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Topic: Macrophysiology: What is the role of large-scale vegetation data in understanding climate change?

Author: Jonathan Scott Schurman, Ph.D.

Vegetation plays a major role in regulating environmental conditions, locally, regionally and globally. In order to maintain their functioning, plants pump large quantities of water into the atmosphere and sequester carbon dioxide in their tissues. Plants thereby participate in a climatic feedback: climate regulates the biogeographic distribution of plant species, and plants in turn stabilize the climatic conditions that benefit their growth. I strongly encourage you to read Bonan (2008) for an excellent and accessible overview of plant-climate feedbacks. For some examples particularly interesting examples, consider that the evolution of photosynthesis (which occurred over three billions of years ago) lead to the oxygenation of earth's atmosphere and permitted the evolution complex life forms. Rainforests are also responsible for generating their own climate by pumping such large quantities of water that the atmosphere saturates and water vapor quickly condenses and 're-rains', which localizes the water cycle above these productive regions (Salati et al., 2079). These last two examples are fairly clear, albeit extreme examples, but similar feedbacks occur over all vegetated biomes.

Bonan, G. B. (2008). Forests and climate change: forcings, feedbacks, and the climate benefits of forests. *science*, *320*(5882), 1444-1449.

Salati E, Dall'Olio A, Matsui E, Gat JR (1979) Recycling of water in the Amazon Basin: An isotopic study. Water Resour Res **15**(5):1250–1258

Understanding feedbacks between climate and vegetation is an important component of forecasting the role that plants will play in buffering forthcoming climate change, mostly through the role of forests as a large carbon sink. Plant-climate relationships are also critically important for predicting what our ecosystems will look like 20, 50 or 100 years from now, which will greatly alter the services we extract from our landscapes. For example, much of Europe has been aggressively reforested over the past 70 years, with Norway spruce (Picea abies) generally selected as the primary species, because it is a good source of cheap and fast-growing lumber. However, it has become increasingly apparent, that more these Picea abies plantations are quite susceptible to hazards associated with rising temperatures, and forestry operations are struggling to make decisions surrounding the management of their current wood resources and what wood crops constitute potential spruce replacements (Hanewinkel et al., 2013).

The following document provides a brief guided reading to introduce several important developments, both theoretical and empirical, in the field of understanding feedbacks between vegetation and climate. This overview is extremely brief, but aims to map how the scientific process bounces back and forth between theory and empirical testing to address surprising discoveries and tackle problems surrounding the well-being over people and our natural environments. This overview ends with the introduction with a new branch of science that was born out of this gradual evolution of scientific ideas, which my colleagues and I conduct here at the Faculty of Forestry, in the Czech University of Life Sciences.

Hanewinkel, M., Cullmann, D. A., Schelhaas, M. J., Nabuurs, G. J., & Zimmermann, N. E. (2013). Climate change may cause severe loss in the economic value of European forest land. *Nature climate change*, *3*(3), 203-207.

1. A predictive model of our biosphere: integrating findings across scales

Biology is divided into subdisciplines based on subject matter and also their spatial and temporal scales of investigation. Regarding plants, physiologists work with cells and leaves, plant populations biologists deal with groups of individual plants, sometimes along environmental gradients, and biogeographers concern themselves with collections of species distributed across entire continents. The methods employed by each subdiscipline have scope (a conceptual space to which the findings are relevant) and limitations to their generality. Often, a model of a plant system generated by a specialist working at one level of biological organization will make a number of simplifying assumptions about whether dynamics at a smaller scale are relevant to the broader picture. This line of reasoning and its common pitfalls is excellently laid out in the paper: "How close are we to a predictive theory of the biosphere" Moorcroft 2006. Moorcroft outlines the development of dynamic vegetation models and the evolution from 'big leaf models' (which largely attempted to predict continental vegetation dynamics from the photosynthetic properties of leaves) to models which depict the population dynamics of trees.

Moorcroft, P. R. (2006). How close are we to a predictive science of the biosphere? *Trends in Ecology & Evolution*, *21*(7), 400-407.

2. Upscaling from demographic data

Insights from papers like Moorecroft show that conventional, random sampling of forest structure (i.e., counting trees in standardized forest inventories) is a critical, because demographic processes that causes changes population structure are a necessary step stone between tree physiology and plant mediation of biogeochemical cycles. This revelation has been employed in order to explain a rather surprising discovery made at the turn of the last century: the terrestrial biosphere is absorbing approximately 25% of human CO2 emissions. For decades, we have been operating under the assumption that large forested areas are more or less in equilibrium with growing conditions; an assumption that has long formed the basis of our forest management practices, but was reinforced by simulation studies in the early days of computational ecology (Shugart 1981). Equilibrium implies that carbon gains should be balanced by carbon losses, so increasing terrestrial C sequestration thus implied that changes were taking place in the terrestrial sphere. In developed regions like Europe and the Eastern USA, increasing forest area was causing increased C uptake. Another, more hypothetical mechanism, is that global increases in temperature and CO2 are promoting plant productivity, leading areas which are already forested to absorb additional C.

