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FORUM

Is climate a stronger driver of tree growth than disturbance? A comment on Toledo *et al.* (2011)

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Summary

1. A recent article published by Toledo *et al.* (2011b) investigates the effects of spatial variations in climate and soil, and of logging disturbance, on tree and forest growth in Bolivia. It concludes that climate is the strongest driver of tree and forest growth and that climate change may therefore have large consequences for forest productivity and carbon sequestration. However, serious methodological and conceptual discrepancies have been found that challenge these conclusions.

2. Because of an errant coding of 'time after logging' in the regression analysis, and because floristic changes induced by logging could not be incorporated into the analysis, the effect of logging on the average diameter growth is likely to have been strongly underestimated.

3. Basal area growth was improperly calculated as basal area change, and it displayed surprisingly high values, even among unlogged plots. We hypothesize that either these plots may be actually located in secondary forests recovering from past logging, or measurement biases may have hampered the data set.

4. Regardless of climate–growth relationships established across these plots, any inference concerning the potential effects of climate change on forest growth would require a specific quantitative assessment.

5. *Synthesis*. It is critical to re-assess the relative weight of climate and logging disturbance as driving factors of tree and forest growth, and to find an explanation for the very high basal area increment reported among the unlogged plots. We provide specific recommendations for further analyses of this and similar data sets.

Key-words: basal area change, Bolivia, climate, disturbance, logging, plant–climate interactions, tree growth, tropical forest

Introduction

In a recent article, Toledo *et al.* (2011b) analysed tree growth and stand basal area change in 165 1-ha forest plots distributed in logging concessions across tropical lowland Bolivia, in relation to spatial variation in climate and soil factors, and to the occurrence and intensity of logging, which half of the surveyed plots experienced. This impressive data set, and the broad variation of rainfall and soil fertility conditions over the studied area, allowed the authors to perform an original analysis of the combined effects of climate, soil and logging-related disturbance on average tree diameter growth and stand basal area change. The study concludes that climate is the strongest driver of forest growth and suggests that climate changes may reduce forest productivity and carbon sequestration, a statement that has received significant media coverage (Nature highlights, 2010).

We contend that this interpretation should be re-evaluated for three reasons. First, two errors were found in the analysis that lead to a severe underestimate of the effects of disturbance on forest growth. Second, a serious confusion between the concepts of basal area change, and basal area growth prevented the authors from detecting surprisingly high basal area increments during the study period, which questions the accuracy of the data set. Finally, we argue that the likely effects of climate change on forest growth cannot be inferred from the existing study without complementary investigations.

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First, we report on the most critical errors of the article; we then point out several necessary discussions for interpreting the results. Finally, we suggest complementary analyses that help to answer the questions that arise from this critical analysis.

Errors in variable definition and factor coding

UNLOGGED PLOTS SHOULD NOT BE CONFUSED WITH RECENTLY LOGGED PLOTS

In Toledo *et al.* (2011b), figure 2 (parts a, c, e and g) illustrates the relationship between average diameter growth (DGR_{avg}) in the studied plots and four variables: rainfall, temperature, soil fertility and time after logging. When considering only the logged plots, the factor 'time after logging' (TAL) appears to be the best predictor of DGR_{avg}, with a clear decreasing effect reported by the authors. However, the non-significant correlation reported between TAL and DGR_{avg} conflicts with this observation (their table 2). We suggest that this discrepancy may be explained by an errant coding of the factor TAL, which was considered to be equal to 0 years in the 80 unlogged plots. Obviously, plots that have never been logged should not be confused with recently logged plots (with a TAL value near to zero) and should not be used in a strict analysis of the TAL effect. This unfortunate confusion leads to the severe underestimation of the negative effect of TAL on diameter growth, resulting in the bias found in the aforementioned correlation analysis and in the multiple regression analysis of DGR_{avg} (their table 3).

