VOL.5 NO. 2 MARCH 2013

FluxLetter

THE NEWSLETTER OF FLUXNET

In this issue of the FLUXLETTER, we present two historical accounts; one is a history of flux measurements using the eddy covariance method. The second is a history of the development of flux measurements specific to urban ecosystems. We also profile the Yatir Forest in Israel; a pine forest established at the semi-arid dry timberline. Lastly, Dennis Baldocchi offers a tribute to Shashi Verma; a pioneer in the flux community who has recently retired.

A Brief History on Eddy Covariance Flux Measurements: A Personal Perspective

Dennis Baldocchi

Because so many practitioners are new to the field of eddy covariance flux measurements, we felt it would be a good time to provide a short and broad history on the topic of fluxes in general and focusing on eddy covariance.

The field of eddy covariance has experienced rapid, exponential growth since the 1990s due to a convergence of developments in instrumentation, personal computers, data storage devices and advances in micrometeorological theory; Figure 1 shows the growth in publications associated with the key word, eddy covariance.

As I write this history, the web of science informs me that nearly 5000 papers have been published that are linked to the key words 'eddy covariance' or 'eddy correlation'.

Micrometeorology

The idea of using micrometeorological methods to assess mass and energy exchange can be traced back to before and around the turn of the 20th Century. The concept of Fickian diffusion led early fluid mechanics, such as Ludwig Prandtl, G.I. Taylor and Bowen (1920s), to propose the flux-gradient approach, as a concept for evaluating fluxes of momentum, water and heat.

Sir Osborne Reynolds (Reynolds, 1895) is credited with devising the theoretical idea of the eddy covariance method after he laid down his famous concept of Reynolds averaging. Application of this method was delayed many years due to technical reasons as it relies on fast anemometry and meteorology. One of the first applications of this method was applied in 1926 and was reported by F.J. Scrase (1930, Some characteristics of eddy motion in the atmosphere, Geophysical Memoirs, #52, Meteorological Office. London, 56 pp). His instrumentation and digitization methods, however, were quite primitive. He evaluated the three wind vectors using rapid measurements of wind speed and wind direction. He digitized the data by photographing the wind meter dial and using a kinematograph to record the

Editors: Laurie Koteen and Dennis Baldocchi,
The FLUXNET Office at the University of California, Berkeley

In This Issue:

A Brief History on Eddy Covariance Flux Measurements: A Personal Perspective

Dennis Baldocchi

movement of the wind vane! Obviously, he could only apply the method for short time durations.

A contemporary study, in the German literature, was reported by W. Schmidt (1928); famous also for the Schmidt number. And most recently, I found a citation outlining coordinate rotations for momentum transfer measurements dating back to the German literature in 1935 (Tollmien, 1935).

In the 1940s Monin and Obukhov laid down the theoretical principles for computing scalar and momentum gradients and fluxes in the surface layer. The theory would be the pivot point for later work and would prove to be successful over a range of surface roughness lengths and thermal stratification scenarios (Foken, 2006). And, Kolmogorov, the famous Russian Statistician, Academician and Fluid Mechanic, developed theory for interpreting the spectral decay of turbulence, giving us more information on the range of eddy sizes that must be sampled.

Major advances in the eddy covariance method occurred in the 1950s with the development of fast responding hot-wire anemometry and thermometry (instrumentation capable of sampling multiple times per second in response to perturbations that occur within fractions of a second). The digitation methods of the early studies, however, were crude at best. Light from a galvanometer was recorded on a revolving cylinder of photographic paper. The data were later digitized by hand! One of the first research teams to exploit this method was associated with the CSIRO laboratory of CHB Priestly in Australia (Priestley and Swinbank, 1947). The most innovative work was conducted by Bill Swinbank (Swinbank, 1951). Other notables in the group included Len Deacon, Ian McIlroy, Eric Webb and Reg Taylor (Hess et al., 1981). A few years later this group would be joined by Arch Dyer and Bruce Hicks; my mentor in Oak Ridge who gave me many insights on developments in the early years (Dyer and Hicks, 1970; Dyer and Hicks, 1972). Much basic and pioneering information on the fundamental properties of the atmospheric surface layer is linked to members of this group. for Any competent literature review on the topic would find this to be an excellent starting point; especially a good read of the Swinbank paper.

For over 50 years micrometeorologists focused their efforts on the development of theory, instrumentation and methods to measure trace gas, energy and momentum fluxes between the land surface and the atmosphere. The earliest studies were interested in testing the scaling con-

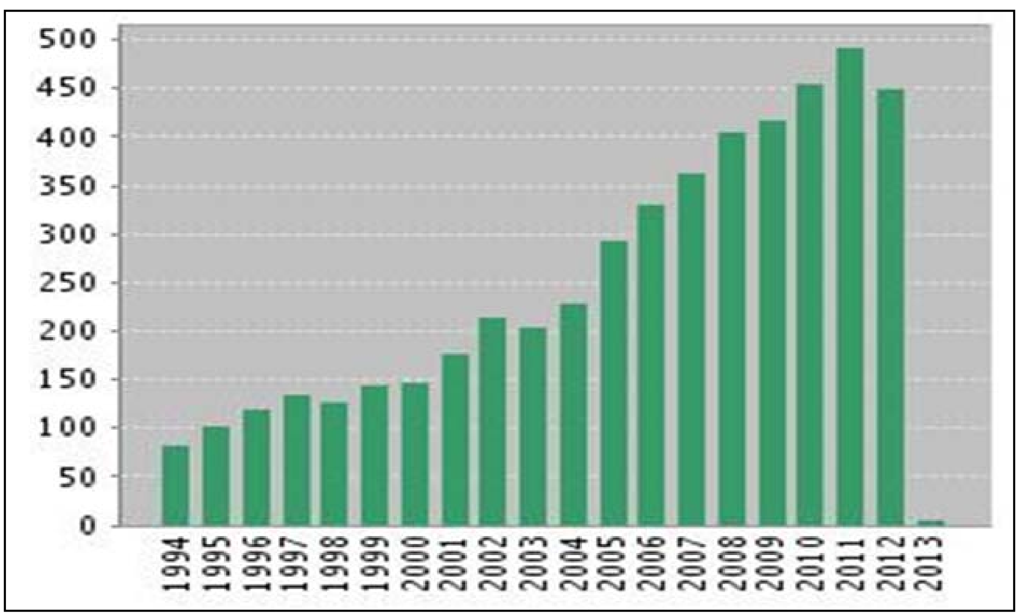

Figure 1. Growth in publications associated with the key word, ‘eddy covariance’ or ‘eddy correlation’.

A Brief History on Eddy Covariance Flux Measurements: A Personal Perspective

Dennis Baldocchi

cepts of Monin and Obukhov, understanding the spectral properties of turbulence and the statistical properties of turbulence in the surface boundary layer during stable, neutral and unstable thermal stratification.

Many of the earliest micrometeorological studies were conducted over very ideal landscapes. These locales consisted of extremely level terrain with negligible or short vegetation and were in windy and sunny climes where atmospheric conditions could be expected to be steady. Examples include the O'Neill, Nebraska (Project Prairie Grass, Lettau and Davidson, 1957), the Kansas (Businger, 1971; Kaimal and Wyngaard, 1990) and Davis (Pruitt et al., 1973) experiments in North America, the Australian Wangara experiment (Hess et al., 1981) and its predecessors near Hay and Kerang (Swinbank and Dyer, 1967) and studies near Tsimlyanskoye in Russia (Zilitinkevich and Chalikov, 1968). These are powerful datasets still being used to parameterize and model surface layer turbulence and are summarized in Foken (Foken, 2006).

The publication of Workshop on Micrometeorology in 1973 summarized the many field experiments and codified many of the theories that are used to this day. In the 1970s, theoretical advances in boundary layer meteorology were led by J. Deardorff. He developed early models on surface boundary layer fluxes, large eddy simulation and mixing layer theory (Deardorff, 1972; Deardorff, 1978). du Pont Donaldson is credited with introducing higher order closure theory to micrometeorology and K. Shankar Rao and John Wyngaard are among the first who applied higher order closure theory to describe advection (Rao et al., 1974).

Ag/Forest Meteorology

By the early 1960s, many concepts pioneered by micrometeorologists, such as Swinbank and coworkers, were ready for practical application to agricultural and ecological problems. Among the first experimentalists to apply flux-gradient theory to assess CO_2 and water vapor exchange over crops included E. Inoue (1957, Japan), John Monteith ((Monteith and Szeicz, 1960), Sutton Bonnington and Nottingham), Champ Tanner (1960, Univ Wisconsin), Ed Lemon (1962, Cornell), Tom Denmead (1966, CSIRO, Australia), and Norm Rosenberg (1966, Univ. Nebraska). It is my understanding that Dr. Inoue was a developer of the Zero airplane that was used by kamikaze pilots during World War 2 by the Japanese. The demilitarization of Japan following the War enabled Inoue to apply his skills towards peaceful activities like agriculture and crop production. Among the other important technical advances were the development of the net radiometer by Verner Suomi, as well as his contributions to the development of the sonic anemometer, with Joost Businger and J.C. Kaimal. Tanner made many advances in wet bulb psychrometry, which lended itself towards measuring water vapor fluxes with gradient methods.

