Final Report for agreement 11:ER65189, D.O.E.: Office of Biological and Environmental Research Terrestrial Ecosystem Science

"Quantifying the effect of nighttime interactions between roots and canopy physiology and their control of water and carbon cycling on feedbacks between soil moisture and terrestrial climatology under variable environmental conditions"

This proposal was a collaboration: Jean:Christophe Domec is the point of contact and coordinator for the combined research activity. (**jdomec@ncsu.edu**)

Collaborating Institutions: North Carolina State University and Duke University
PIs for North Carolina State University: Jean-Christophe Domec, John King, Asko Noormets
PIs for Duke University: Sari Palmroth (lead PI), Jennifer Swenson, Ram Oren
Master student: Andrew Radecki (North Carolina State University)
Post:doctoral associate: Chris Oishi (Duke University)

Collaborators: Gaby Katul, Marco Marani, Jerome Ogee, Steve McNulty, Ge Sun

Project duration: 01/09/2011:08/31/2015
Reporting period: 01/09/2011:31/08/2015

Aims of the project

The primary objective of this project is to characterize and quantify how the temporal variability of hydraulic redistribution (HR) and its physiological regulation in unmanaged and complex forests is affecting current water and carbon exchange and predict how future climate scenarios will affect these relationships and potentially feed back to the climate.

Specifically, a detailed study of ecosystem water uptake and carbon exchange in relation to root functioning was proposed in order to quantify the mechanisms controlling temporal variability of soil moisture dynamic and HR in three active AmeriFlux sites, and to use published data of two other inactive AmeriFlux sites. Furthermore, data collected by our research group at the Duke Free Air CO_2 enrichment (FACE) site was also being utilized to further improve our ability to forecast future environmental impacts of elevated CO_2 concentration on soil moisture dynamic and its effect on carbon sequestration and terrestrial climatology. The overarching objective being to forecast, using a soil:plant:atmosphere model coupled with a biosphere:atmosphere model, the impact of root functioning on land surface climatology. By comparing unmanaged sites to plantations, we also proposed to determine the effect of land use change on terrestrial carbon sequestration and climatology through its effect on soil moisture dynamic and HR.

The proposed research supported the accomplishment of the BER Long Term Measure because our results provided improved scientific data about the effect of a changing climate in complex forests **on** the Earth's climate through their impact on **soil moisture.** Specifically, we predicted which threshold levels of soil moisture can reduce significantly energy transfer in the form of latent heat and influencing mixed layer potential temperature and water vapor, convective rainfall triggers and incidence of droughts.

Main results

Our simulations of HR by roots indicated that in some systems HR is an important mechanism that buffers soil water deficit, affects energy and carbon cycling**;** thus having significant implications for seasonal climate**.** HR maintained roots alive and below 70% loss of conductivity and our simulations also showed that the increased vapor pressure deficit at night under future conditions was sufficient to drive significant nighttime transpiration at all sites, which reduced HR. This predicted reduction in HR under future climate conditions played an important regulatory role in land atmosphere interactions by affecting whole ecosystem carbon and water balance. Under future climatic scenarios, HR was reduced thus affecting negatively plant water use and carbon assimilation. The discrepancy between the predicted and actual surface warming and atmospheric water vapor caused by the persistence of evapotranspiration during the dry season, increasing energy transfer in the form of latent heat.

Under those simulations, we also evaluated how the hydraulic properties of soil and xylem limited the rate of carbon uptake, and carbon net ecosystem exchange. The multilayered hydraulically driven soil vegetation atmosphere carbon and water transfer model was designed to represent processes common to vascular plants, so that ecosystem atmosphere exchange could be captured by the same processes at different sites. Those models shown to be well suited for investigating the impact of drought on forest ecosystems because of its explicit treatment of water transport to leaves. This modeling work also confirmed that unmanaged, mixed hardwood site are more resilient to climatic variations than an adjacent pine plantation, but that future climatic conditions will reverse this trends.

