Effects of temperature and precipitation on vegetation structure

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Goal

To theoretically investigate the consequences of changing temperature and precipitation (water availability) on salient aggregate properties of single-species forest dynamics.

Background and motivation

Current informal estimates place the number of species inhabiting our planet around 1.7 billion. This impressive diversity is the result of evolution over millions of years, in which many more species emerged that are now extinct. Though countless factors affect this evolutionary process, climate has clearly played an important role in determining which species lived on and which species went extinct.

Climate on earth has changed several times during the past millions of years, according to studies using a broad range of proxies such as ice cores, pollen, and tree rings (LaMarche 1974; Dansgaard et al. 1993; Lara and Villalba 1993; Briffa et al. 1995; Petit et al. 1999; Fowell et al. 2003). These changes have mainly been due to natural factors, such as solar cycles and biotic influences. Since the last century, however, one single species is shifting the natural atmospheric equilibrium: human impacts are causing an unprecedentedly quick elevation of atmospheric carbon-dioxide levels, leading to an elevation in the earth's average temperature. Although every living organism is affected by these changes, plants may be particularly at risk, as they are not able to migrate at the same timescale as the climate changes. Instead, plants largely have to rely on metabolic, physiological, and ecological strategies to compensate for environmental changes.

In an effort to secure understanding of how plants adapt to changing climate, a number of studies have considered changes in observables such as phenological characters and physiological rates, but due to methodological limitations, most of these studies only analyzed a limited period of a plant's life. These limitations make it difficult to obtain a complete picture of how species adapt in response to environmental changes. Furthermore, it is difficult to elucidate which responses are occurring in response to natural processes and which are related to anthropogenic influences. Quantitative models can help address these challenges, by integrating the impacts of a variety of environmental factors on the life cycle of a tree. This yields a particularly promising approach to studying the vegetation consequences of climatic changes. Naturally, such models need to be informed by empirical data. For this purpose, and also to address the other questions above, it is important to obtain long-term records of how vegetation has changed in response to climatic conditions.

Dendrochronology (from the Greek dendros = trees, chronos = time, and logos = knowledge) is a well-established science that can be used to infer growth rates under different environmental conditions (Schweingruber 1989; Stokes and Smiley 1996). It provides accurate and long series of data that provide yearly records of changes in environment conditions at a study site. As one example, tree-ring width (one of the characters used in dendrochronology) shows strong correlations with temperature and precipitation across different landscapes throughout the world (Lara and Villalba 1993; Briffa et al. 2001; Briffa et al. 2004).

Although most of dendroclimatic studies have considered trees of temperate species, some tropical tree species have been shown to be especially suited for this kind of study. Worbes (2001), Schöngart et al. (2002, 2004, 2005, 2006), and Oliveira et al. (2009) have all shown that many tropical species are particularly suited for dendroclimatological analyses (in addition to unpublished works on the genera *Cedrela*, *Hymenaea*, and *Podocarpus* that also show promising results).

In this project, I will incorporate dependences on temperature and precipitation in an established model of plant growth developed by a former YSSP participant (Falster et al. 2010). The extended model will be used to study how emergent properties of vegetation, such as net primary productivity (NPP) and total biomass, are expected to change in response to future changes in temperature or precipitation changes.

Research questions

The present study aims to elucidate the effects of changes in temperature and precipitation on vegetation structure. In particular, the following questions will be addressed:

- How do different temperature and precipitation regimes affect salient aggregate statistics of vegetation structure, in particular, average height, leaf-area index, net primary productivity, and biomass density?
- Which factor – temperature, precipitation, or stand age – is most limiting for tree development?
- How will tree stands develop under plausible future environmental scenarios?
- Do temperature and precipitation significantly interact in determining the population dynamics of trees?
- If time allows, I will also consider how different temperature and precipitation regimes affect evolutionary dynamics of leaf mass per area and height at maturation.