With the success of micrometeorological measurements over short vegetation came a desire to apply them over tall vegetation. A number of pioneering flux studies were conducted between the late 1960s and early 1970s. Tom Denmead (Denmead, 1969), Baumgartner (Baumgartner A, 1969), Jarvis et al.(Jarvis et al., 2007) and Lemon et al (Lemon et al., 1970) were among the first investigators to apply flux-gradient methods over forests. Coyne and Kelley (Coyne and Kelley, 1975), Saugier and Ripley (Saugier and Ripley, 1978) were among the earliest ecologist to make CO_2 measurements over native ecosystems, such as tundra and grasslands, respectively.

Researchers soon found that forests did not operate like tall crops. A series of measurements at Thetford forest in England by Raupach (Raupach, 1979; Raupach and Legg, 1984), Stewart, Gash, Thom and colleagues (Stewart and Thom, 1973) drew attention to the fact that the application of flux gradient theory would prove to be troublesome over tall forests. Evidence was growing showing that Monin-Obukhov scale theory—a theory that was successfully

A Brief History on Eddy Covariance Flux Measurements: A Personal Perspective

Dennis Baldocchi

predicting gradient behavior over short vegetation--breaks down within the roughness layer over tall forests. Direct measurements were showing that eddy exchange coefficients were enhanced by turbulent transport because the turbulence length scales are long compared to the length scale of scalar gradients (Garratt, 1978; Raupach, 1979). Measurements over forests also have logistical difficulties, which arise from the need to suspend delicate instrumentation tens of meters above the ground. The efficient turbulent mixing afforded by tall forests also caused vertical gradients of scalar properties to be small and difficult to resolve.

One of the first applications of the eddy covariance method to agricultural meteorology and on the subject of carbon dioxide exchange occurred in the late 1960s. This work is attributed to Ray Desjardins; a graduate student of Ed Lemon (Desjardins, 1974). Dr. Desjardins was also instrumental in developing the eddy accumulation method and was a pioneer in applying the eddy covariance method on aircraft to measure eddy fluxes across landscapes (Desjardins et al., 1982). In the late 1970s, the US Department of Energy funded Lawrence Livermore Laboratory to develop and build open path CO2 sensors. Three sensors were built and were used in a series of pioneering flux measurements over crops by Shashi Verma and students in Nebraska (Anderson and Verma, 1985; Anderson et al., 1984) and by Marv Wesely and colleagues at Argonne (Wesely et al., 1983). And in Japan, E. Ohtaki successfully developed an instrument that was applied over rice (Ohtaki, 1984).

The logistical difficulties associated with making micrometeorological flux-gradient measurements over forests lead to a relative hiatus on mass and energy studies over forests between the mid 70's and mid 80's (Paul Jarvis, personal communication).

Exceptions included forest meteorology studies in Germany and Sweden using the Flux-Gradient method. The development and commercial availability of sonic anemometers (Kaimal and Businger, 1963), fast response hygrometry, and infrared spectrometry (Auble and Meyers 1992; Hyson and Hicks, 1975; Ohtaki and Matsui, 1982) in the 1980/90s lead to a renaissance of work in the eddy covariance field. It is important to note that studies in this era were based on datasets that consisted of tens of hours of data. The sensors drifted and had to be calibrated frequently. Computer data storage media were small, and investigators tended to baby sit their instruments for each moment of data collection.

Among the first modern eddy covariance studies over forests were sets of measurements conducted in the early 1980s by the ATDD/NOAA lab in Oak Ridge, TN (McMillen, 1988; Verma et al., 1986), the Institute of Hydrology in the Amazon (Shuttleworth, 2007; Shuttleworth et al., 1984), Argonne National Lab (Wesely et al., 1983) and the CSIRO Centre for Environmental Mechanics (Denmead, 1984; Denmead and Bradley, 1987). The studies of Denmead and colleagues were particularly revolutionary, as they were among the first to directly measure counter-gradient transfer inside forest canopies.

Until the 1990s, open and closed path CO2 sensors remained a rare quantity. The development of a home-made open path CO2 sensor by Auble and Meyers at the NOAA Atmospheric Turbulence and Diffusion Laboratory in Oak Ridge, TN,(Auble and Meyers 1992) changed this course. They were able to produce tens of sensors that were soon purchased and implemented by colleagues in Oregon and San Diego. Simultaneously, LICOR was making advances in producing a closed path sensor that used a solid state detector, that enabled one to conduct eddy covariance measurements. These advances, and further developments in computers and data storage, lead to a new generation of studies that started collecting data for hundreds of hours and tens of days at a time.

The cited technical advancements corresponded with the political and scientific decision to conduct large-scale multi-investigator experiments (Shuttleworth, 2007).

A Brief History on Eddy Covariance Flux Measurements: A Personal Perspective

Dennis Baldocchi

Among the first studies of this scope was the HAPEX-MOBILHY experiment in southwestern France (Gash et al., 1989), followed by another experiment in Kansas; FIFE in 1986 and 1987 (Sellers and Hall, 1992). By this time, experimentalists dared to expose their instruments to time periods exceeding a week or two- of ideal conditions. FIFE-- the First ISLSCP (International Satellite Land Surface Climatology Project) Field Experiment--was conducted on a multiple campaign mode, and covered the duration of the growing season of a grassland.

Success with these campaigns increased interest in additional large-scale studies, but over more complex landscapes, e.g. 'FIFE in a Forest'. Planning led to the design and execution of the BOREAS experiment in Canada (Sellers et al., 1995; Sellers et al., 1997) and the HAPEX-Sahel experiments over the 1992 through 1995 period (Gash et al., 1997). These studies are notable for providing a strong understanding of how forests and short-statured vegetation operated under ideal summer time conditions; data collected from these studies included thousands of hours and a hundred days.

Unfortunately, plant and atmosphere interactions do not abide by the academic calendar and operate when researchers, professors and students are ready to go to the field. They operate 24 hours a day, seven days a week, 52 weeks a year. So we needed to attain information on mass and energy fluxes on time scales of days to years. At set of experiments at Harvard Forest, starting in 1990 by Wofsy et al. (Wofsy et al., 1993) were among the first studies to attempt to measure eddy fluxes of carbon dioxide, water and energy exchange over the course of a year. Andy Black's group started the boreal aspen study in 1993 as part of the BOREAS project (Black et al., 1996). And around the early to mid-1990s, Riccardo Valentini and students were measuring continuous fluxes in Italy (Valentini et al., 1995), S. Yamamoto and colleagues were making flux measurements in Japan (Yamamoto et al., 1999), and my own group started long term eddy covariance flux measurements at Walker Branch Watershed in Tennessee (Greco and Baldocchi, 1996; Wilson and Baldocchi, 2001). With the encouragement of the first set of long term flux measurements, we were able to develop regional flux networks, like CarboEuroflux, AmeriFlux, Fluxnet-Canada, China-Flux, AsiaNet, Ozflux and LBA (Brazil) networks, and combine them into the global network, FLUXNET (Baldocchi et al., 1996).

Bibliography

Denmead, O.T. 1983. Micrometeorological methods for measuring gaseous losses of nitrogen in the field. In: Gaseous Loss of Nitrogen from plant-soil systems. eds. J.R. Freney and J.R. Simpson. pp 137-155.

Denmead, O.T. and M.R. Raupach. 1993. Methods for measuring atmospheric gas transport in agricultural and forest systems. In: Agricultural Ecosystem Effects on Trace Gases and Global Climate Change. American Society of Agronomy.

Lenschow, DH. 1995. Micrometeorological techniques for measuring biosphere-atmosphere trace gas exchange. In: Biogenic Trace Gases: Measuring Emissions from Soil and Water. Eds. P.A. Matson and R.C. Harriss. Blackwell Sci. Pub. Pp 126-163.

Endnote References

Anderson, D.E. and Verma, S.B., 1985. Turbulence spectra of CO_2 water -vapor, temperature and wind velocity fluctuations over a crop surface. Boundary-Layer Meteorology, 33(1): 1-14.

Anderson, D.E., Verma, S.B. and Rosenberg, N.J., 1984. Eddy-correlation measurements of CO_2, latent-heat, and sensible heat fluxes over a crop surface. Boundary-Layer Meteorology, 29(3): 263-272.

Auble, D.L. and Meyers , T.P., 1992. An open path, fast response infrared-absorption gas analyzer for H_2O and CO_2. Boundary Layer Meteorology, 59: 243-256.

Baldocchi, D.D., R.Valentini, Running, S.R., Oechel, W. and Dahlman, R., 1996. Strate-

A Brief History on Eddy Covariance Flux Measurements: A Personal Perspective

Dennis Baldocchi

gies for measuring and modelling CO_2 and water vapor fluxes over terrestrial ecosystems. Global Change Biology., 2: 159-168..

Baumgartner A, 1969. Meteorological approach to exchange of CO2 between atmosphere and vegetation, particularly forest stands. Photosynthetica, 3(2): 127-&.

Black, T. et al., 1996. Annual cycles of water vapour and carbon dioxide fluxes in and above a boreal aspen forest. Global Change Biol, 2: 219-229.

Businger, J.A., 1971. Flux-profile relationships in the atmospheric surface layer. Journal of Atmospheric Science, 28: 181.

Coyne, P.I. and Kelley, J.J., 1975. CO2 Exchange over Alaskan Arctic tundra—Meteorological assessment by an aerodynamic method. Journal of Applied Ecology, 12(2): 587-&.

Deardorff, J.W., 1972. Parameterization of Planetary Boundary-Layer for Use in General Circulation Models. Monthly Weather Review, 100(2): 93-&.