Summary of activities for years 3 and 4 (no cost extension year)

A no-cost extension was requested in 2015 to finish our modeling tasks that were: 1) to incorporate HR into a coupled biosphere-atmosphere model for further evaluation of the impact of root functioning in land-surface climatology by examining the effect of soil moisture on the mixed layer potential temperature and water vapor and on rainfall triggers and, 2) to forecast using a soil-plant-atmosphere model how the predicted increases in temperature, vapor pressure deficit and CO_2 will affect ecosystem functioning. To reach those final objectives, we finished collecting and analyzing flux data from three active AmeriFlux sites, and used published data of two other inactive AmeriFlux sites, representing two old growth sites of the western USA and three mature sites of the eastern USA.

We collaborated with Nate Mc Dowell to reach objective 1 and with Gaby Katul at Duke University to reach objective 2, i.e. predict the effect of HR on water and carbon exchange and to assess the effect of future climate on HR. Those runs were part of an outreach program involving two visiting students from the University of Torino in Italy.

Specifically, we developed a multilayered hydraulically driven soil–vegetation–atmosphere carbon and water transfer model that was designed to represent processes common to vascular plants, so that ecosystem–atmosphere exchange may be captured by the same processes at different sites. This model was well suited for investigating the impact of drought on forest ecosystems because of its explicit treatment of water transport to leaves (Bonetti et al. 2015). In the model, root water uptake was hydraulically controlled and is a function of the difference between local root water potential and local soil water potential at the root–soil interface. This soil-plant-atmosphere model was coupled to a simplified atmospheric boundary layer model

(Figure 1) generating estimates of heat and moisture budget to explore the feedback mechanisms between soil moisture and convective rainfall and simulating energy, water and heat exchanges within the atmosphere-biosphere system (Manoli et al.2015, 2016). The resultant Coupled Biosphere Atmosphere model operated at a spatial and temporal scale relevant to measurements of both ecological and atmospheric processes. In this model, the linkages between soil moisture dynamics and convection triggers was defined as the first crossing between the boundary layer height and lifting condensation level (Figure 1). The model will be tested against both stand-based measurements (e.g., eddy covariance estimates of surface fluxes and surface meteorology) and against atmospheric profile measurements (radiosonde measurements in the planetary boundary layer).

Our modeling work also contributed to research on the cause of tree mortality in Arizona and New Mexico/ Along with 11 other modelers, Domec was invited in November 2011 to Santa Fe (NM) to predict whether tree mortality will increase under future climate and whether trees are dying because of carbon starvation or hydraulic failure (McDowell et al. 2013, 2015).

Graduate student (MSc) at NC State University (Andrew Radecki) who finished is Master in 2015. Andrew worked at the Alligator River site by measuring soil depth and the partitioning between water used between over and understory species.

The post-doctoral associate at Duke University (Chris Oishi) finished working on the project in March 2014 (Chris was funded 8 months on the project). As part of his work, C. Oishi finished analyzing existing dataset regarding nighttime transpiration at the Duke Hardwood site.

In addition to training in ecological science, we have worked with the graduate student and postdoc on writing and speaking skills, enhancing their communication abilities.

Final publications related to the project

30 peer-reviewed scientific articles that benefited from the analyses and methods developed in this project were published. Seven of these papers were directly related to our modeling work.

Domec, J-C, Palmorth S., Oren R. 2016 Effects of *Pinus taeda* leaf anatomy on vascular and extravascular leaf hydraulic conductance as influenced by N-fertilization and elevated CO_2 . Journal of Plant Hydraulic, in press

Manoli, G., Domec, J.-C., Novick, K., Oishi, A. C., Noormets, A., Marani, M. and Katul, G. 2016. Soil-Plant-Atmosphere Conditions Regulating Convective Cloud Formation Above Southeastern US Pine Plantations. *Global Change Biology*. Accepted, doi:10.1111/gcb.13221

