Climate Change, Vegetation Dynamics, and the Landscape Water Balance

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Carbon dioxide (CO_2) in the atmosphere has increased by over 100 parts per million since the beginning of the Industrial Revolution, resulting in one of the most unambiguous effects of human activities on the globe. While rising CO_2 concentration has implications for atmospheric temperature change due to its greenhouse gas characteristics, it also has significant ramifications for how vegetation functions on landscapes and its ecohydrological consequences. Therefore, a large effort over the past decade has aimed at understanding the coupled ecological and hydrological responses to global change, such as rising CO_2 concentrations, temperatures, and alterations in precipitation. Of these, numerous studies have focused solely on how plants and ecosystems may respond to this change in atmospheric composition, giving us confidence to predict vegetation change in the face of predicted future CO_2 concentrations and potential feedbacks of the biosphere on the atmospheric change.

Contrasting Scenarios for Rising CO_2

Carbon dioxide is the primary substrate for photosynthetic energy acquisition by life, the process of using light energy to combine CO_2 and water to produce organic compounds. Since photosynthesis is an unsaturated biochemical reaction in plants, rising CO_2 concentrations increase photosynthetic rates under current conditions. Studies have shown that this change in photosynthetic rate results in greater above- and below-ground plant growth, especially in water-limited regions. Also, at higher than current ambient CO_2 concentrations, plants reduce the apertures of the small pores in their leaves that permit CO_2 and water vapor exchange with the atmosphere. These changes in plant function foster greater growth with less water demand, and the end result is a decrease in whole-plant water use. These alterations in plant behavior influence the storage of water in the soil surface and scale up to affect the landscape water balance. Thus, through its impacts on plant water use and surface soil water storage, rising CO_2 is predicted to increase recharge and streamflow when scaled to landscapes. This is likely to be most profound in areas where evapotranspiration (ET), and thus vegetation characteristics, dominates the behavior of the water cycle (see diagram below).

> *Rising CO_2 is predicted to increase recharge and streamflow when scaled to landscapes.*

A second major finding is that the composition of plant communities changes at greater than ambient CO_2 concentrations due to differential growth and resource use by the major plant types in a region. For example, several biochemical types of photosynthesis are found in terrestrial plants, resulting in plants that respond differently to changes in CO_2 concentration. C_4 photosynthetic species (which initially form four carbon-atom molecules) tend to be less responsive to rising atmospheric CO_2 concentration than C_3 species. In the southwestern United States, the deeply rooted woody species are predominantly of the C_3 photosynthetic type, which also comprises the far dominant plant species on Earth, while the summer-active perennial grasses are dominated by the C_4 photosynthetic type. Elevated CO_2 concentrations favor woody plants over grasses, and may accelerate woody-plant thickening or encroachment. Changes in the ratio of woody plants to grasses can influence the landscape water balance by affecting recharge and streamflow: larger woody vegetation populations would be expected to increase the amount of water leaving landscapes as ET (see diagram).

Thus, rising CO_2 concentration suggests two contrasting water resource scenarios. On one hand, we expect greater plant performance with respect to water use that will increase landscape yield, but on the other hand, changes in vegetation will influence how much water is returned to the atmosphere by evapotranspiration.

increasing scale of observation

Scale (micro to macro)	Response to Increased CO_2	Water Balance Effects
Leaf function	• increased CO_2 concentration within leaf • partial stomatal closure	↑ leaf photosynthetic rates ↓ leaf water loss
Whole plant function	• increased leaf water-use efficiency • reduced plant stress and better function during water deficit	↓ plant water use ↑ plant growth or season length
Vegetation dynamics	• biomass allocation shifts more to above-ground plant structure	↑ canopy leaf area ↓ active rooting area
	• C_3 plant species favored over C_4	↑ abundance of woody plants compared to grass
System water balance (competing scenarios/ outcomes)	↓ $H_2$0 loss through evapotranspiration	*greater* soil $H_2$0 storage / yield
	↑ $H_2$0 loss through evapotranspiration	*less* soil $H_2$0 storage / yield

Vegetation impacts on water balance due to rising atmospheric CO_2 concentration. At larger scales, two different scenarios emerge, one that would provide greater water and the other providing less water.

Unfortunately we cannot experimentally manipulate atmospheric CO_2 at sufficient spatial scales to directly test these two hypotheses. Instead, parallel research programs have been developed at different spatial and temporal scales. First, small-scale experimentation has focused on plant and plot-scale water balance responses to CO_2 concentration manipulation for the development of mechanistic models. Second, landscape studies have been expanded to evaluate natural vegetation variation and processes associated with vegetation change. The overall goal is to develop the appropriate ecohydrological framework and landscape context in which to undertake small-scale modeling to understand atmospheric change, vegetation responses, landscape water balance, and feedbacks that may affect the current rate of atmospheric CO_2 change.

Research at the Landscape Scale

Over the past five years we have been tackling the landscape-scale dynamics of this problem: How do ecosystems comprised of different woody plant densities relative to grasses use water and photosynthetically capture CO_2? What are the mechanisms associated with water use by individual plants, the impacts on intact vegetation stands, and the subsequent availability of water resources? Our focus has been on understanding how water and carbon processes are coupled because both of their exchanges are important for understanding water resources and potential feedbacks of ecosystems on rising CO_2 in the atmosphere.

