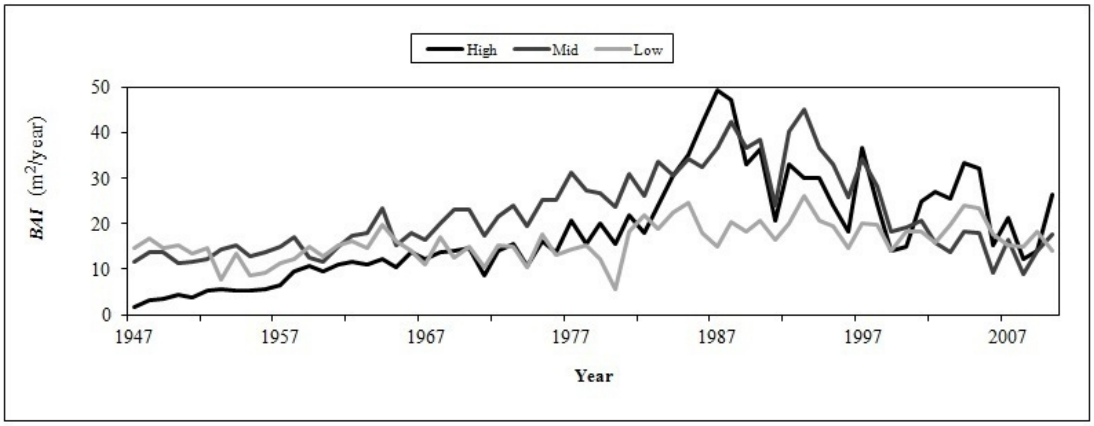

Fig. 1. *Pinus cooperi BAI* chronologies growing at different elevations at "Las Rusias" mountain.

3.2 Tree basal area increment and Climate Relationships

As shown in Fig. 2, the bootstrapped procedure conducted between the *BAI* and climatic variables showed significant correlations for the study area. All correlation coefficient values ranged from -0.5 to 0.42 ($p<0.05$). The Pearson´s coefficients indicated that P, T_{max}, and T_{mean} were important climatic variables along the gradient.

P. cooperi basal area increment was positively correlated with precipitation during the previous November and current January in High elevation. At mid-elevation, basal growth responded to precipitation during the previous November and December, whilst lower elevation show positive association with previous June, September and October. Radial growth response to T_{max} was negatively correlated at upper elevations, while L did not show any significant association. The basal area for the high elevation site was influenced by T_{max} during the previous June, July, August, September and December and also during the current January, February, April and August. In addition, a similar pattern was observed at mid-elevation, starting in the previous July and ending in the current September, showing higher values during the previous winter season. *BAI* was negatively associated with T_{mean} in high and mid-elevation sites. In contrast, low sites had a positive correlation with T_{mean} during the previous October and current September. Lastly, T_{min} did not show any significant association with *BAI*, although we observed positive coefficients in single months for mid and low elevations.