Deardorff, J.W., 1978. Efficient Prediction of Ground Surface-Temperature and Moisture, with Inclusion of a Layer of Vegetation. Journal of Geophysical Research-Oceans and Atmospheres, 83(NC4): 1889-1903.

Denmead, O.T., 1969. Comparative micrometeorology of a wheat field and a forest of Pinus radiata. Agricultural Meteorology, 6 (5): 357-371.

Denmead, O.T., 1984. Plant Physiological Methods for Studying Evapotranspiration - Problems of Telling the Forest from the Trees. Agricultural Water Management, 8(1-3): 167-189.

Denmead, O.T. and Bradley, E.F., 1987. On Scalar Transport in Plant Canopies. Irrigation Science, 8 (2): 131-149.

Desjardins, R., 1974. Technique to Measure Co2 Exchange under Field Conditions. International Journal of Biometeorology, 18 (1): 76-83.

Desjardins, R.L., Brach, E.J., Alvo, P. and Schuepp, P.H., 1982. Aircraft Monitoring of Surface Carbon-Dioxide Exchange. Science, 216(4547): 733-735.

Dyer, A.J. and Hicks, B.B., 1970. Flux-Gradient Relationships in Constant Flux Layer. Quarterly Journal of the Royal Meteorological Society, 96 (410): 715-&.

Dyer, A.J. and Hicks, B.B., 1972. Spatial Variability of Eddy Fluxes in Constant Flux Layer. Quarterly Journal of the Royal Meteorological Society, 98(415): 206-&.

Foken, T., 2006. 50 years of the Monin-Obukhov similarity theory. Boundary-Layer Meteorology, 119 (3): 431-447.

Garratt, J.R., 1978. Flux Profile Relations above Tall Vegetation. Quarterly Journal of the Royal Meteorological Society, 104 (439): 199-211.

Gash, J.H.C. et al., 1997. The variability of evaporation during the HAPEX-Sahel intensive observation period. Journal of Hydrology, 189(1-4): 385-399.

Gash, J.H.C. et al., 1989. Micrometeorological Measurements in Les-Landes Forest During Hapex-Mobilhy. Agricultural and Forest Meteorology, 46(1-2): 131-147.

Greco, S. and Baldocchi, D.D., 1996. Seasonal variations of CO_2 and water vapor exchange rates over a temperate deciduous forest. Global Change Biology., 2: 183-198.

Hess, G.D., Hicks, B.B. and Yamada, T., 1981. The Impact of the Wangara Experiment. Boundary-Layer Meteorology, 20(2): 135-174.

Hyson, P. and Hicks, B.B., 1975. Single-Beam Infrared Hygrometer for Evaporation Measurement. Journal of Applied Meteorology, 14(3): 301-307.

Jarvis, P.G., Stewart, J.B. and Meir, P., 2007. Fluxes of carbon dioxide at Thetford Forest. Hydrology and Earth System Sciences, 11 (1): 245-255.

Kaimal, J.C. and Businger, J.A., 1963. A continuous wave sonic anemometer thermometer. Journal of Applied Meteorology, 2: 156-164.

Kaimal, J.C. and Wyngaard, J.C., 1990. The Kansas and Minnesota Experiments. Boundary-

A Brief History on Eddy Covariance Flux Measurements: A Personal Perspective

Dennis Baldocchi

Layer Meteorology, 50(1-4): 31-47.

Lemon, E., Allen, L.H. and Muller, L., 1970. Carbon dioxide exchange of a tropical rain forest .2. Bioscience, 20(19): 1054-&.

McMillen, R.T., 1988. An Eddy-Correlation Technique with Extended Applicability to Non-Simple Terrain. Boundary-Layer Meteorology, 43(3): 231-245.

Monteith, J.L. and Szeicz, G., 1960. The Carbon-Dioxide Flux over a Field of Sugar Beet. Quarterly Journal of the Royal Meteorological Society, 86 (368): 205-214.

Ohtaki, E., 1984. The Budget of Carbon-Dioxide Variance in the Surface-Layer over Vegetated Fields. Boundary-Layer Meteorology, 29(3): 251-261.

Ohtaki, E. and Matsui, T., 1982. Infrared Device for Simultaneous Measurement of Fluctuations of Atmospheric Carbon-Dioxide and Water-Vapor. Boundary-Layer Meteorology, 24(1): 109-119.

Priestley, C.H.B. and Swinbank, W.C., 1947. Vertical transport of heat by turbulence in the atmosphere. Proceedings of the Royal Society of London Series a-Mathematical and Physical Sciences, 189 (1019): 543-561.

Pruitt, W.O., Morgan, D.L. and Lourence, F.J., 1973. Momentum and Mass Transfers in Surface Boundary-Layer. Quarterly Journal of the Royal Meteorological Society, 99 (420): 370-386.

Rao, K.S., Wyngaard, J.C. and Cote, O.R., 1974. Structure of 2-Dimensional Internal Boundary-Layer over a Sudden Change of Surface-Roughness. Journal of the Atmospheric Sciences, 31(3): 738-746.

Raupach, M.R., 1979. Anomalies in Flux-Gradient Relationships over Forest. Boundary-Layer Meteorology, 16(4): 467-486.

Raupach, M.R. and Legg, B.J., 1984. The Uses and Limitations of Flux-Gradient Relationships in Micrometeorology. Agricultural Water Management, 8(1-3): 119-131.

Reynolds, O., 1895. On the dynamical theory of incompressible viscous fluids and the determinatino of the criterion. Philosophical Transactions of the Royal Society of London, A, 186: 123-164.

Saugier, B. and Ripley, E.A., 1978. Evaluation of aerodynamic method of determining fluxes over natural grassland. Quarterly Journal of the Royal Meteorological Society, 104 (440): 257-270.

Sellers, P.J. and Hall, F.G., 1992. Fife in 1992 - Results, Scientific Gains, and Future-Research Directions. Journal of Geophysical Research-Atmospheres, 97(D17): 19091-19109.

Sellers, P.J. et al., 1995. Boreal Ecosystem Atmsophere (BOREAS): an overview and early results from the 1994 field year. Bulletin of the American Meteorological Society., 76: 1549-1577.

Sellers, P.J. et al., 1997. Boreas in 1997: Scientific results; experimental overview and future directions. Journal of Geophysical Research., 102: 28731-28770.

Shuttleworth, W.J., 2007. Putting the 'vap' into evaporation. Hydrology and Earth System Sciences, 11 (1): 210-244.

Shuttleworth, W.J. et al., 1984. Eddy-Correlation Measurements of Energy Partition for Amazonian Forest. Quarterly Journal of the Royal Meteorological Society, 110(466): 1143-1162.

Stewart, J.B. and Thom, A.S., 1973. Energy Budgets in Pine Forest. Quarterly Journal of the Royal Meteorological Society, 99 (419): 154-170.

Swinbank, W.C., 1951. The Measurement of Vertical Transfer of Heat and Water Vapor by Eddies in the Lower Atmosphere. Journal of Meteorology, 8 (3): 135-145.

Swinbank, W.C. and Dyer, A.J., 1967. An experimental study in micrometeorology. Quarterly Journal of the Royal Meteorological Society, 93 (398): 494-&.

Tollmien, W., 1935. Über die Korrelation der Geschwindigkeitskomponenten in periodisch schwankenden Wirbelverteilungen. ZAMM - Journal of Applied Mathematics and Mechanics /

A Brief History on Eddy Covariance Flux Measurements: A Personal Perspective

Dennis Baldocchi

Zeitschrift für Angewandte Mathematik und Mechanik, 15(1-2): 96-100.

Valentini, R., Mugnozza, G.S., De Angelis, P. and Matteucci, G., 1995. Coupling water sources and carbon metabolism of natural vegetation at integrated time and space scales. Agricultural and Forest Meteorology, 73(3-4): 297-306.

Verma, S.B., Baldocchi, D.D., Anderson, D.E., Matt, D.R. and Clement, R.E., 1986. Eddy Fluxes of CO_2, water vapor and sensible heat over a deciduous forest. Boundary Layer Meteorology.. 36: 71-91.

Wesely, M.L., Cook, D.R. and Hart, R.L., 1983. Fluxes of Gases and Particles above a Deciduous Forest in Wintertime. Boundary-Layer Meteorology, 27(3): 237-255.

Wilson, K.B. and Baldocchi, D.D., 2001. Comparing independent estimates of carbon dioxide exchange over five years at a deciduous forest in the southern United States. Journal of Geophysical Research, 106: 34167-34178.

Wofsy, S.C. et al., 1993. Net Exchange of CO_2 in a Midlatitude Forest. Science, 260(5112): 1314-1317.

Yamamoto, S., Murayama, S., Saigusa, N. and Kondo, H., 1999. Seasonal and inter-annual variation of CO_2 flux between a temperate forest and the atmosphere in Japan. Tellus, 51B: 402-413.

Zilitinkevich , S.S. and Chalikov, D.V., 1968. On momentum heat and moisture exchange in process of interaction between atmosphere and underlying surface. Izvestiya Akademii Nauk Sssr Fizika Atmosfery I Okeana, 4(7): 765-&.