Methods and work plan

Dendrochronological data

We have available two datasets of tree-ring width measurements for two different tropical tree species (*Cedrela fissilis – Meliaceae* and *Hymenaea courbaril – Leguminosae*). These datasets have already been used to build chronologies of approximately 110 years, and both have been demonstrated to show significant relationships with climate (*Cedrela* mainly with temperature, *Hymenaea* mainly with precipitation). These relationships, between tree rings and temperature/precipitation, are well described by linear models with normally distributed residuals.

Photosynthetic effects of temperature and precipitation

The rate of photosynthesis is well known to vary with temperature and precipitation. For temperature, this relationship is accurately represented by an initially exponentially increasing function, usually with a saturating maximum, and it is related to the optimal temperatures of the chemical reactions of this process (Bernacchi et al. 1992, 2001; Taiz and Zeiger 2004). On the other hand, water availability acts as a limiting factor on photosynthesis since it affects the opening or closure of stomata, which changes CO_2 fluxes, and thereby alters photosynthetic rates and the transport of photoassimilates (Taiz and Zeiger 2004).

Model adaptation and extension

The vegetation model by Falster et al. (2011) will be adapted and extended to account for temperature and precipitation. As the relationships between tree rings and temperature/precipitation are well described by linear models with normally distributed residuals, a reasonable first assumption might be that, for the ranges of these two variables represented in the dendrochronological data, temperature and precipitation have linear and additive effects on photosynthesis, and thus also carbon assimilation. However, this assumption may not be adequate, as there are known interaction effects between temperature and precipitation (for example, high temperatures augment soil-water evaporation, leaving less water available for the trees). Moreover, using such simple models might hinder considering the effects of climate changes that are falling outside of those that have occurred in the past.

To overcome these challenges, we will first explore the extent to which interaction effects are affecting growth dynamics, by exploring selected interaction models. Second, we will make the leaf photosynthesis parameter that describes light-saturated photosynthesis a function of temperature and water use. The leaf will operate at constant maximum water use if it has enough water, which depends on this leaf water use and total leaf area. If water availability for the tree is less than the maximum water use, stomata will close, which means that water use per leaf and photosynthesis decline in parallel. To account for effects on respiration, we will include a temperature-dependent factor in the maintenance respiration.

Finally, the vegetation model by Falster et al. (2011) has been developed for Australian conditions, and will thus need to be parameterized with Brazilian trees data. Fortunately, as both countries have similar vegetation and are both influenced by ENSO (El Niño Southern Oscillation), only a few adjustments may be needed to account for the differences.

Model implementation

The model will be implemented in Matlab using an upwind scheme to solve the non-local partial differential equations that underlie the population dynamics.

Influence of climate on forest dynamics

After the model has been implemented, the available dendrochronological data will be used to parameterize the dependence on temperature and precipitation. Since the trees of the dendrochronological dataset are from well-mixed forests, we will examine several constant light environments sampled from an assumed heterogeneous forest.

Once the model has been parameterized, we will explore how the modeled stands grow under the three future temperature scenarios proposed by IPCC (2007). If possible, we will also investigate the potentially interacting effects of changes in water availability. The outputs will be compared with the original model by Falster et al. (2011) , as well as with literature data.

Work plan

The first step in this work will be to test, using R, if there are significant interaction effects of temperature and precipitation on tree growth. We will then adjust the photosynthesis parameter as a function of temperature and/or precipitation, initially as a linear additive effect. After this, we will parameterize the new version of the model with the available data (biomass, tree density, diameter distribution, etc. – if possible) from the sampling sites.

Once the model has been properly parameterized, the new model will be implemented in Matlab, accounting for population-level feedbacks. After implementing the model, we will finally investigate how the modeled stands grow under different future temperature scenarios.

Relevance and link to EEP's research plan

This project, which is an extension of a previous YSSP project by Daniel Falster in 2006, will contribute to EEP's ongoing research on *Evolving Biodiversity*, by establishing a framework in which the impacts on vegetation of changes in temperature and precipitation can be assessed.

Expected output and publications

The results of this project are intended to be published as a coauthored article in an international scientific journal.

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