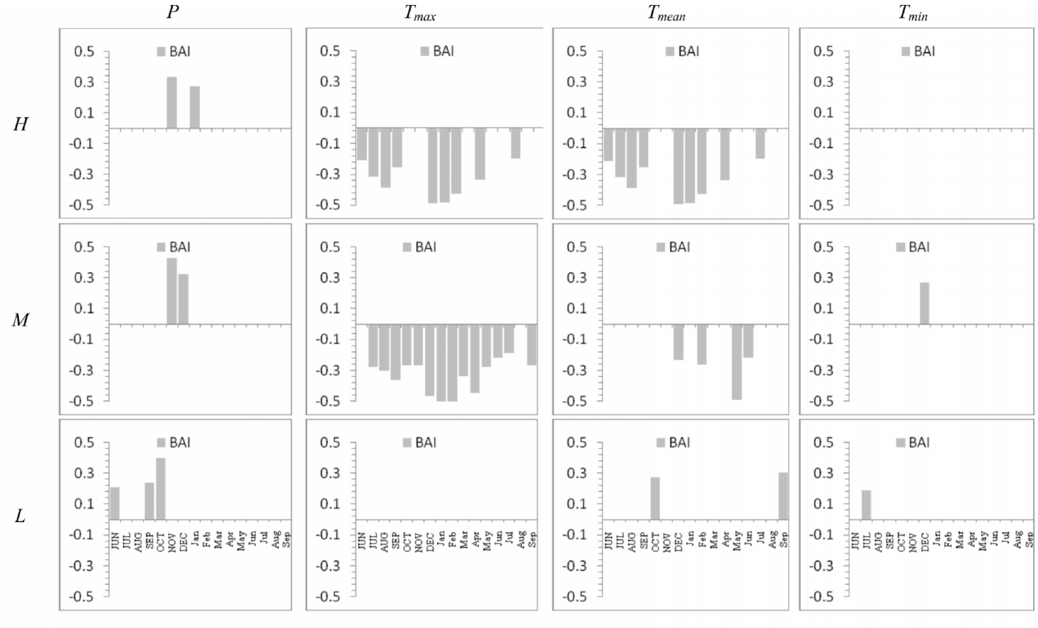

Fig. 2. Pearson's correlation coefficients between the *BAI* of *Pinus cooperi* and climate variables from 1946 to 2010 at three elevations. The correlation values are significant ($p < 0.05$). Uppercase denotes previous months of current year, whilst lowercase means months of current year. Numbers on y axis refer to Pearson´s values.

Table 2 displays the values of the estimated parameters and their corresponding approximated standard errors along with the goodness-of-fit statistics. Both parameter estimates were highly significant (Pr> |t| <0.0001). According to the results, the models had good fits because of their low *RMSE* and *E* values and over 97% of the variance was explained for all sites.

Table 2. Results of the adjustment of the model generated for BA_{CAI} estimation (significance (Pr> |t| <0.0001)

Elevation	Parameter	Estimation	Standard error	Statistics of fit		
				$\overline{E}$ (m^2)	*REMC*	R^2_{adj}
H	β_0	0.461167	0.0168	0.0008	0.0036	0.991
	β_1	-86.436	1.8743			
M	β_0	1.082085	0.0741	0.0046	0.0068	0.976
	β_1	-200.718	5.7995			
L	β_0	0.385722	0.0149	0.0022	0.0047	0.983
	β_1	-122.986	3.0198			

According to the goodness-of-fit statistics and for a given year, the model satisfactorily describes the data for *BAI* for the different elevation sites. We found a similar trend of BA_{CAI} for all sites (Fig. 3) with three clear phases: Juvenile phase, with growth rising moderately from 0 to 20 years; Mature phase from 20 to 45 years; and Senescent phase, with growth starting to slow down by 80 years. *H* had the maximum value at 105 years with 0.0029 m^2/year; *M* showed its higher value of 0.0024 at 96 years, while *L* did at 84 years with 0.002

m^2/year. Thus, the proposed model is suitable for describing the basal increment of *P. cooperi* along the elevational gradient on "Las Rusias" mountain.

