

TECHNICAL REPORT FOR PROJECT PERIOD 2003-2006

GRANT: DE-FG02-03ER63683 (00001685)

REGULATION OF CARBON SEQUESTRATION AND WATER USE IN A OZARK
FOREST: PROPOSING A NEW STRATEGICALLY LOCATED AMERIFLUX
TOWER SITE IN MISSOURI

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INTRODUCTION

We received funding approval in late August of 2003; by June 14, 2004, the MOFLUX site was fully instrumented and data streams started to flow. A primary accomplished deliverable for the project period was the data streams of CO₂ and water vapor fluxes and numerous meteorological variables (from which prepared datasets have been submitted to the AmeriFlux data archive for 2004-2006 and which are available at: ftp://cdiac.ornl.gov/pub/ameriflux/data/Level1/Sites_ByName/Missouri_Ozark/), Additionally, measurements of leaf biochemistry and physiology, biomass inventory, tree allometry, successional trends other variables were obtained. Elsewhere in this report is a list of papers and conference presentations supported by project funding. Here is presented a report of major findings for the project period.

ECOSYSTEM CARBON UPTAKE

Although 2005 was characterized by a prolonged drought in July, the total amount of rainfall received during the period of June to September of 2005 was actually much larger than the amount received in the same four months of 2004 (538 mm vs. 388 mm). For these four months, the only month that 2005 received less rainfall than in 2004 was July. However, averaged over the period from June 14 to September 30 (we did not have flux measurements before June 14, 2004), the ecosystem in 2005 absorbed only about half of what it did in 2004 (a sink of $2.52 \pm 0.13 \mu\text{mol m}^{-2} \text{s}^{-1}$ vs. $4.62 \pm 0.19 \mu\text{mol m}^{-2} \text{s}^{-1}$) (Fig. 1). Although it extends beyond the reporting period for this project, a more severe drought in 2006 reduced annual C uptake in this year even further compared to 2005 ($320 \text{ g m}^{-2} \text{ yr}^{-1}$ in 2006 vs. $457 \text{ g m}^{-2} \text{ yr}^{-1}$ in 2005). Uneven rainfall distribution in the early 2005 growing season may have also affected the development of leaf photosynthetic capacity in this year. The maximal carboxylation rates (V_{cmax}) at the top of the canopy measured with leaf gas exchange chambers in June of 2005 were almost 30% less than corresponding values in June of 2004 ($80 \mu\text{mol m}^{-2} \text{s}^{-1}$ in 2005 vs. $110 \mu\text{mol m}^{-2} \text{s}^{-1}$ in 2004). These results indicate that carbon relations of this deciduous forest are highly regulated by seasonal water availability.