Voelker, S.L., J.R. Brooks, F.C. Meinzer, R. Anderson, M.K.-F. Bader, G. Battipaglia, K.M. Becklin, D. Beerling, D. Bert, J.L. Betancourt, T.E. Dawson, J-C Domec, R. P. Guyette, C. Körner, S.W. Leavitt, S. Linder, J.D. Marshall, M. Mildner, J. Ogée, I. Panyushkina, H.J. Plumpton, K.S. Pregitzer, M. Saurer, A.R. Smith, R.T.W. Siegwolf, M.C. Stambaugh, A.F. Talhelm, J.C. Tardif, P.K. Van de Water, J.K. Ward, L. Wingate. 2016. A dynamic leaf gas-exchange strategy is conserved in woody plants under changing ambient CO2: evidence from carbon isotope discrimination in paleo and CO2 enrichment studies. *Global Change Biology*, in press

McDowell N.G., Williams A.P., Xu C., Pockman W. ., Dickman L.T., Sevanto S., Pangle R., Limousin J., Plaut J., Mackay D.S., Ogee J., Domec J.C., Allen C.D., Fisher R. A., Jiang X., Muss J. D., Breshears D. D., Rauscher S.A. and Koven C. 2016. Multi-scale predictions of massive conifer mortality due to chronic temperature rise. *Nature Climate Change*, in press. doi:10.1038/nclimate2873

Noormets A., Epron D., Domec J.C., McNulty S.G., Fox T.D., Sun G., King J.S. 2015. Effects of forest management on productivity and carbon sequestration: a review. *Forest Ecology and Management* 355:124-140.

Domec J.C., J. S King, E. Ward, A. C. Oishi, S. Palmroth, A. Radecki, D. M. Bell, G. Miao, M. Gavazzi, D. M. Johnson, S.G. McNulty, G. Sun, A. Noormets. 2015. Conversion of natural forests to managed forest plantations decreases tree resistance to prolonged droughts. *Forest Ecology and Management* 355:58-71

Bonetti S., G. Manoli, J.C. Domec, M. Putti, M. Marani and G.G. Katul. 2015. The influence of water table depth and the free atmospheric state on convective rainfall predisposition. *Water Resources Research*, 51, 2283–2297. doi: 10.1002/2014WR016431.

Boggs J., Sun G., Domec J-C., McNulty S. and E. Treasure. 2015. Clearcutting upland forest alters transpiration of residual trees in the riparian buffer zone. *Hydrological Processes* 29: 4979-4992. DOI: 10.1002/hyp.10474.

Fischer M, Fichot R, Albaugh JM, Ceulemans R, Domec J-C, Trnka M, King JS. 2015. Ecophysiology, above-ground productivity, and stand-level water use efficiency of *Populus* and *Salix* grown in short-rotation coppice for bioenergy. Chapter 7 (157-194p) *In* Bhardwaj AK, Zenone T, Chen J (eds) *Sustainable biofuels: An ecological assessment of the future energy*, HEP deGruyter, Berlin., 366p.

Tor-ngern, P., Oren R., Ward E., Palmroth S., McCarthy H., Domec J.C. 2015 Increases in atmospheric CO2 have little influence on transpiration of a temperate forest canopy. *New Phytologist* 205:215-218. doi: 10.1111/nph.13148

Henriksson N., Tarvainen L., Lim H., Tor-Ngern P., Palmroth S., Oren R., Marshall J.D.M., Näsholm T. 2015. Phloem compression reversibly reduces belowground carbon transport in Scots pine, *Tree Physiology* 35, 1075–1085, doi:10.1093/treephys/tpv078.

Lim H., Oren R., Palmroth S., Tor-ngern P., Mörling T., Näsholm T., Linder S. 2015. Inter-annual variability of precipitation constrains the production response of boreal Scots pine stand to nitrogen-fertilisation, *Forest Ecology and Management* 348: 31–45, dx.doi.org/10.1016/j.foreco.2015.03.029.