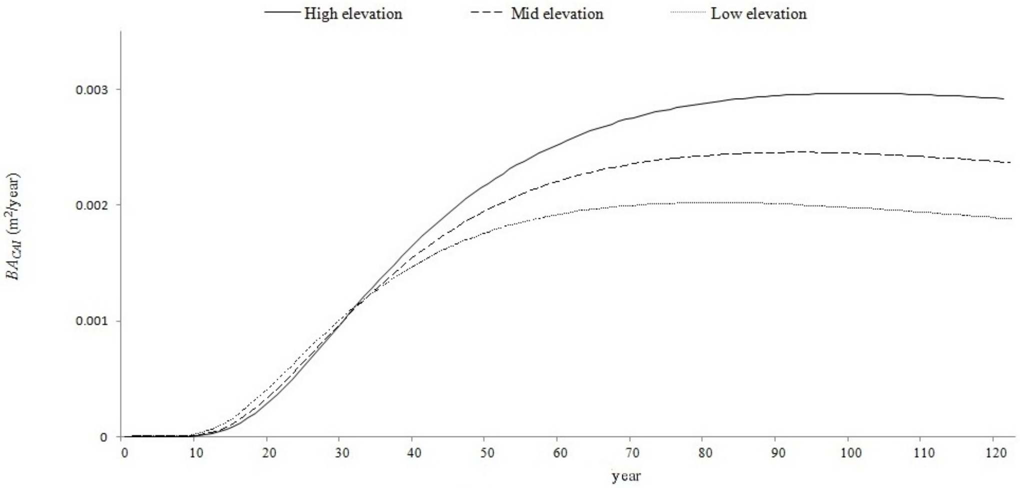

Fig. 3. Current annual increment of *BA* for *Pinus cooperi* in sites at three elevations on "Las Rusias" mountain.

The empirical model showed BA_{CAI} had an exponential increase with elevation explaining 98% of the variance (Fig. 4). The culmination of the maximum BA_{CAI} is reached at a higher altitude, ascending exponentially with increasing elevation. This relationship is shown in Fig. 4.

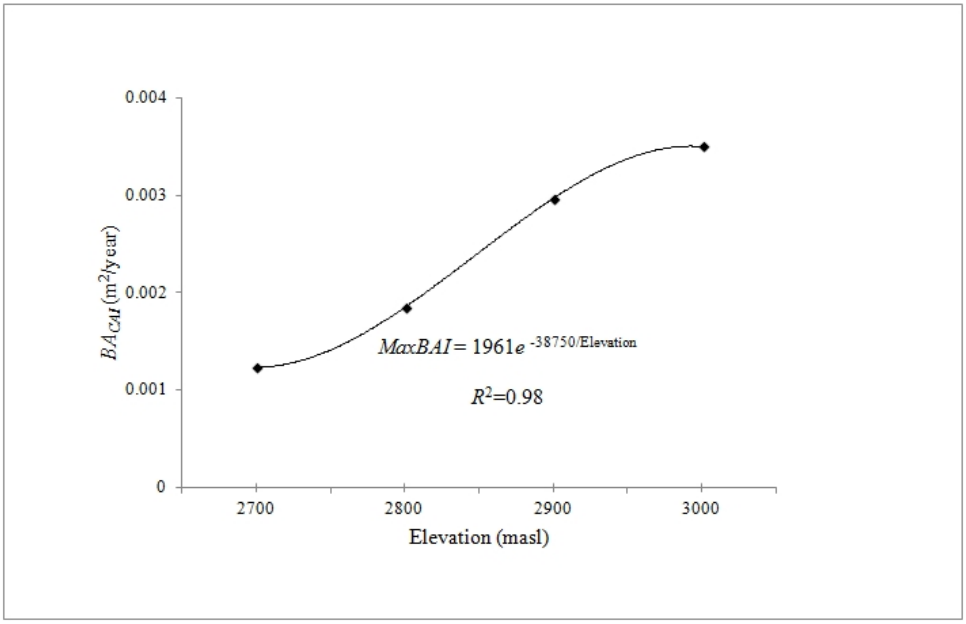

Fig. 4. Empirical function of BA_{CAI} for *Pinus cooperi* along the different elevations on "Las Rusias" mountain.

Elevation has been shown to control growth variation in several conifer forests [8]. The BA_{CAI} of *P. cooperi* stands reflected spatial variability among sites and responded to climatic variables from a nearby weather station with data from 1946 to 2010. The growth trends observed in Fig. 1 were useful to understand the effects of local microclimatic conditions on the *BAI* from temperate forest ecosystems subjected to gradual changes in precipitation and temperature. Although some differences in *BAI* data were found along the three elevation sites, the general trends in radial growth variation were comparable. A period of increased *BA* was precede by a stable growth phase in the 1950s, 1970s, 1990s, and 2000s which is in agreement with findings reported for nearby mixed conifer forests [6],[7]. These similarities suggest that *BAI* of *P. cooperi* is influenced by microclimatic conditions changing in an elevational gradient from 2,680 to 2,905 masl.