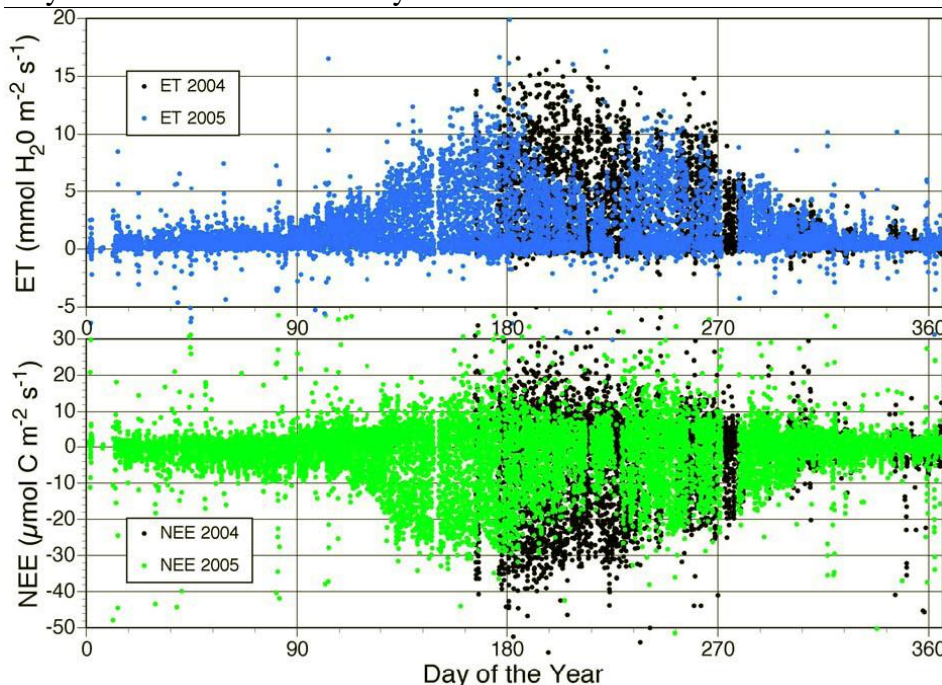


Fig. 1. Net ecosystem exchange (NEE) of CO₂ and evapotranspiration (ET) at the MOFLUX site in 2004 and 2005. Eddy covariance measurements began on June 14, 2004.

Model simulations with the terrestrial ecosystem Fluxes and Pools Integrated Simulator (FAPIS) parameterized with these measured leaf biochemical properties reproduced the observed net ecosystem exchanges of CO₂ from the eddy covariance system. The substantially smaller V_{cmax} in 2005 may be due to a drier spring (50 mm of precipitation in May 2005 vs. 140 mm in May 2004). It is also possible that the ecosystem nutrient dynamics produced the difference in leaf biochemical properties between the two years. The strong plant growth in 2004 may have increased substrate input to heterotrophic microorganisms. This may have stimulated microbial competition for nutrients and reduced leaf photosynthetic capacity in the early part of the growing season of 2005 (before the drought occurred).

SOIL RESPIRATION

Soil respiration (R_{soil}) measured with 8 soil chambers followed the expected seasonal patterns driven by temperature and phenological changes in plant biology in all years, but significant midsummer drought resulted in dramatic reductions (67% reduction at peak drought between 2004 and 2005, for example, Fig. 2) in soil respiration. Dormant season R_{soil} rates were typically less than 1 μmol CO₂ m⁻² s⁻¹, but midsummer rates averaged between 4 and 6 μmol m⁻² s⁻¹ with maximum individual chamber values as high as 8 μmol m⁻² s⁻¹. The bulk Q₁₀-style forest R_{soil} model proposed by Hanson et al. (2003) which includes parameters allowing for the influence of drought stress provided

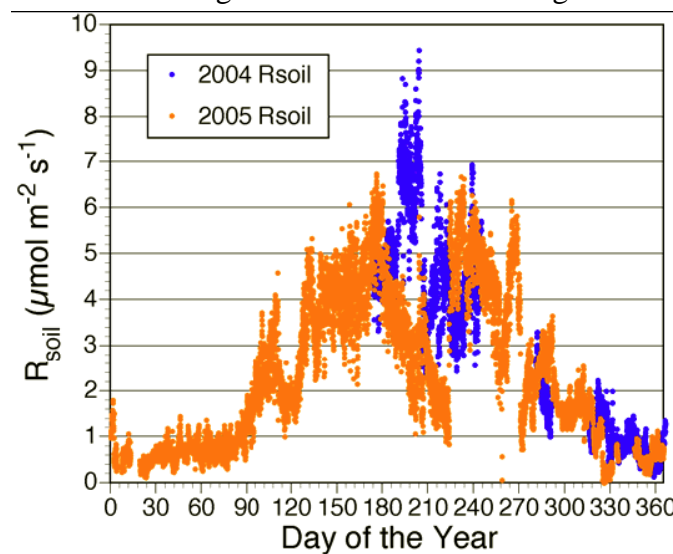


Fig. 2. Soil respiration in automated chambers at the MOFLUX site in 2004 and 2005.