BASAL AREA CHANGE IS NOT BASAL AREA GROWTH AND DISPLAYS SUPRISINGLY HIGH VALUES

Toledo *et al.* (2011b) explain that they 'calculated the basal area growth rate at the stand level (hereafter $BAGR_{stand}$) as the net yearly basal area change per plot. The $BAGR_{stand}$ was calculated as: $(BA_f - BA_i)/t$, where BA_f is the final total plot basal area and BA_i is the plot basal area at the start of the measurement interval (for control plots) or just after logging (for logged plots). In both formulae, t is the time, in years, between the two measurement dates. Note that $BAGR_{stand}$ includes the effects of growth, recruitment and mortality' (p. 256). According to this definition, and contrary to the proposed variable name, $BAGR_{stand}$ is a basal area change. Surprisingly, it was indistinctly interpreted as a basal area change related to carbon sequestration issues (third paragraph of the abstract), or as a basal area growth related to forest productivity (fifth paragraph of the abstract). Because basal area change is equal to basal area growth (biological increment) minus the basal area of trees experiencing mortality over the period, plus recruitment if taken into account, these two quantities should not be confused.

Unfortunately, this lexical confusion resulted in distorted comparison with the published literature. Thus, Toledo *et al.* (2011b) compared their '$BAGR_{stand}$' with the basal area growth of old-growth Amazonian forest plots (Lewis *et al.* 2004), finding no average difference (*c.* 0.5 m^2 ha^{-1} $year^{-1}$). However, had the comparison been performed using the basal area change of the same plots (Baker *et al.* 2004; Lewis *et al.* 2004), much lower values would have been found in Amazonia (*c.* 0.10 m^2 ha^{-1} $year^{-1}$ on average, with 20% of negative values). Furthermore, even when considering only the unlogged plots studied by Toledo *et al.* (2011b), the reported basal area change remains of a surprising magnitude: 0.48 m^2 ha^{-1} $year^{-1}$ on average, with a minimum value of 0.17 m^2 ha^{-1} $year^{-1}$. This questions the accuracy of the data set.

Refining spatial and temporal interpretations: climate proxies and floristics

MEASUREMENT PERIODS ARE SHORT AND SOME LIKELY ENCOMPASS A SEVERE DROUGHT

Toledo *et al.* (2011b) write that 'The 165 selected plots were all established between 1995 and 2005 and measurement periods varied between 2 and 11 years, with the last measurements taking place in 2007' (p. 256). Figure 2 (parts g and h) further shows that the median measurement period is around 3 years for the logged plots, with minimum values of 1 year. Such brief measurement periods can seriously compromise the accuracy of the data set, given the (i) reduced precision of tree-growth measurements and (ii) increased sensitivity to strong climatic events. These measurement periods most likely include the exceptionally severe drought that occurred in Amazonia in 2005, especially in the south-western region (Marengo *et al.* 2008). This event has been shown to have increased tree mortality (Phillips *et al.* 2010); it has likely also lowered tree diameter growth (Brienen & Zuidema 2005; Brienen *et al.* 2010), thereby reducing forest biomass sequestration (Phillips *et al.* 2009). In addition, the desiccation of tree's bark during a drought can lower a tree's apparent diameter to the same order of magnitude of annual growth (Stahl *et al.* 2010). Because the authors used 30-year averages as proxies for climate factors (rainfall, temperature, etc.), the effect of such climate disturbance and of different measurement periods cannot be accounted for in their analysis, resulting in bias in the reported growth–climate relationship.

LOGGING EFFECTS ON FLORISTIC CHANGE SHOULD BE CONSIDERED

Logging is well-known to induce changes in floristic composition in favour of fast-growing light-demanding species (Favrichon 1998; Flores, Gourlet-Fleury & Picard 2006; Peña-Claros *et al.* 2008; Bonnell, Reyna-Hurtado & Chapman 2011). Such changes amplify the positive effect of logging on the mean diameter growth of stands, both in intensity and over time. However, since Toledo *et al.* (2011b) calculated tree growth from only two censuses, they could consider only trees that were alive and of a minimum inventory size during the whole of the survey period, excluding any trees recruited during this period. As a result, the effect of post-logging floristic change on tree growth was completely ignored. This introduces a

strong difference of approach in the comparison of logging with climate and soil as drivers of tree growth, since floristic composition also displays marked variation across plots, largely in relation to local climate and soil conditions (Toledo *et al.* 2011a), and having an implicit contribution to the estimated effects of climate and soil on tree growth.