Correlation analysis demonstrated significant contributions of *P* to the *BAI* (Fig. 2). The climatic conditions of months previous to the start of the growing season showed the greatest influence on *BAI* for the three sites. *P* during the previous summer months had a significant response at *L* elevation site. Furthermore, less precipitation at lower elevation sites results in decreased radial growth, which is consistent with [4].

The negative influence of T_{max} and T_{mean} on *BAI* could be related to physiological dysfunction. Some scientists argue that maximum temperature induces defoliation of trees and loss of vigor, hence drought may cause a reduction in basal area [14]. The negative correlations observed between *BAI* and extreme temperatures have also been reported for subalpine tree species in the western USA [3].

The lack of a systematic and weak association with *BAI* found for T_{min} may indicate an adaptation of the species to low temperatures. Thus, *P. cooperi* takes advantage of colder conditions that extend the growing season into the winter, thus favoring a greater *BAI*. Minimal temperatures during winter may favor an increase in *BAI.* This is consistent with previous studies on other conifers in mountainous areas around the world [15,16].

Previous studies of *BAI* in pine species have been focused on epidometric approaches [17], [18]. They consider variables measured at specific locations and rarely take into account variations due to climatic fluctuations. Nevertheless, we found significant relationships between climatic variables and elevation for *P. cooperi*. We point out that *BAI* was dependent on elevation, which is also related with temperature and precipitation variability.

BAI showed exponential performance along the time as was expected [19]. In the first 20 years *P. cooperi* grew slowly, but from 20 to 45 years had its greatest *BA* increase, and at 80 and 100 years reached its maximum value. This is in line with previous results obtained in similar ecosystems [18]. In addition, BA_{CAI} increased as altitude increased. Thus, these results confirm the interaction of climatic variables and tree growth across an altitudinal gradient [20]. The results agree with our hypothesis that *P. cooperi* is more sensitive to temperature and precipitation at higher elevations. Thus, our results could be used to suggest strategies for forest management in the near future, as climatic changes become more apparent. Understanding the relationship between BA_{CAI} and elevation, as well as the influence of water and temperature variability, can provide useful managements tool in ecology and timber production in order to predict different responses to future environmental conditions [21].

Despite the great progress that has been made in the field of dendrochronology [22], the use of the epidometric approach is not common in this field, and we believe that the application of this data should be more widely utilized. Dendrochronological perspective captures the historical long-term growth patterns, which could not be achieved by traditional forest inventories. Also provide an accurate representation of year-to-year growth patterns, thereby giving managers helpful information for forest management. Nevertheless, tree-rings records usually have limited spatial information of the entire stand, hence they cannot provide a complete picture of stand growth [5].

4. CONCLUSION

In this study, we found that dendrochronological and epidometric approaches were useful to describe the response of *P. cooperi* populations to local climatic variables. Correlation analysis indicated that precipitation and temperature regulate the ecophysiological processes of the studied species along the elevational gradient. The climate factors in the previous year played a strong role in positively affecting radial growth of *P. cooperi*. The *BAI* variation was determined by exponential regression parameters according to the elevation. Thus, the hypothesis that sensitivity to rainfall and temperature will vary along the elevation gradient appears reasonable. The results showed that tree growth was influenced by both precipitation and temperature, indicating the importance of future climate change during 21st century. These projections have implications for tree growth on ecosystems that are characterized by pronounced gradients in precipitation and temperature. Foresters should take into account that climate change could significantly influence tree growth, particularly in those mountains landscapes.

Combining both approaches we detected the limits for change in BA_{CAI}. Indeed, these findings could be useful for analyzing stand productivity and carbon balance. However, some complementary factors including tree density, soil effects and silvicultural treatments should be considered as well. We recommend taking this finding into account as new information for forest management, particularly in mixed conifer forests.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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