a useful fit to the data ($r^2 = 0.84$) with a base respiration term at 0°C of $0.68 \pm 0.01 \mu\text{mol m}^{-2} \text{s}^{-1}$, a seasonal Q₁₀ value of 2.76 ± 0.03 , and minimum soil water potential associated with zero respiration of $-2.41 \pm 0.03 \text{ MPa}$. Integration of this model for the entire 2005 calendar year suggested total annual soil respiration of $862 \text{ gC m}^{-2} \text{ yr}^{-1}$ in 2005 which would represent a 16% reduction from maximum levels of R_{soil} if the water stress conditions had not been present. The measured pattern of R_{soil} is similar to that observed for Walker Branch Watershed in eastern Tennessee, but it is missing the dramatic transient positive response to rain inputs. This difference likely results from the limited mass of the Oi and Oa layers in the MOFLUX forest. In fact, heavy rain events in Missouri appear to temporarily restrict loss of CO₂ from the soil surface (i.e., the opposite

pattern). This phenomenon is hypothesized to result from the formation of a diffusion cap which develops when rain water fills the soil pore space.

TREE WATER USE AND SPECIES-SPECIFIC RESPONSES TO DROUGHT

Variation in mid-day rates of sap flow measured at three points around the stems of trees monitored tended to be less than 10%. All species had a pronounced gradient in sap flow with sapwood depth. The profile, however, was more abrupt in ring-porous species. Sap flow was lowest adjacent to the cambium, maximum at a sapwood depth of 1.0 to 1.5 cm, and then declined to the sapwood/heartwood interface. During the drought in 2005, all species monitored showed modest to marked reductions in sap flow with increasingly negative soil and leaf water potentials. The species that showed the least response was hickory, maintaining sap flow rates throughout the drought. White oak and northern red oak showed modest reductions in sap flow, followed by more significant reductions for eastern redcedar. Compared to the other species, ash and sugar maple showed severe reductions in sap flow with drought, with daily rates of sap flow declining 40 to 60% over the duration of the 2005 drought. Stand transpiration scaled up from sap flow rates and a sapwood area-DBH relationship developed at the site was reduced up to 35 to 40% late in the season due to the 2005 drought.

LEAF BIOCHEMISTRY AND PHYSIOLOGY

Means of periodic measurements of predawn leaf water potential for major site species did not decline below -0.6 MPa in 2004 (Fig. 3). However, during the droughts in 2005 and 2006 means were substantially lower, reaching a minimum of -2.5 MPa or below in early August. We compared the seasonal patterns of leaf and soil water potentials in 2005 (Fig. 4). We found that although the overall patterns of soil water potential and predawn leaf water potential tracked each other well, some systematic differences between them existed. During the early part of major drought periods, the predawn leaf water potential was

