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The Harvard Forest Carbon Budget: Patterns, Processes and Responses to Global Change

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How, where and why carbon (C) moves into and out of an ecosystem through time is a long-standing question in biogeochemistry. In forests, C balance both affects and is influenced by disturbance, successional and trophic dynamics, climate change and atmospheric chemistry. The biogeochemistry of C in forests is also key to understanding whether, how, and for how long this important sector of the terrestrial biosphere will mitigate global environmental changes driven by human activity. Here we bring together hundreds of thousands of observations on the C cycle for the Harvard Forest in central Massachusetts, USA, a mid-latitude landscape dominated by closed-canopy forests 80 to >250 years old that has experienced a land-use history of harvesting, agricultural land clearance and reforestation that is shared by much of eastern North America. We synthesize these data to answer four questions: (i) how much C is stored and in what forms; (ii) what is the rate of C accrual or loss for the period 1990–2015 and what biotic and abiotic factors affect its variability; (iii) is there evidence that climatic and atmospheric change is affecting the phenology and seasonality of the C fluxes; and (iv) how do C-cycle conclusions drawn from experimental studies intended to simulate changes in soil temperature, atmospheric N deposition, hurricanes and invasive insects compare to ongoing climate change and prior land use? We find that soil and tree biomass have been nearly equal in their contribution to C storage but gains or losses of C from the soil pool remain poorly constrained. The legacy of land-use change dominated rates of net primary production (NPP), averaging 730–970 gC/m2/yr, with belowground NPP contributing 30–60% of the total. Net ecosystem production (NEP) averaged 300 gC/m2/yr. Longer growing seasons and warmer winters in the last two decades were correlated with a nearly 30% increase in NPP and 50% increase in NEP. Rising atmospheric CO_2 and greater water-use efficiency may have reinforced this pattern. In contrast to 25 years of extreme soil warming (+5 °C) with average soil C losses of −60 gC/m2/yr, ongoing climate warming resulted in a net sink of C that is 2–7 times larger than soil C loss. Climate and atmospheric chemistry changes resulted in an annual increment of ecosystem C equivalent to that simulated by high rates of N deposition (+50 kgN/ha/yr). The incipient loss of hemlock forests due to the nonnative hemlock woolly adelgid resulted in an average net ecosystem C loss of 140 gC/m2/yr. This data synthesis suggests that changes in climate, atmospheric chemistry, invasive insects, forest harvesting, and forest conversion to development strongly modulate the C cycle of mid-latitude forests but that great care is needed when extrapolating the results of global change manipulations. The example with soil warming will be highlighted.