Contact

Dennis Baldocchi
Dept. of Environmental Science, Policy and Management, University of CA, Berkeley 94720-3114
baldocchi@berkeley.edu

The Yatir Forest Site: Postcards from the edge

Dan Yakir

At the dawn of the new Millennium, in early 2000, we decided to setup a flux station site that will provide information on forest activities at the semi-arid 'dry timber-line' (Figure 1), which was not covered by the extensive efforts of the young Fluxnet. The only funding opportunity available was for a regular "large-equipment" grant as done when requesting a new microscope. This was not inappropriate: in adopting the flux tower as our research tool, we essentially 'inverted the microscope'. We shifted from a reductionist approach of trying to understand an organism by breaking it apart, to a holistic approach trying to understand how the parts integrate to explain the functioning of the Ecosystem. In reality, one cannot put up a flux site for the price of a microscope. And so, to make ends meet, we set out to a large junkyard. A set of sections of an old building construction crane was found that had the potential, with some imagination, to form a tower at the right height and stability and at a bargain price (Figure 2). These were shipped to a friendly machine shop, cleaned up, mended, and painted (green, of course). Within a couple of months a 19m tower was ceremonially set down and leveled at the bottom of a 3x3x3 m hole and fixed, for ever, with the help of 11 tons of concrete, at the center of the largest (~20,000 ha) and driest (290 mm precipitation) 40 year old pine forest in Israel (31^{0}20'N, 35^{0}00'E). Together with Tongbau Lin, a dedicated postdoc from China, and a few part time students, we added the scientific coating onto the tower, and before long a state of the art flux tower began its operation (Figure 3). Being a field research site, not just a monitoring station, students and postdocs were recruited for a range of projects to obtain a comprehensive perspective on questions such as as:

Figures 1&2. Yatir Forest (above) and an old building construction crane converted to a flux tower (below).

How a forest functions where experts predicted a forest should not exist;

What defines the 'dry timberline';

What lessons can we learn from Yatir, with respect to the future of forests in wetter areas undergoing warming and drying?

More than ten years down the road, 4 MSc. and 4 Ph.D. theses, and 10 postdoc projects, with team members from China, New Zealand, Nepal, UK, Germany, and Israel, over 30 scientific papers and dozens of proceedings chapters, abstracts and posters, we are still fascinated, and indeed awestruck, by the intricacies of the operation of the dryland forest. Surprisingly the forest turned out to be a carbon sink of ~2.3 t C Ha, not very different from the FLUXNET mean of about 2.6 (Grunzweig et al., 2002, 2007; Maseyk et al., 2008; Rotenberg & Yakir, 2010). Reconstructing the evolution of the carbon stock in the forest,

The Yatir Forest Site: Postcards from the edge

Dan Yakir

from aerial photography (Bar-Masada et al., 2006) showed that the accumulation is nearly linear in time with no signs of decline. The forest productivity is associated with distinct phenology (Maseyk et al., 2007), tight water budget (with over 90% of precipitation measured as ET; Raz Yaseef et al., 2009). It also shows a "closed energy budget", with a counterintuitive cooler canopy surface that emits larger sensible heat fluxes, compared to the non-forested shrubland (Rotenberg & Yakir, 2010, 2011). A detailed nitrogen budget showed that the threefold increase in carbon stock in the forest was associated with a large increase in NUE (nitrogen use efficiency) and N remobilization, but not in N stock as initially expected (Gelfand et al., 2011). Isotopic analysis of tree-rings indicated a ~25% increase in WUE (water use efficiency) over the past 30 years, most likely due increasing atmospheric CO_2 concentrations (Maseyk et al., 2011). Finally, the time has come to extend our measurement range beyond the flux tower anchored in 11 tons of concrete in Yatir. And so, we are off to conduct another ten years of exciting research using a mobile flux system that will allow us to move around the forest and into other forests and ecosystems in different climatic zones (Figure 4). Some highlights of our exciting ten years project are briefly discussed below by their specific authors. Clearly, this short "postcard" is doing an injustice to the enormous efforts under harsh conditions made by the large team of talented and

Figure 3. The instrumented flux tower at Yatir Forest.

Figure 4. The new mobile flux tower.

The Yatir Forest Site: Postcards from the edge

Dan Yakir

dedicated students and scientists, but we hope it will serve as an invitation to read more of the results from one of the most remote and unique Fluxnet sites.

References:

Grünzweig JM, Lin T, Rotenberg E and Yakir D (2002) Carbon sequestration potential in arid-land forest. *Global Global Change Biology*, 9,791-799.

Bar Massada A, Carmel Y., Even Tzur G., Grünzweig JM, and Yakir D (2006) Assessment of temporal changes in above-ground forest tree biomass using aerial photographs and allometric equations. *Canadian J Forest Res.* 10, 2585-2594.

Grunzweig JM, Gelfand I and Yakir D (2007) Biogeochemical factors contributing to enhanced carbon storage following afforestation of semi-arid shrubland. *Biogeochemistry 4*, 891-904.

Maseyk K, Tongbao L, Rotenberg E, Grünzweig J, Schwartz A and Yakir D (2007) Physiology phenology interactions in a productive semi-arid pine forest. *New Phytology*, 178, 603-616.

Maseyk K, Grünzweig J, Rotenberg E and Yakir D (2008) Respiration acclimation contributes to high carbon-use efficiency in a seasonally dry pine forest. *Global Change Biology*, doi: 10.1111/j.1365-2486.2008.01604.x

Rotenberg E and Yakir D (2011) Distinct long- and short-wave radiation regimes in high productivity semi-arid pine forest. *Global Change Biology*. 17, 1536-1548. Doi: 10.1111/j/1365-2486.2010.02320.x

Rotenberg R and Yakir D (2010) Contribution of semi-arid forests to the climate system. *Science*, 327, 451-454 DOI: 10.1126/science.1179998.

Maseyk K, Angert A, Hemming D, Leavitt S and Yakir D (2011) The control of temperature and precipitation and CO_2 on tree growth and water use efficiency in semi-arid woodland. *Oecologia,* 167, 573-585. Doi:10.1007/s00442-011-2010-4.

Gelfand I, Grunzweig JM and Yakir D (2011) Slowing of nitrogen cycling and increasing nitrogen use efficiency following afforestation of semi-arid shrubland. Oecologia, DOI 10.1007/s00442-011-2111-0

Raz-Yaseef N, Yakir D, Rotenberg E, Schiller G, Cohen S (2009) Ecohydrology of a semi-arid forest: partitioning among water balance components. *Ecohydrology*, DOI: 10.1002/eco.65

Contact:

Dan Yakir
Department of Environmental Sciences and Energy Research Weizmann Institute of Science
Rehovot 76100 ISRAEL
Tel: 972-8-934-2549
Dan.Yakir@weizmann.ac.il

The Yatir Forest Site: Solving the energy dissipation riddle in Yatir

Eyal Rotenberg

With annual incoming solar radiation of ~7.5 GJ m^{-2} (~238 W m^{-2}), the Yatir forest is exposed to a radiation load similar to that at the heart of the Sahara desert. Clearly, an evergreen forest needs to develop means to cope with such energy inputs, and with limited water availability this cannot be through the common evapotranspiration route. Furthermore, Charney, who carried out pioneering studies on the surface radiation budget in semiarid regions in the 1970s postulated that "..reduction of vegetation, with consequent increase of albedo in the Sahel region would cause sinking (air) motion, additional drying, and would therefore perpetuate the arid conditions…" (Charney, 1975; 1977 More recently, with greater awareness of the importance of the CO2 rise in the atmosphere, the contrasting effects of vegetation in removing atmospheric carbon reducing its warming effect, while also decreasing surface albedo, enhancing surface warming. But detail studies generally focused on relatively wet regions (temperate, tropical). These aspects motivated us to link geophysical (energy fluxes) and biogeochemical (carbon fluxes) studies in the Yatir forest to explore the potential for and implications of afforestation and desertification in semi-arid regions (Rotenberg & Yakir, 2010, 2011).

Both remote sensing (MODIS) and local measurements indicate that the forest canopy surface temperature in Yatir is lower than the surface temperature in adjacent non-forested areas. While some surface cooling due to added forest cover may sound reasonable, this finding is counter to expectations in Yatir for the following reasons. First, the forest albedo is 0.1 lower than the surrounding, translating