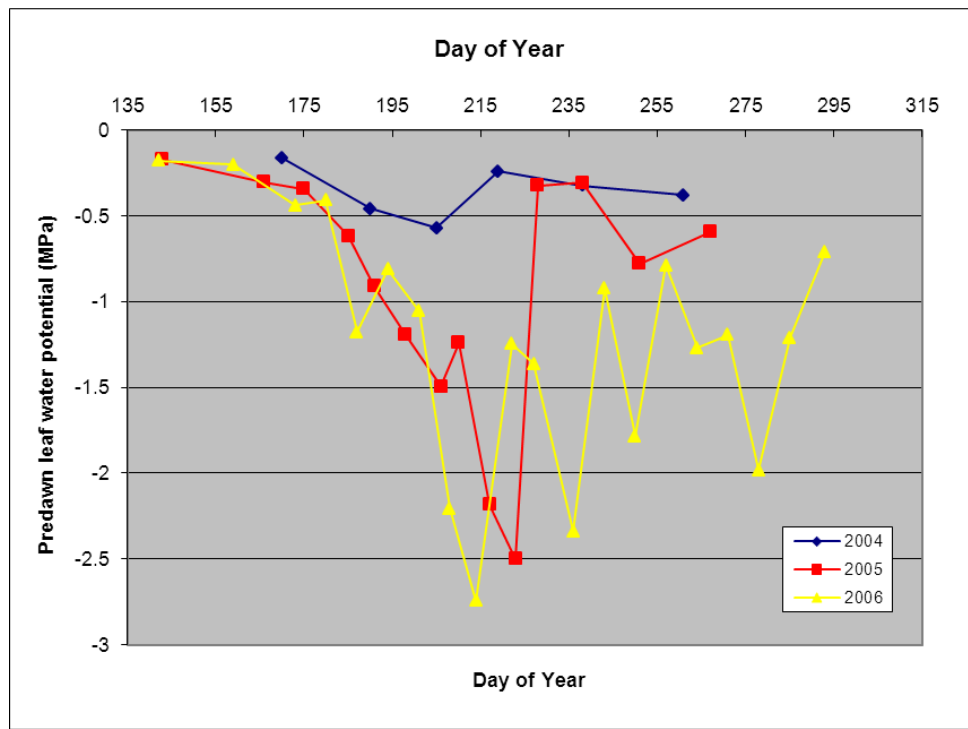


Fig. 3. Mean predawn leaf water potential at the MOFLUX site for the study period. Lower (greater negative) values of this parameter signify greater level of site water stress.

less negative than the soil water potential (e.g., Fig. 4); however, as the drought progressed, the relationship between the two potentials eventually reversed. Predawn leaf water potential is a good integrative indicator of the overall soil water status if roots keep close contact with a moist soil. As soil dries, soil water content increases with the depth in the soil. Since the soil water potential was measured near the soil surface (top 70 cm) while plant roots could access water in deeper soil, predawn leaf water potential was higher than the measured soil water potential. As the soil became very dry, however, hydraulic conductivity declined dramatically and some soil-root contact may have been lost. These factors prevented overnight equilibration of the plant with the soil and accounted for the pattern of lower predawn leaf than soil water potential under severe drought (Fig. 4).

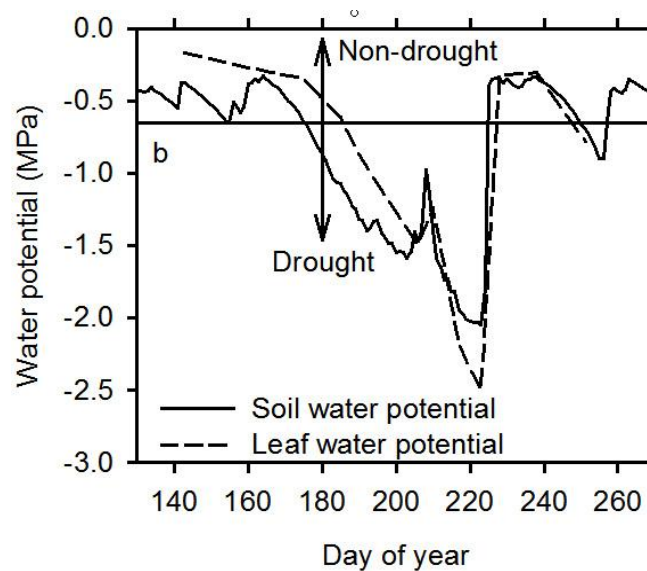


Fig. 4. Comparison of mean soil water potential in the top 70 cm of soil with predawn leaf water potential (20-21 leaf sample from MOFLUX site trees) during the growing season of 2005 under drought (<-0.7 MPa) and non-drought (>-0.7 MPa) conditions (from Yang et al., 2007).

Over 300 A/Ci curves were generated for leaves of white, black and post oak, sugar maple, shagbark hickory and eastern redcedar in early-, mid- and late-growing season campaigns from all canopy heights using a boom lift. During the analysis phase of this work, we improved an algorithm for A/Ci curve optimization and uncertainty analyses in biochemical parameter estimation. This effort has led to the establishment of a publicly-accessible website for A/Ci curve analysis (<http://leafweb.ornl.gov/Pages/LeafWeb.aspx>). The biochemical parameters estimated from these A/Ci curves were used to support modeling efforts (see below). Modeling using process-based models and site parameters developed in the current project has identified some later-season overestimates of predicted fluxes of CO₂ that may be attributable to subtle reductions in canopy function (perhaps due to gradual reduction in leaf photosynthetic capacity and the complex mosaic of late-season canopy senescence). For example, sugar maple leaves showed progressive decline in functional green area that is photosynthetically competent

(Fig. 5). Portions of leaves that have colored show essentially no capacity for carbon fixation, while green areas still fix substantial carbon.

