Ecography

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Vanderwel, M. C. and Purves, D. W. 2013. How do disturbances and environmental heterogeneity affect the pace of forest distribution shifts under climate change? – Ecography 36: xxx–xxx.

Supplementary material

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Appendix 1. Details of CAIN Forest Dynamics Model

A.1 Tree Growth and Mortality

For each plant functional type (PFT), annual tree diameter growth (*G*, cm·y^{-1}) and mortality rates (*M*, y^{-1}; the inverse of longevity, *L*) were modelled as the product of a maximum rate term (δ, ψ) and three terms that account for the effects of tree size (diameter at breast height, *DBH*), local competition (crown area index, CAI_h), and environmental conditions (mean annual temperature, *MAT* (°C), and precipitation, *MAP* (cm·y^{-1})):

$$G = \delta \times G_S(DBH) \times G_C(CAI_h) \times G_E(MAT, MAP) \tag{A1}$$

$$M = \{1 + \psi \times L_E(MAT, MAP) \times L_S(DBH) \times L_C(CAI_h)\}^{-1} \tag{A2}$$

Size effects: To account for the effect of tree size, growth varies as a log-normal function of diameter, whereas longevity both increases as a power function of diameter and decreases as a sigmoidal function of diameter to produce an overall U-shaped mortality function:

$$G_S(DBH) = \exp\{-0.5 \times [\ln(DBH/\gamma)/\nu]^2\} \tag{A3}$$

$$L_S(DBH) = \frac{(DBH/10)^{\phi}}{1 + \exp[\lambda \times (DBH - \theta \times DBH_{0.01})]} \tag{A4}$$

where γ, ν, ϕ, θ, and $D_{0.01}$ are PFT-specific parameters and

$$\lambda = \ln(99)/[D_{0.01} \times (1 - \theta)] \tag{A5}$$

Competition effects: Height-structured competition is implemented through a state variable for a forest inventory plot's crown area index (CAI_h), a unitless measure for the projected area of all tree crowns ($CA_{h,i}$, m^2) at a given height *h* (m), normalized by the area of the plot (*A*, m^2):

$$CAI_h = \frac{\sum_i^N CA_{h,i}}{A} \tag{A6}$$

The summation is performed across all *N* trees within the plot, including those belonging to other PFTs. Projected crown areas were calculated based on the tree height and crown allometry models described in Purves et al. (2007) and in Vanderwel et al. (2013a). Projected crown area remains constant from the base of a tree's crown to the ground, so CAI_h increases montonically from the top of the canopy to the ground.

To account for the effect of competition, both growth and longevity decrease as negative exponential functions of CAI_h:

$$G_C(CAI_h) = \zeta + (1-\zeta)\times \exp(-\kappa \times CAI_h) \quad \text{(A7)}$$

$$L_C(CAI_h) = \omega + (1-\omega)\times \exp(-o \times CAI_h) \quad \text{(A8)}$$

where ζ, κ, ω, and o are PFT-specific parameters and CAI_h is evaluated at the mid-crown height, h (m), of the tree.

Climate effects: To account for the effects of climate, we first defined the major climatic axes of variability in growth and mortality (E_G, E_L) as linear combinations of mean annual temperature and precipitation. For each vital rate, this climate axis was defined by a single parameter (g_1, l_1) that determined whether performance varied most strongly with a spatial gradient in temperature, with precipitation, or with some combination of temperature and precipitation:

$$E_G = \cos(g_1) \times MAT' + \sin(g_1) \times MAP' \quad \text{(A9)}$$

$$E_L = \cos(l_1) \times MAT' + \sin(l_1) \times MAP' \quad \text{(A10)}$$

where g_1 and l_1 are PFT-specific parameters, and MAT' and MAP' are mean annual temperature and precipitation values that have been rescaled to the range [0, 1]. We rescaled E_G and E_L to the range [0,1] for each PFT, and allowed growth and mortality to vary as Gaussian functions of these climate gradients:

$$G_E(MAT, MAP) = \exp\left[-\left(\frac{E'_G - g_2}{g_3}\right)^2\right] \quad \text{(A11)}$$

$$L_E(MAT, MAP) = \exp\left[-\left(\frac{E'_L - l_2}{l_3}\right)^2\right] \quad \text{(A12)}$$

where g_2, g_3, l_2, and l_3 are PFT-specific parameters, and E'_L and E'_G represent positions along the rescaled climate gradient. Ranging for MAT, MAP, E_G, and E_L introduced additional calculations, but greatly aided parameter fitting by ensuring that the variables were always bounded by 0 and 1.

A.4 Recruitment

Annual recruitment for each PFT (I, $ha^{-1}\cdot y^{-1}$) was defined as the density of stems, per year, that reach the minimum DBH threshold used in our simulations (3 cm). Recruitment was modelled as the product of a maximum rate term (τ) and three terms that account for the effects of local competition, landscape-level propagule sources, and environmental conditions (*MAT*, *MAP*):

$$I = \tau \times I_C(CAI_0) \times I_L(LBA) \times I_E(MAT, MAP) \tag{A13}$$

where *LBA* ($m^2 \cdot ha^{-1}$) is the basal area of the PFT in the landscape surrounding a given plot.

Competition effects: Like growth and mortality, recruitment decreases as a negative exponential function of crown area index. For recruitment, CAI_h is evaluated at the level of the ground (h=0). We modified the negative exponential function to have a flat shoulder up to a certain value of CAI_0, above which estimated recruitment begins to decrease:

$$I_C(CAI_0) = \min\{1, \chi + (1 - \chi) \times \exp[-\upsilon \times (CAI_0 - i_5)]\} \tag{A14}$$

where χ, υ, and i_5 are PFT-specific parameters.

Source effects: The CAIN model accounts for variation in recruitment with the abundance of the PFT in the surrounding area by allowing recruitment to increase as a power function of *LBA*:

$$I_L = (LBA/5)^{i_4} \tag{A15}$$

where i_4 is a PFT-specific parameter. In most of the simulations presented here, *LBA* represents the average basal area of each PFT across 30 stands simulated for a given 0.5° grid cell. In one of our scenarios ("no recruitment limitation"), we fixed *LBA* for each PFT to the global constant of 5.66, which was the average basal area of each PFT in counties for which a given PFT had a mean abundance of at least one tree per plot. This had the effect of removing landscape-level source effects on recruitment within our simulations.

Climate effects: The effects of climate on recruitment were modelled in the same manner as they were for growth and mortality.

$$E_I = \cos(i_1) \times MAT' + \sin(i_1) \times MAP' \tag{A16}$$

$$I_E(MAT, MAP) = \exp\left[-\left(\frac{E'_I - i_2}{i_3}\right)^2\right] \tag{A17}$$

where i_2, i_3, and i_4 are PFT-specific parameters.

References

Purves, D.W., Lichstein, J.W., Pacala, S.W. 2007. Crown plasticity and competition for canopy space: a new spatially implicit model parameterized for 250 North American tree species. PloS ONE 9:e870.

Vanderwel, M.C., Lyutsarev, V., Purves, D.W. 2013a. Climate-related variation in mortality and recruitment determine regional forest-type distributions. Global Ecology and Biogeography, in press.