Shugart, H. H., & West, D. C. (1981). Long-term dynamics of forest ecosystems: Computer simulation models, which allow for numerous seedlings and the long lives of large trees, predict how forests will respond to different management techniques. *American Scientist*, *69*(6), 647-652.

Quantifying whether environmental changes are causing forests to accumulate extra CO2 is a considerable complicated problem to solve. This is because most forests are at some stage of recovery from an event in the past which released C, such as a fire, drought, incept outbreak, etc. The following papers deal with the conceptual issues surrounding how we deduced the drivers of C accumulation in forests, including the validity of equilibrium assumptions and how spatial variation interacts with the size of observation networks to alter the stability of empirical estimates.

Luyssaert, S., Schulze, E. D., Börner, A., Knohl, A., Hessenmöller, D., Law, B. E., ... & Grace, J. (2008). Old-growth forests as global carbon sinks. *Nature*, *455*(7210), 213-215.

McMahon, S. M., Parker, G. G., & Miller, D. R. (2010). Evidence for a recent increase in forest growth. Proceedings of the National Academy of Sciences, 107(8), 3611-3615.

Chambers, J. Q., Negron-Juarez, R. I., Marra, D. M., Di Vittorio, A., Tews, J., Roberts, D., ... & Higuchi, N. (2013). The steady-state mosaic of disturbance and succession across an old-growth Central Amazon forest landscape. *Proceedings of the National Academy of Sciences*, *110*(10), 3949-3954.

3. Measuring biomass increments: Using tree rings to study climate vs. using tree rings to study forests

Tree-rings are an extremely useful anatomical feature of trees for studying interaction between climate and the biosphere. Most people are familiar with tree rings: by looking at the cross section of a tree trunk, the delineation of each growing season can be easily observed. Trees growing in climatically extreme locations thus provide a record of climatic variability experienced throughout their lifetime. However, sampling traditions in 'Dendroclimatology' are largely focused on eliminating biological sources of variation imprinted on a tree's growth history, to better reveal the climatic imprint. The challenges in generalizing from dendroclimatic data to understanding the roles of forests in biogeochemical cycles are covered by the following papers:

Nehrbass-Ahles, C., Babst, F., Klesse, S., Nötzli, M., Bouriaud, O., Neukom, R., ... & Frank, D. (2014). The influence of sampling design on tree-ring-based quantification of forest growth. *Global change biology*, *20*(9), 2867-2885.

Klesse, S., DeRose, R. J., Guiterman, C. H., Lynch, A. M., O'Connor, C. D., Shaw, J. D., & Evans, M. E. (2018). Sampling bias overestimates climate change impacts on forest growth in the southwestern United States. *Nature communications*, *9*(1), 1-9.

4. Learning from dendroecological datasets

Recognizing these pitfalls of traditional tree ring data has motivated more extensive approaches in tree ring science, often broadly classified under "dendroecology". This new wave of research emphasizes random sampling methods that integrate over both environmental and demographic sources of variables. An interesting technique that has been developed to make sense of these large datasets has been to quantify the degree of growth synchrony among trees growing throughout biogeographic regions. Since climate is the only mechanism that could reasonably coordinate tree growth over such large areas, quantifying the degree of synchrony in tree growth an dhow this changes through time provides a tidy way to measure the degree of climatic stress exerted over forested areas. This then provides a starting point to explore in more detail, which climate factors (drought, frost, etc), are responsible for large scale changes in tree physiology. Our group at CZU has been increasingly finding new applications for large tree rings datasets. We also used synchrony to highlight shifting climatic drivers and invoke several of the theoretical arguments claimed throughout this guided reading to argue that forest productivity is increasing in the Carpathians.

Shestakova, T. A., Gutiérrez, E., Kirdyanov, A. V., Camarero, J. J., Génova, M., Knorre, A. A., ... & Voltas, J. (2016). Forests synchronize their growth in contrasting Eurasian regions in response to climate warming. *Proceedings of the National Academy of Sciences*, *113*(3), 662-667.

Schurman, J. S., Babst, F., Björklund, J., Rydval, M., Bače, R., Čada, V., ... & Svoboda, M. (2019). The climatic drivers of primary Picea forest growth along the Carpathian arc are changing under rising temperatures. *Global change biology*, *25*(9), 3136-3150.