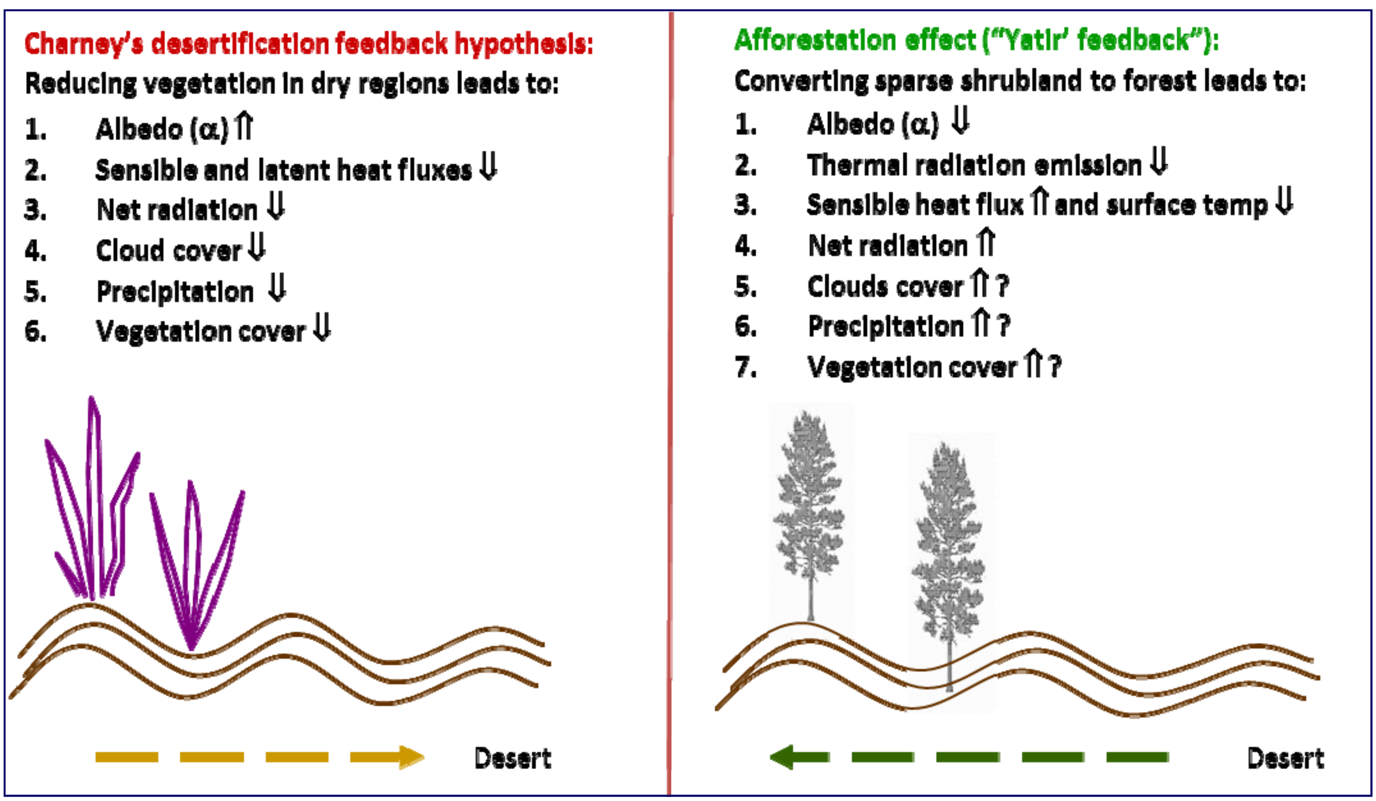

Figure 1. Changes in surface energy fluxes associated with desertification (left; the Charney effect) and afforestation (right, the "Yatir effect). Upward and downward arrows indicate expected enhancement or suppression in flux associated with the land cover change.

The Yatir Forest Site: Solving the energy dissipation riddle in Yatir

Eyal Rotenberg

into a 24 W m^{-2} increase in radiation absorption by the forest canopy. Second, the forest "skin" surface (canopy and soil surface) is cooler, by 5°C on annual mean.. Cooler surface emits less long-wave thermal radiation, and additional 25 W m^{-2} are held back by the forest. Combined, the increased absorption and reduced emission, translate tothe nearly 50 W m^{-2} increase in radiation load associated with afforestation in this region. For comparison, this is as large as the difference in net radiation between, the Sahara desert and Denmark, for example. Moreover, latent heat flux, the common cooling and energy dissipation mechanism in temperate forests, is not an option where water is virtually unavailable for some 7 months a year. And so, we are left with sensible heat flux as the only major heat dissipation route. But sensible heat fluxes are normally directly proportional to the surface temperature, and our forest surface is cooler… As it turned out sensible heat flux is indeed the major heat dissipation route. So much so that in summer the Bowen ratio (the ratio of sensible to latent heat fluxes), which is often

Figure 2: The radiation measurement setup over the Yatir forest, included: 2 - Kipp& Zonen CM21 for the solar radiation range, 2 - Eppley PIR for the thermal range,2 - Kipp&Zonen PQS1 for the PAR and 2 - Skye 4 Channel SKR 1850 sensors. A set of sensors is looking upward (to the atmosphere) the other downward.

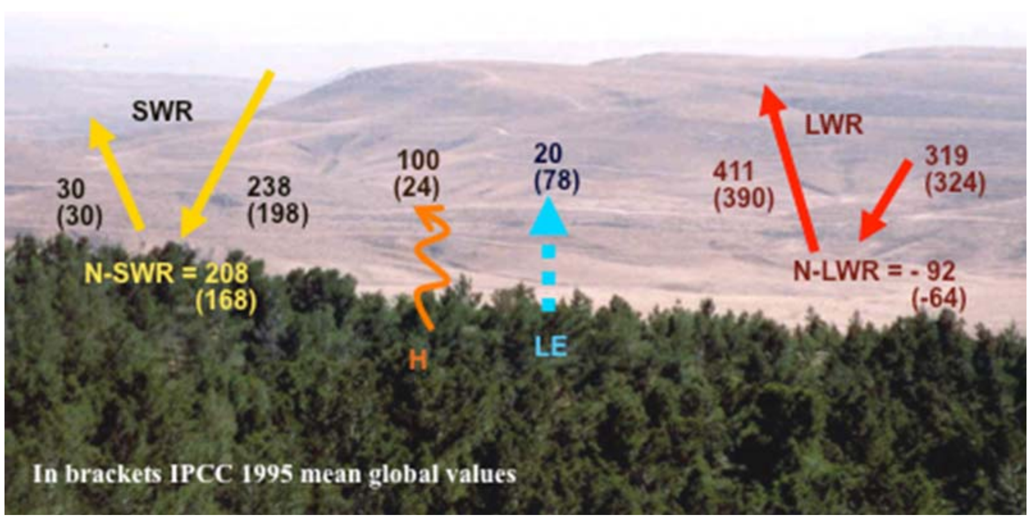

Figure 3. Forest vs background and the characteristic mean annual values of energy fluxes above the semi-arid Yatir forest, compared to global mean values (in brackets). Note the high incoming short wave solar radiations (SWR) and low albedo (ratio of out-going to incoming SWR), the low latent heat (LE) and large sensible heat (H) fluxes.

The Yatir Forest Site: Solving the energy dissipation riddle in Yatir

Eyal Rotenberg

around 1 in temperate forests, goes beyond 20 in Yatir, when the entire net solar radiation flux of ~800 W m^{-2} is dissipated as large sensible heat flux of the same magnitude. The solution to this apparent “riddle” is simple when we recall that while sensible heat flux is indeed directly proportional to the surface temperature, but inversely proportional to the aerodynamic resistance of the surface layer. And a semi-arid forest with its low tree density and large surface area becomes an efficient low resistance “convector” well coupled to the surrounding atmosphere. In Yatir, the ‘canopy convector effect’ is so efficient that the sensible heat flux is even greater than in the Sahara desert. It of course remains to be tested what are the consequences of the massive sensible heat fluxes above a sufficiently large forest area for the local circulation and synoptic systems. The Yatir forest is too small for that, but a modeling exercise is under way to address such questions now that we have quantified the surface behavior.

References

Charney, J. (1975). "Dynamics of deserts and drought in the Sahel." Quarterly journal of the Royal Meteorological Society **101**(428): 193-202.

Charney, J., W. J. Quirk, et al. (1977). "Comparative-Study of Effects of Albedo Change on Drought in Semi-Arid Regions." Journal of the Atmospheric Sciences **34** (9): 1366-1385.

Rotenberg, E. and D. Yakir (2010). "Contribution of Semi-Arid Forests to the Climate System." Science **327**(5964): 451-454.

Contact:

Eyal Rotenberg
Department of Environmental Sciences and Energy Research Weizmann Institute of Science
Rehovot 76100 ISRAEL
Tel: 972-8-934-2549
eyal.rotenberg@weizmann ac.il

The Yatir Forest Site: "Decoupling" phenology to maximize carbon uptake

Kadmiel Maseyk

Pushing a forest to the edge, like the case for the Yatir Forest, can provide insights into the responses and strategies that can be produced in response to climate change. This includes changes in the timing of individual life-cycle events (phenophases), which represent adaptations to maximise fitness in a particular environment.

Vegetative growth goes for the comfort zone: Vegetative growth in forests normally peaks during periods that provides near optimal combinations of soil moisture, temperature and solar radiation. This occurs in late summer in high latitude forests and in spring in dry Mediterranean forests (Figure 1). In the latter case, little physiological activity can be expected during the long, hot, and dry summer period. However, leaf and shoot growth can be observed in some species during summer. This is the case with pine trees, whose origins predate the Mediterranean climate that developed about 3.2 million years ago. In the pine trees in Yatir, this gives rise to a remarkable separation of needle growth from other physiological processes.