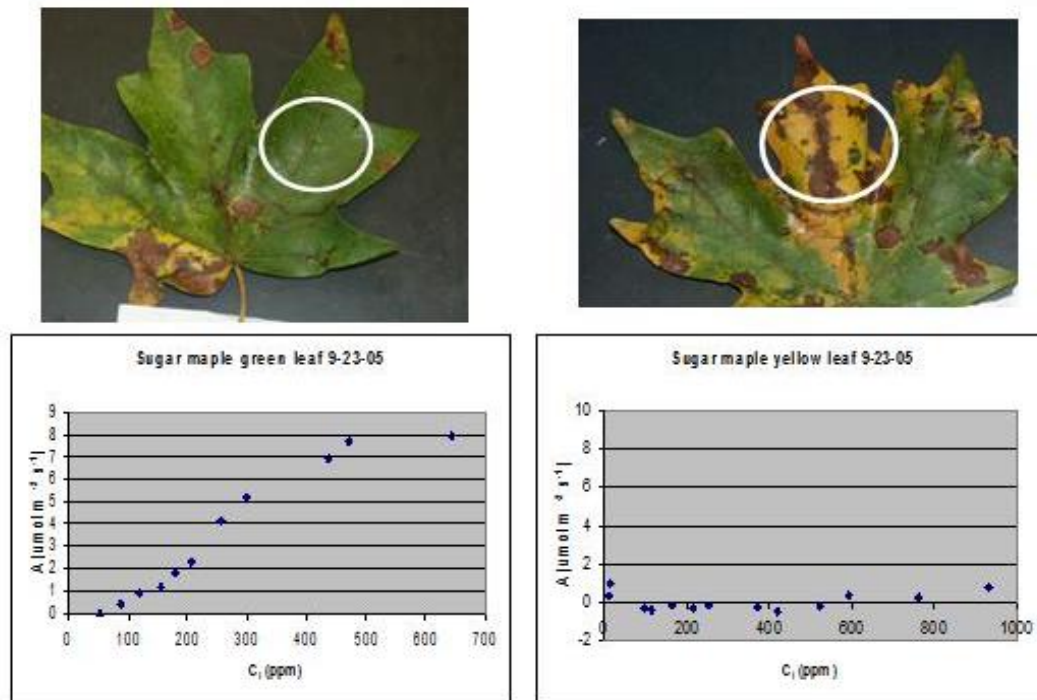


Fig. 5. A/C_i (photosynthesis vs. internal leaf CO_2 concentration) curves from non-senescent green (left) and senescent (right) locations of upper-canopy leaves from a single sugar maple tree obtained on Sept. 23, 2005. Green areas of leaves retain the capacity for substantial CO_2 uptake, while senescent areas have totally lost capacity for any photosynthesis.

SURFACE ENERGY PARTITIONING

We found that soil moisture, atmospheric vapor pressure deficit (VPD), and net radiation have both direct and indirect effects on surface energy partitioning. The direct effects of soil moisture and net radiation are monotonic: a decrease in soil moisture and an increase in net radiation increase the Bowen ratio. In contrast, the direct effect of VPD is nonlinear: increased VPD decreases the Bowen ratio at low VPD but increases the Bowen ratio at high VPD. The indirect effects are much more complicated. Reduced soil moisture weakens the influence of VPD but enhances the influence of net radiation on surface energy partitioning. Soil moisture also controls how net radiation influences the relationship between surface energy partitioning and VPD and how VPD affects the relationship between surface energy partitioning and net radiation. Furthermore, both increased VPD and increased net radiation enhance the effect of drought on surface energy partitioning.