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Albaugh, J.M., Domec, J.-C., Maier, C.A., Sucre, E.B., Leggett, Z.H., King, J.S. 2014. Gas exchange and stand-level estimates of water use and gross primary productivity in an experimental pine and switchgrass intercrop forestry system on the Lower Coastal Plain of North Carolina, U.S.A. *Agricultural and Forest Meteorology* 192-193: 27-40.

Manoli G., S. Bonetti, J.C. Domec, M. Putti, G. Katul and M. Marani. 2014. Tree root systems competing for soil moisture in a 3D soil-plant model. *Advances in Water Resources* 66:32-42.

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McDowell, N. G., R. A. Fisher, C. Xu, J. C. Domec, T. Hölttä, D. S. Mackay, J.S. Sperry et al. 2013. "Evaluating theories of drought-induced vegetation mortality using a multimodel–experiment framework." *New Phytologist* 200: 304-321.

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and Carolina hemlock (*Tsuga caroliniana*). *New Phytologist* 199:452-63; doi: 10.1111/nph.12263.

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Palmroth S., Bach L., Nordin A., Palmqvist K. 2014. Nitrogen addition effects on leaf traits and photosynthetic carbon gain of boreal forest understory shrubs, *Oecologia***,** 175: 457–470, doi**:** 10.1007/s00442-014-2923-9.

Ward, E.J., R. Oren, D.M. Bell, J.S. Clark, H.R. McCarthy, H. Seok:Kim and J.:C. Domec. 2013. The effects of elevated CO2 and nitrogen fertilization on stomatal conductance estimated from scaled sap flux measurements at Duke FACE. *Tree Physiology*, 33 (2):135:151.

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Sun G., Caldwell P., Noormets A., McNulty S.G, Cohen E., Moore Myers J., Domec J:C., Treasure E. Mu Q., Xiao J., Ranjeet J., Chen J. 2011. Upscaling key ecosystem functions across the conterminous United States by a water:centric ecosystem model *J. Geophys. Res.*, Vol. 116, No. null, G00J05.

Presentations

Palmroth S., Controls of gross primary production of boreal understory vegetation. Workshop on Boreal forest systems in a changing climate: from physiological mechanisms to ecosystem responses, Vindeln, Sweden, 2015

Palmroth S., Katul G.G., Maier C.A., Ward E., Manzoni S., Vico G. Complementarity between marginal nitrogen and water use efficiencies among Pinus taeda leaves at DUKE FACE (poster presentation). The 2nd annual joint investigators meeting of the Terrestrial Ecosystem Science (TES) and Subsurface Biogeochemical Research (SBR) programs of DOE, in Potomac, MD, 2014.

Noormets A., Domec JC, Oishi C., Palmroth S et al. Interactive effects of nocturnal transpiration and climate change on the root hydraulic redistribution and carbon and water budgets of unmanaged forests. 2st annual PI Meeting, DOR:TER Washington DC, May 2013.

Oishi AC, Palmroth S, Domec JC, Oren R. Significant nighttime transpiration in an unmanaged Oak/Hickory forest is species:dependent. 2nd annual PI Meeting, DOE:TER Washington DC, May 2013

Domec JC, Noormets A, King JS, Warren J., Ogee J. et al. Convergence of the effect of root hydraulic functioning and root hydraulic redistribution on ecosystem water and carbon balance across divergent forest ecosystems. In: **Measurement and Modeling of Root:Zone Processes Influencing Water, Carbon, and Nitrogen Cycles at Various Scales.** AGU Fall meeting, San Francisco CA, December 2013.

Oishi AC, Palmroth P, Johnsen KH, Butnor JR, McCarthy HR, Oren R. Spatial and temporal variability in forest soil CO2 flux among stands and under elevated [CO2] and fertilization. AGU Fall meeting, San Francisco CA, December 2013

Tor-ngern P., Oren T., Ward E.J., Palmroth S., McCarthy HR, Domec J.C. Stomatal closure imposed by slow physical acclimation of forest canopies to atmospheric CO_2. AGU Fall meeting, San Francisco, CA, 2013.