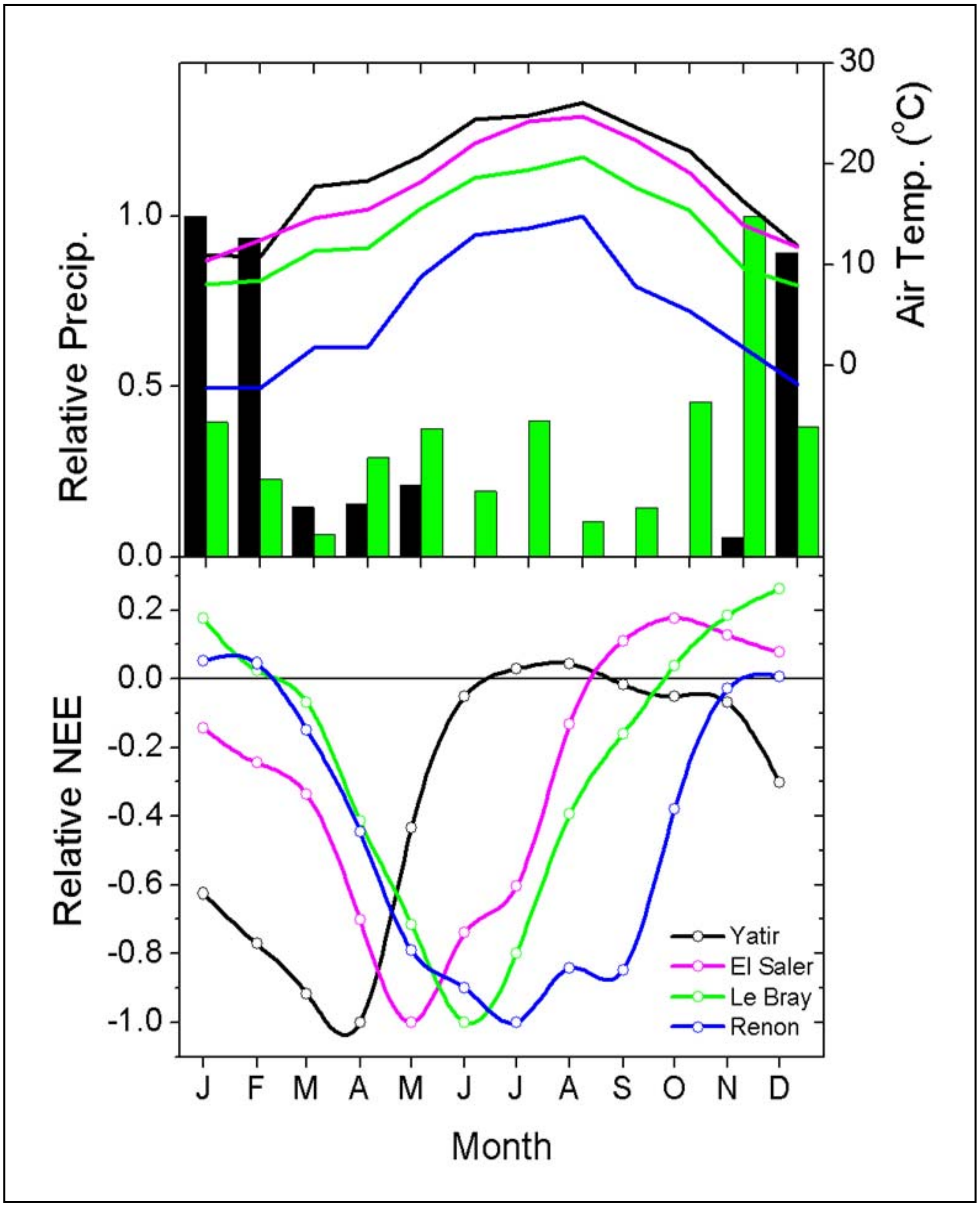

Figure 1: Temporal shift in ecosystem activity across a climatic gradient in different FluxNet stations (Renon, northern Italy, Lat. 46.6; Le Bray, France, Lat. 44.7; El Saler, Spain, Lat. 39.3; Yatir, Israel, Lat. 31.3). All sites show the typical northern hemisphere temperature seasonality, with warm summer and cold winters. Water limitation is evident only in the southern sites with dry summers. This is reflected in a marked shift in peak CO_2 uptake (NEE) from later summer to early spring.

The Yatir Forest Site: "Decoupling" phenology to maximize carbon uptake

Kadmiel Maseyk

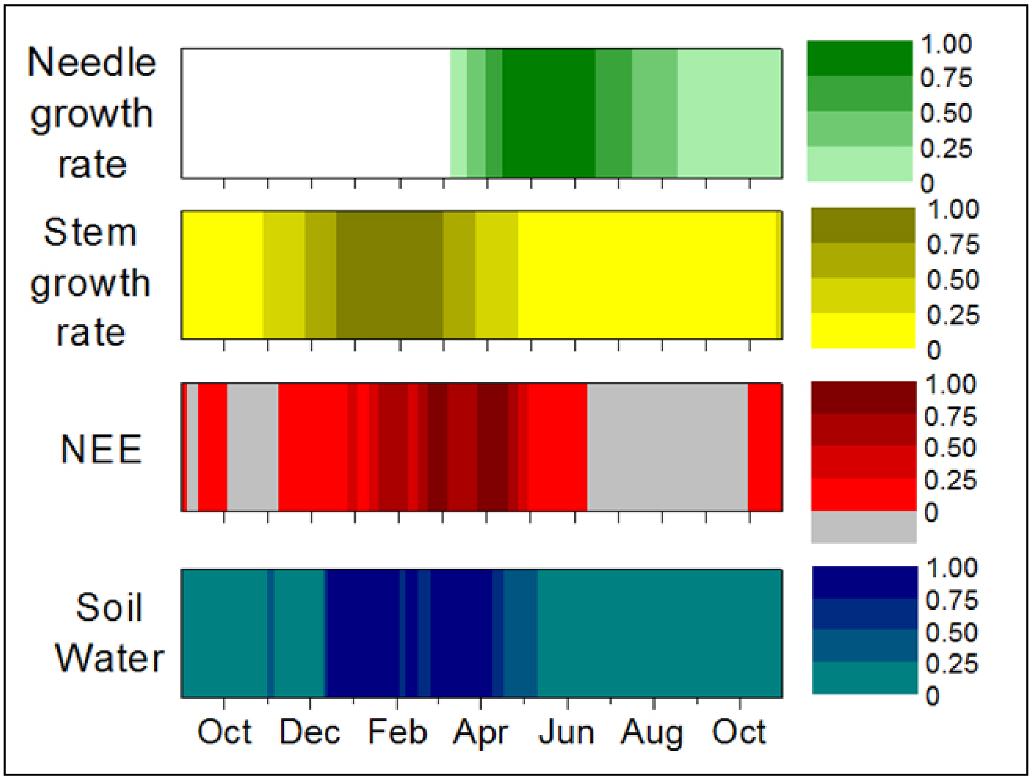

Figure 2. Normalised (relative to seasonal maximum) phenograms of needle elongation, stem increment, net ecosystem exchange (grey periods indicate when respiration exceeds gross photosynthesis) and soil water content. The phasing of needle development is separated from that of the stem growth, occurring through the summer when soil water contents and photosynthesis approach their minimum values.

Needle growth stands it's ground: Needle growth in Yatir occurs throughout the long stressful summer period (March to October), decoupled from the main period of photosynthetic activity (December to May, see Fig. 2)[2]. Photosynthesis continues during the summer, albeit at very low rates for limited times, mostly in early morning, supporting the developing leaves that do not seem to rely on storage. The timing of needle growth is highly conservative and was found to be insensitive to inter-annual variations in climate and manipulation treatments. Yet, needle number, length and thickness varied significantly among years, and in response to experimental manipulation (summer-time irrigation or defoliation). We therefore concluded that needle growth is sensitive to carbon supply during the growth period (as opposed to relying on storage), but the seasonal timing of growth is controlled by environmental cues having little or no inter-annual variation.

Stem growth follows the money: Unlike needles, stem growth is a very plastic feature and generally closely follows photosynthesis[3]. This suggests that cambial development is linked more to physiological processes than to a direct climatic cue, and is considered a more Mediterranean-adapted feature.

A winning combination: Species with both concentrated overlapping phenophases (in spring) and sequential phenophases (e.g. spring and summer) can be seen in Mediterranean vegetation. Phenophase separation distributes growth demands over the time period when resource availability is limited by, for example, cold in winter or water stress in summer, which in turn, reduces intra-plant competition for resources. But perhaps the most obvious advantage of dry summer leaf phenology is that it results in little or no lag period to reach maximal leaf and canopy area of functional needles in the following short wet season. When conditions are finally favourable for photosynthesis, high carbon assimilation rates are achieved early in the short season. Indeed, the young fully

The Yatir Forest Site: "Decoupling" phenology to maximize carbon uptake

Kadmiel Maseyk

expanded needles show the highest rates of assimilation at that time among the leaf cohorts. Achieving this high early season capacity is also supported by high leaf nitrogen contents at the start of the season due to the completion of growth-related N remobilisation and translocation (see section on Nitrogen in this Letter), and other adjustments to the semi-arid conditions including dynamic pigmentation to protect needles from photo-damage (reduction in chlorophyll and increase xanthophyll cycle pigments). Having canopy development during the hydrological limitation period also helps maintain canopy size at sustainable levels.

These results highlight important features when considering functional responses to environmental change: the response across phenological processes of a species will differ, depending on the nature of the change, the drivers of the phenophases and evolutionary constraints on plasticity. It appears that the separation of wood and foliage phenophases in this dry environment enables more efficient allocation of resources, optimizes canopy development and maximizes carbon gain. Some investment is required, however, in mechanisms preventing photo-oxidative damage and hydrological stress to maintain dry season leaf phenology. Understanding the interactions between climate, physiology and phenology in this system provides insights into features contributing to the success of pines under warm and dry conditions, and may have more general relevance to (warming and drying) temperate regions as well.

References

Orshan, G. Plant Phenomorphological Studies in Mediterranean Type Ecosystems. Vol. 12 (Kluwer Academic Publishers, 1989).

Maseyk, K. S. et al. Physiology-phenology interactions in a productive semi-arid pine forest. New Phytologist **178**, 603-616, doi:10.1111/j.1469-8137.2008.02391.x (2008).