SHIFT FROM VARIATION IN SPACE TO VARIATION IN TIME IS NOT SIMPLE

Toledo *et al.* (2011b) claim (synthesis of their abstract) that 'Climate is the strongest driver of spatial variation in tree growth, and climate change may therefore have large consequences for forest productivity and carbon sequestration'. However, the existence of a significant effect of spatial climatic variation on forest growth does not demonstrate that climate change will have particularly large consequences. The assessment of likely climate change impacts on forest productivity and carbon sequestration would require additional exploration. As a first attempt, the authors could have used multiple regression models (their table 3) to simulate the consequences of future climate scenarios. Such an analysis would be based on the assumption that a given climate variation across space will have the same effect on forest growth when occurring over time. Since spatial differences in forest plots are subject to biogeographical floristic variations that are unlikely to be comparable with floristic change of a given plot, this assumption requires supporting evidence.

Conclusions and suggestions for further analyses

The effect of logging on average diameter growth is likely to have been strongly underestimated, because of the errant coding of 'time after logging' in the regression analysis, and because floristic changes induced by logging could not be incorporated into the analyses. In addition, the cited effect of climate is also inaccurate, since the stationary proxies of climate used in this study are unable to take into account the unequal periods of growth measurement across plots and climatic events such as the drought that occurred in 2005.

It is therefore necessary to re-evaluate the authors' main conclusion that climate has a stronger effect on mean tree and forest growth than soil or disturbance. While the study could be refined in terms on several aforementioned aspects, solving the coding problem would immediately bring about considerable clarification. Using the same regression analysis, the authors could adjust the TAL value of the unlogged plots to maximize the coefficient of determination. The adjusted value could be interpreted as a return time after logging to the initial diameter growth. However, the effect of TAL is unlikely to be linear, nor independent of the impact of logging (Sist & Ferreira 2007). Therefore, we suggest using the variable $BA_{lk}/(TAL + Ct)$, where BA_{lk} is the basal area of the trees removed or killed by logging and Ct is a constant adjusted for maximizing the prediction of growth. BA_{lk} is similar to the 'lost basal area' index that has been proved efficient for predicting the abundance of light-demanding species 10 years after logging (Molino & Sabatier 2001), and Ct can be interpreted as the half-life of the effect of logging on diameter growth.

The most striking observation of Toledo *et al.* (2011b) is the very high basal area increment of the Bolivian forests during the measurement period, whereas negative values would be expected in a number of plots that experienced the severe drought in 2005 (Phillips *et al.* 2009). As a possible explanation, Toledo *et al.* (2011b) report that 'Field observations found that past logging affected some plots in the Bolivian network, which led to an opening in the canopy and the establishment of (long lived) pioneer species. Plots that showed the highest growth rate also had a high density of (long lived) pioneer species' (p. 261). This statement suggests that forests that are presumed to be undisturbed may actually remain under the influence of ancient logging. Although this would explain the high discrepancy in basal area change between the measures of Toledo *et al.* (2011b) and the aforementioned literature, it would also imply that these 'old-growth' forests were secondarized to a very large extent in the study area. Consequently, the accuracy of these plot measurements also appears to be an issue for debate. Possible biases in estimating basal area change have been identified by Phillips *et al.* (2002) and Wright (2005), and they include measures carried out by different teams in the successive censuses. It may be worth conducting specific investigations on this issue. In particular, we suggest separating basal area change into basal area growth, recruitment and mortality and then testing for an effect of the different teams involved in the census measures on these three components.

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