Lin W, Noormets, Domec JC, King JS, Sun G, McNulty S. 2012. A conifer:friendly high:throughput alpha cellulose extraction method for delta 13C and delta 18O stable isotope ratio analysis. In: ***Climate Impacts on Ecosystems Quantified Using a Combination of Proxy Records and Instrumented Observatories II Posters***. AGU Fall meeting, San Francisco CA, December 2013.

Sun G, Fang Y, Caldwel P, Noormets A; Domec JC, McNulty S, King JS, McLaughlin S, Uddling S, *Chen J* Environmental Controls of Ecosystem Evapotranspiration (ET): Why generalized ET models do not work for forests? In: ***Advances in the Theory, Modeling, Measurement, and Remote Sensing of Evapotranspiration From Terrestrial Surfaces III Posters.*** AGU Fall meeting, San Francisco CA, December 2013.

Noormets A., Domec JC, Mia G., Sun G, McNulty S. King JS. CO2 and CH4 exchange in an undisturbed coastal forested wetland in North Carolina. In ***Carbon Release and Storage Mechanisms in Peatland Ecosystems II Posters*.** AGU Fall meeting, San Francisco CA, December 2013.

Domec JC, Noormets A, King JS, Katul. G. Oren R. Palmroth S. et al. Interactive effects of nocturnal transpiration and climate change on the root hydraulic redistribution and carbon and water budgets of unmanaged forests. 1st annual PI Meeting, DOR:TER Washington DC, April 2012

Radecki A, Domec JC, Norrmets A et al. The partitioning of water fluxes in an unmanaged wetland: tree hydraulic redistribution and nighttime transpiration. 1st annual PI Meeting, DOR:TER Washington DC, April 2012

Guofang M, Noormets A. King JS et al. Hydrology Controls Soil Respiration and its Isotopic Composition from Different Soil Types in a Forested Wetland in Southeast U.S.A . AGU Fall meeting, San Francisco CA, December 2011.

Domec JC, Ogee J. New Phytologist Workshop on Tree Mortality, Santa Fe, November 2011.

Swenson JJ, Carter CE, Domec JC, Delgado CI. Land Use Change Driven by Gold Mining; Peruvian Amazon. AGU Fall meeting, San Francisco CA, December 2011.

Synergistic activities

1. Domec organized a 2:day sapflow sensor making session November 2012 where 12 graduate students from 5 universities attended (Florida State, Texas A&M, North Carolina State U., Oklahoma State U. and Virginia Tech).
2. In April 2013, Domec and Palmroth have proposed to organize a session at the AGU Fall Meeting on the last set of data collected at the Duke FACE following the discontinuation of the site.

3. As part of the outreach component of the project Domec (together with the class teacher, Linda Schmalbeck) is already teaching 12 high school students how to use the STELLA model to predict tree carbon allocation under future climate. This educational outreach is a natural continuation of the past activities of the PIs who were involved in teaching high school students at the North Carolina School for Science and Mathematics (NCSSM) in Durham, NC. In addition to this hands on research experience an Online Research Experience course was developed in fall of 2011 involving 12 more students from nine high schools throughout North Carolina.
4. The ongoing study serves as foundation for building "climate change observatory" an interagency research, education and outreach collaborative for finding ecologically facilitated adaptation strategies for the rise in sea level and changing environmental services. Two proposals have been submitted by Oren, Way, Palmroth, Oishi and Domec (DOE TES), by King, Noormets and Domec (NASA) and others are underway. Collaborators on these efforts include US Fish and Wildlife Service (Mike Bryant and Dennis Stewart of Alligator River National Wildlife Refuge), Los Alamos National Lab (Nate McDowell), Duke University (Daniel Johnson) as well as collaborators from The Nature Conservancy (Brian Boutin of the Albemarle Climate Change Adaptation Project), USDA Forest Service (Steve McNulty) .
5. Domec has been invited to serve in the expert advisory panel for the French Climate Change Program (ACCAF).