Maseyk, K., Grunzweig, J. M., Rotenberg, E. & Yakir, D. Respiration acclimation contributes to high carbon-use efficiency in a seasonally dry pine forest. Global Change Biology **14**, 1553-1567, doi:10.1111/j.1365-2486.2008.01604.x (2008).

Liphschitz, N. & Lev-Yadun, S. Cambial Activity of Evergreen and Seasonal Dimorphics around the Mediterranean. Iawa Bulletin **7**, 145-153 (1986).

Contact:

Kadmiel Maseyk
Kadmiel.Maseyk@grignon.inra.fr

The Yatir Forest Site: Decoupling of the tree hydraulic components in Yatir Forest

Tamir Klein

Investment in exploration: When water is scarce, more resources need to be devoted towards exploring for it and extracting it from the soil. This is clearly seen in *Pinus halepensis*, the dominant tree species in Yatir. Increasing water stress triggers dramatic shifts in biomass allocation among leaves, stems, and roots. While in the absence of water stress total root growth is only 34% of freshly synthesized biomass, it increases to as high as 87% under severe water stress conditions (Figure 1; see Klein et al., 2011 for details).

The in and the out of tree water use: Tree water use is often estimated by tree-scale stem sap flow, or by short-term leaf-scale gas exchange measurements. We applied both methods simultaneously, and scaled up both measurements to the stand level by relying on extensive estimates of LAI and local, site-specific allometric equations (Gruenzweig et al., 2007; Sprintsin et al., 2011). As expected, on the daily time-scale, water mass balance exists between the trunk and the leaves. On shorter time-scales, however, strong decoupling between stem sap flow and leaf transpiration was observed (Figure 2). Examining the diurnal dynamics showed that changes in sap flow are gradual, while transpiration rates greatly fluctuate, and peak transpiration can be twice that of sap-flow; Moreover, we found that transpiration ceases at night, whereas sap flow continued long after dark.

The hazards and safeguards of decoupling: The relative magnitude of nocturnal sap flow during summer months surpasses some previously reported values for pine forests. The observations that sap flow occurred at night, temporally decoupled from leaf transpiration, imply that the tree xylem undergoes substantial changes in its water content on a daily basis. Such changes may involve large short-term deficits of up to 15 dm^3 of water per tree, although some of the xylem hydraulic imbalance may be buffered by short-term water storage capacity. Nonetheless, the observed decoupling must also mean the development of embolism in xylem tracheids, as observed in the dynamics of the percent loss of hydraulic conductivity (PLC, up to 40%). This, in turn, would require a capacity to recover hydraulic conductance to maintain the observed hydraulic patterns in a continuous manner. Indeed our latest findings provide evidence on the capacity for rapid recovery from loss of hydraulic conductivity in *Pinus halepensis* (within a few hours and repeating twice in a single daytime cycle).

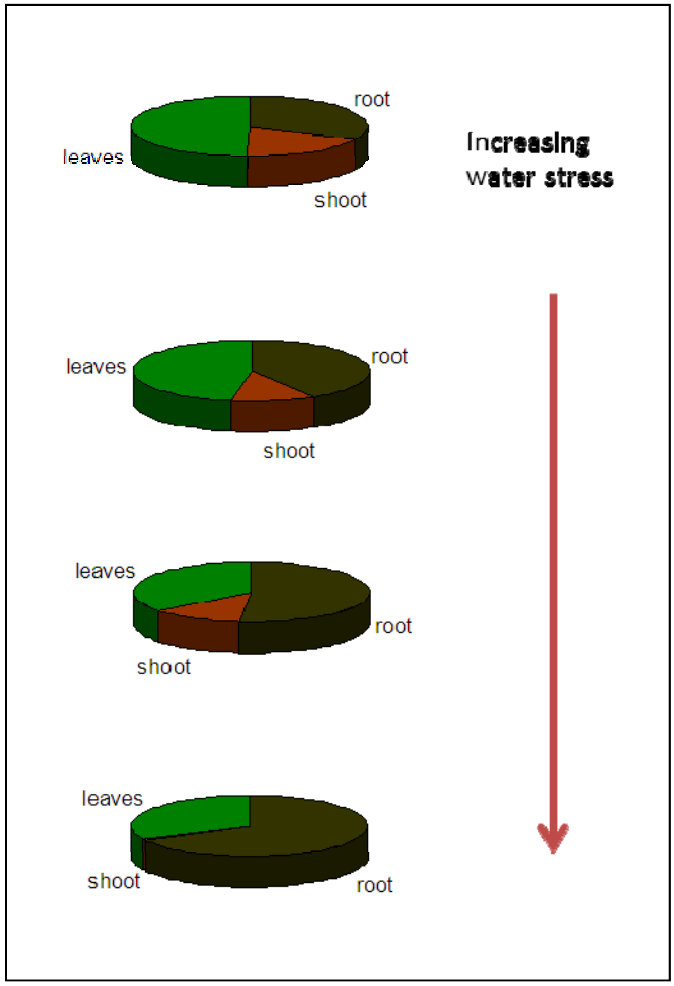

Figure 1. Partitioning of dry biomass accumulation among leaves, stems and roots of *Pinus halepensis* under conditions of increasing water stress.

The Yatir Forest Site: Decoupling of the tree hydraulic components in Yatir Forest

Tamir Klein

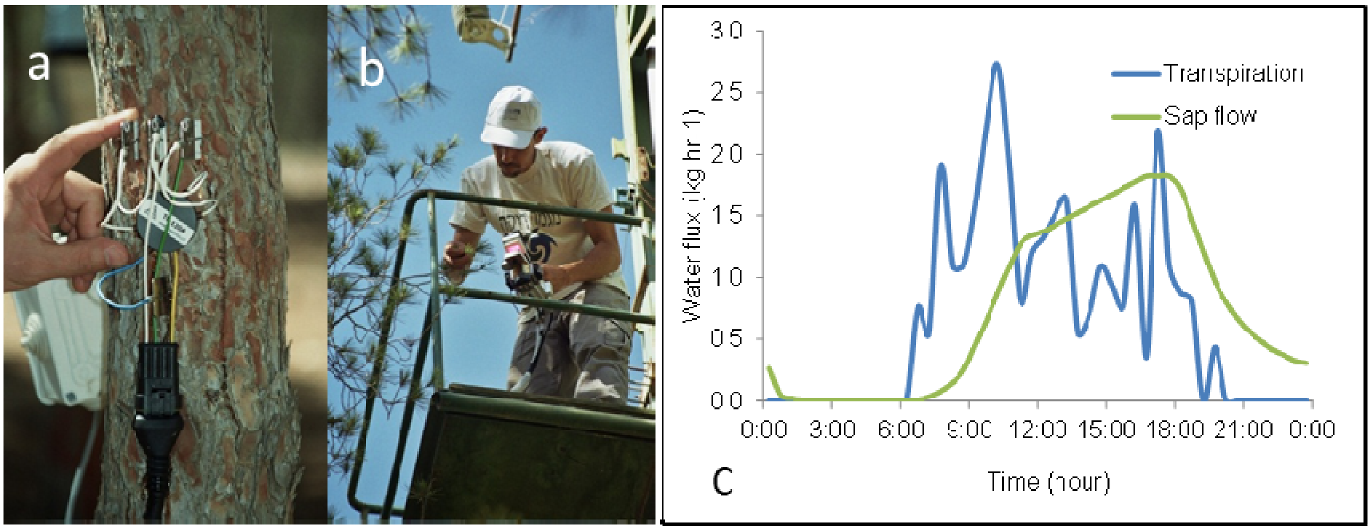

Figure 2. Tree water flux measurements at Yatir, using an installed heat balance sap flow sensor (a) and a LI-6400 leaf gas exchange chamber (b), producing the distinct diurnal curves (c, June 2011).

The results reveal additional insights which help explain the success and relatively high productivity of this Aleppo pine forest at the dry timberline. The trees show a remarkable ability to invest in water exploration, and to decouple and manipulate the tree's hydraulic components (stem and leaves). We believe the results provide an optimistic perspective for pine forests in the Mediterranean region in the face of consistent predictions of warming and drying.

Acknowledgements

Technical assistance was kindly provided by Hagay Sagi and Avram Pelner of WIS and by Avraham Grava of ARO Volcani. Jiri Kucera of EMS Brno and Katarina Strelcova of the Technical University of Zvolen are greatly acknowledged for their guidance.

References

Gruenzweig JM, Gelfand I, Yakir D. 2007. Biogeochemical factors contributing to enhanced carbon storage following afforestation of a semi-arid shrubland. Biogeosciences 4:891–904.

Sprintsin M, Cohen S, Maseyk K, Rotenberg E, Grünsweig J, Karnieli A, Berliner P, and Yakir D. (2011) Long term and seasonal courses of leaf area index in a semi-arid forest plantation. Agri. Forest Meteor. 151, 565-574.

Klein T, Yakir D and Cohen S. (2011) Hydraulic adjustments underlying drought resistance of *Pinus halepensis*. Tree Physiology 31, 637-648.