ALLOMETRIC ANALYSIS AND BIOMASS INVENTORY

Before leaf-out in March of 2005, all boles and branches of 22 trees covering a range of species (*Acer*, *Carya*, *Fraxinus*, *Juniperus* and *Quercus*) and diameters (2 to 50 cm DBH) were harvested to test the applicability of existing allometric relationships between tree diameter and dry mass. Subsamples for the determination of water content were collected

on various sized materials for each tree for the final determination of total tree dry mass. The data were found to be remarkably similar to measurements for eastern Tennessee. Because of the similarity, the Missouri harvest data were combined with the 30-year-old allometry of Harris et al. (1973) and Sollins and Anderson (1971) to generate a new nonlinear function that is easier to apply than the previous log transformed function. Using this updated allometric relationship to estimate the standing live carbon pool in boles and branches for the MOFLUX site yields $59.1 \pm 2.9 \text{ Mg C ha}^{-1}$. The majority of the stand biomass is contributed by *Quercus* spp. (71%) with smaller contributions from *Juniperus virginiana* (8.6%), *Carya* spp. (7.8%), and *Acer saccharum* (6.2%), plus miscellaneous trees and understory saplings.

INTEGRATED MODELING STUDIES

We developed the terrestrial ecosystem fluxes and pools integrated simulator (FAPIS) from a previous ecosystem model. FAPIS has full treatments of all major biophysical fluxes, soil organic matter pool dynamics, soil hydrology and heat transfer. It keeps the strengths of its predecessor in canopy radiative and scalar transfers and separates diffuse and direct beam radiation fully for both carbon assimilation and energy balance calculations. It also employs the recently developed hydromechanical and biochemical model of stomatal conductance of Buckley et al. (2003) together with the widely-used empirical Ball model (Ball et al., 1987). The Ball model has been criticized for lack of mechanisms even though it has worked well for plants that are not under moisture stress. Because our Missouri site frequently encounters drought conditions climatologically, the use of both stomatal models will allow us to evaluate uncertainties caused by different representations of stomatal dynamics. In the process of validating FAPIS using data from MOFLUX, we found that modeled ecosystem fluxes are very sensitive to root distribution. Using a generic root distribution model drastically increased the model response to drought. Only when the observed root distribution at the site was used did the model predictions of fluxes, soil moisture, and soil temperature agree with observations.

LONG-TERM VEGETATIONAL DYNAMICS

To assess the successional development of forests at the MOFLUX site as they recover from early-to-mid 20th Century disturbance, changes in species composition and forest structure were studied over a 36-year period. Permanent plots were established in 1968, tree (>8.75cm) and sapling (<8.75 cm) DBH was measured, and species recorded (Rochow, 1972). Plots were classified as dry ridge and slope, mesic slope, glade-like, or bottomland. The plots were resampled in 2004. Generally, dominant white oak (*Quercus alba*) tree basal area increased but density declined or remained constant. Maple (mostly *Acer saccharum* with a small contribution of *A. nigrum*) tree density, basal area and importance values increased in the dry ridge and slope and mesic slope sites. Eastern redcedar (*Juniperus virginiana*) tree density, basal area and importance values increased on glade-like sites. Regeneration of oaks (*Quercus* spp.) has declined drastically, as shown by much reduced sapling density in all size classes and plot types. Larger sapling size classes of maple showed an increase in density; however, by 2004 *Acer* density in the smallest sapling size class had declined by almost 90% compared to 1968 in all plot types. Measurements of seedling density in 2005 indicated that *Quercus* spp. seedling density was higher than sapling density, but continued shading by taller plants will likely eliminate most of these seedlings. Virtually no *Acer* spp. seedlings were present. At present, *Acer* is showing an increased presence in the overstory. *Quercus* still dominates

the overstory, but with little or no oak in the sapling regeneration a decline in oak importance in the future is virtually assured.

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