Our program measures water use and carbon sequestration (the uptake and storage of carbon) at six sites in riparian and upland settings covering a gradient of vegetation types in southeastern Arizona ranging from grass-dominated to shrub-dominated. We use micrometeorological techniques to quantify water and carbon fluxes between the biosphere and atmosphere at the ecosystem scale (100 m to 1 km), and plant physiological and hydrological techniques to understand how processes like respiration and evaporation from both plants and soils contribute to ecosystem-scale fluxes. Data

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from the 2003 growing season at our riparian sites highlight the coupling of carbon and water cycles on the landscape. At these sites, the density of woody plants compared to grasses strongly controlled water and carbon exchanges (see figure, right). The woodland site had the highest rates of ET throughout the growing season, whereas total ET from the shrubland and grassland sites were similar. By solving a simple water budget at each site, we calculated the amount of ET derived from groundwater, and found it varied by site according to the abundance of woody plants. The woodland used 473 mm of groundwater, while the shrubland used 265 mm and the grassland used 227 mm over the season. However, the net accumulation of carbon in each ecosystem showed a different pattern (see figure). While the woodland exhibited the highest rates of carbon dioxide exchange with the atmosphere, the shrubland showed equivalent carbon storage over the season to the woodland. In contrast, grassland had the lowest rates of carbon exchange and sequestered less atmospheric carbon over the season.

The discrepancy between the ET and carbon accumulation responses at our sites occurs in part due to how the different components of carbon exchange, ecosystem photosynthesis (influx of carbon from the atmosphere), and ecosystem respiration (efflux of carbon to the atmosphere) relate to surface water inputs. As woody plants become more abundant on the landscape, ecosystem photosynthesis becomes more coupled to groundwater rather than surface water. The loss of water to the atmosphere and sequestration of carbon are both controlled by vegetation such that the two processes are negatively related: systems with greater water loss through ET also sequester or accumulate more CO_2 from the atmosphere. As such, land managers likely will need to consider the potential trade-off between these two exchanges at the landscape scale when they make decisions on vegetation management.

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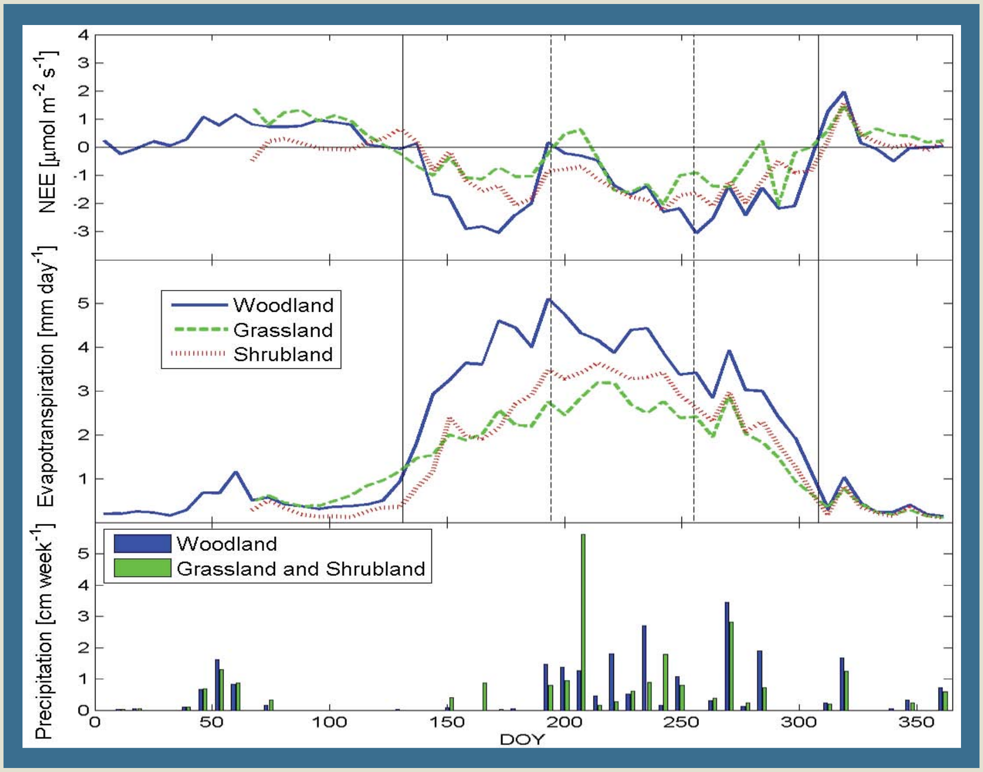

Average weekly net ecosystem exchange (NEE) of CO_2 (top), average weekly evapotranspiration (middle), and weekly total precipitation (bottom) for 2003. Solid vertical lines mark last spring and first fall freeze; dashed vertical lines bound the summer monsoon. Figure modified from Scott, R.L., T.E. Huxman, D.G. Williams, and D.C. Goodrich, 2006. Ecohydrological impacts of woody plant encroachment: seasonal patterns of water and carbon dioxide exchange within a semiarid riparian environment, Global Change Biology, 12, pp. 311-324, Blackwell Publishers.