Contact:

Tamir Klein
tamir.klein@unibas.ch

The Yatir Forest Site: Ecohydrology of Yatir – a forest growing in the desert

Naama Raz-Yaseef

Puzzlement motivated research: The survival and success of the Yatir forest is a puzzle. Average precipitation is 283±88 mm yr^{-1}, but drought years occur regularly, and precipitation as low as 138 mm yr^{-1} has been recorded since the planting of the forest. The rainy season is short, leading to seasonal droughts, with prolonged near-hygroscop-ic surface soil water content levels lasting through the long summer (~5% $m^3\ m^{-3}$ from June to November). Groundwater is deep (~300 m), and because soil water potentials are low, no deep drainage or uptake from depths below 2-3 m can be expected. Yet, a relatively high productivity forest has been growing here over the past 45 years. Understanding the water dynamics within the forest is key to unraveling this puzzle, and helps predict the future of forests across the Mediterranean regions undergoing drying trends. A decade of field measurements and analysis has revealed a range of interesting and unexpected processes.

Developments motivated by technological needs: First, we noted that the afforestation essentially totally eliminated runoff. While impressive flash floods were observed at times in the surrounding shrubland, the runoff monitoring station at the exit of the Yatir forest watershed stays dry even during the strongest storms. Indeed, measurements of evapotranspiration (ET) show that, on average, ET accounts for 94% of annual precipitation (Fig. 1; Raz-Yaseef et al., 2010a). Next, our attention was drawn to soil evaporation (Es). In an open-canopy forest, exposed to high radiation load, we expected soil evaporation to be an important component requiring examination. But reliable methods to directly measure soil evaporation at high spatial and temporal resolution were absent. This motivated us to develop our own

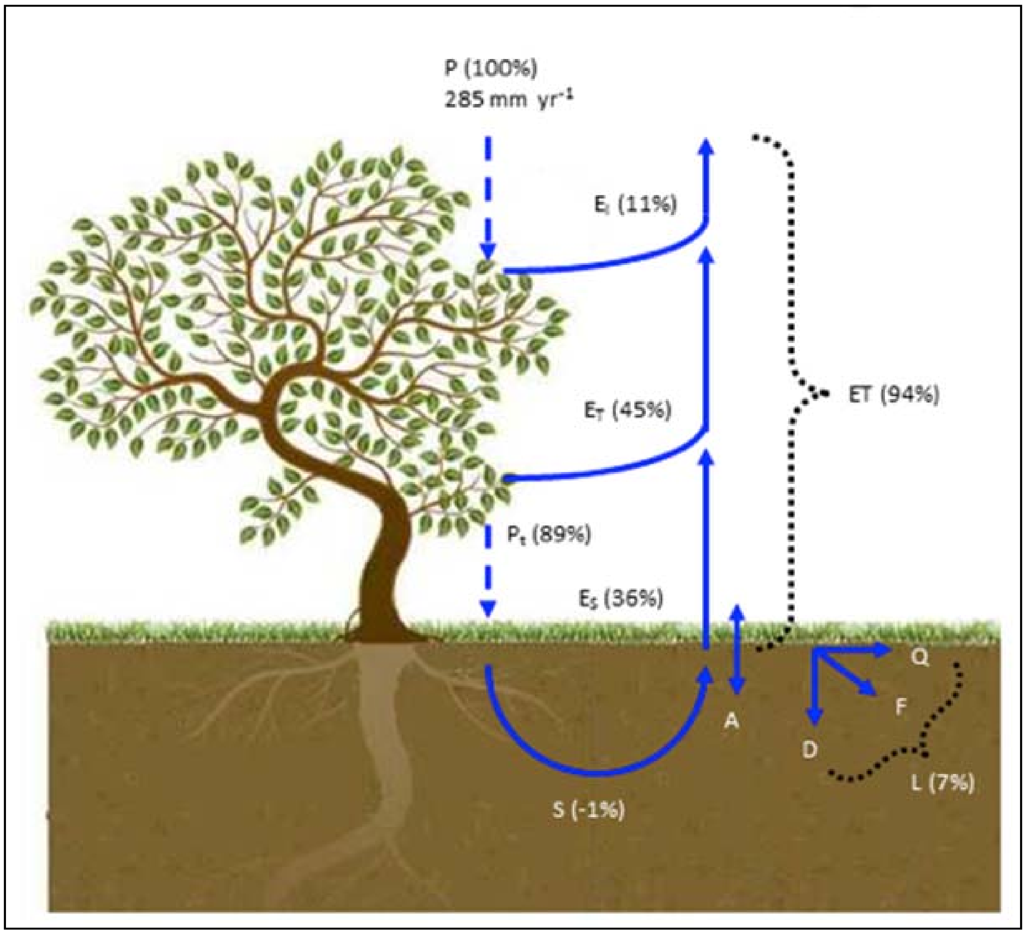

Figure 1. Components of the hydrological cycle in the Yatir forest: Precipitation (P), interception by the canopy (E_I), through-fall (P_t), tree transpiration (E_T), soil evaporation (E_S), soil water adsorption (A), soil water storage (S). Losses (L) out of the system included runoff (Q), subsurface flow (F), deep drainage (D).

The Yatir Forest Site: Ecohydrology of Yatir – a forest growing in the desert

Naama Raz-Yaseef

method by modifying our standard soil respiration chambers and the measurement protocol. The effort was worthwhile. Results indicated that soil evaporation accounted for 39% of the total evaporative losses, with large spatial variability. Evaporation fluxes in open gaps were twice as high as those in shaded areas. Simulating tree shading in our forest allowed us, in turn, to predict how the partitioning of ET would vary with changes in the forest tree density. This simple predictive tool indicated that current tree density (300 trees ha^{-1}, canopy cover of 54%), previously arrived at empirically by foresters, is in fact near optimal. Higher tree density at this site would increase ET demands beyond the average precipitation input and could result in tree mortality. Reducing

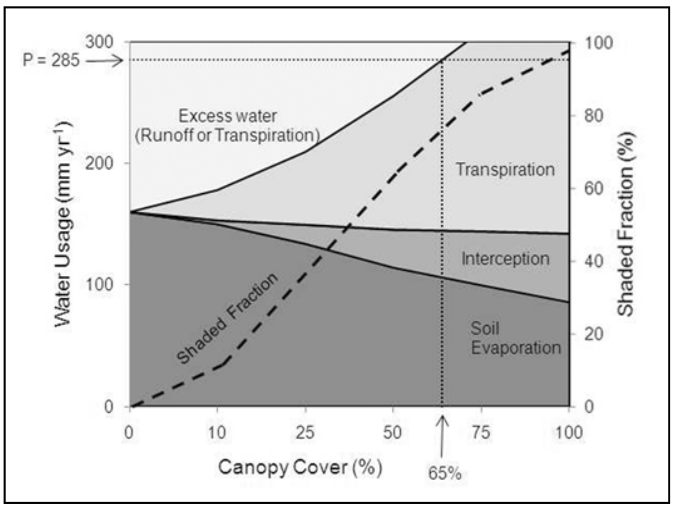

Figure 2. Changes in the proportional contribution to the ecosystem hydrological balance as a function of canopy cover (forest tree density). Shading increases and soil evaporation decreases with increasing canopy cover, but increased interception and tree transpiration reduces residual (excess) water in the system. Excess water is the component available for runoff and recharge to depth or for additional vegetation. Under current precipitation (285 mm yr^{-1}, dotted horizontal line) and tree density (65% cover, 300 tree ha^{-1}) the system is nearly balanced.

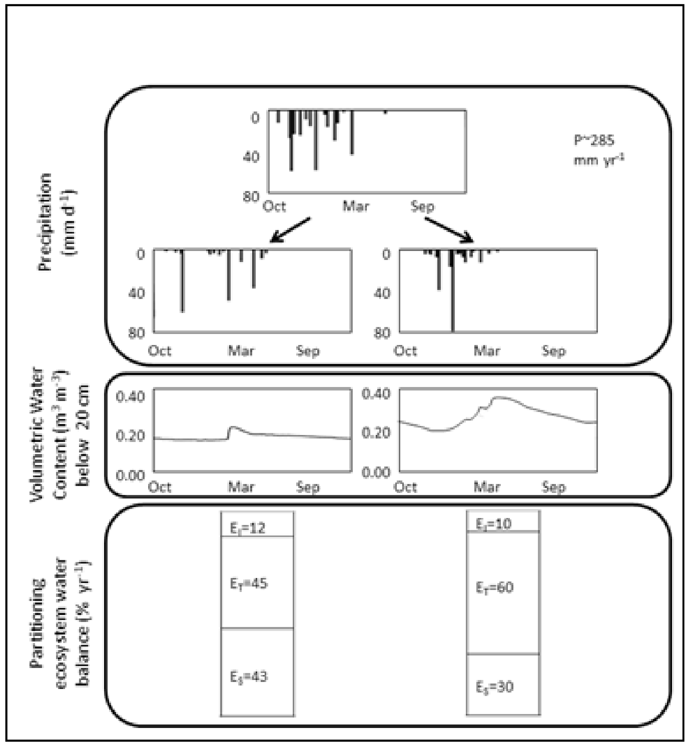

Figure 3. Inter-annual variations: similar annual precipitation but low intensities (2005/6) or high (based 2007/8) years produced significant differences in tree transpiration (Et). Only storms of >30 mm infiltrate below 20 cm soil depth and into the main root zone. Increasing storm intensity can compensate for reduced total precipitation.

tree density would result in greater losses to soil evaporation (Fig. 2; Raz-Yaseef et al., 2010b).

Need to scratch the surface: The proportional contribution of different flux component to total ET varied seasonally, due to their differential response to seasonal environmental drivers (Raz-Yaseef et al., 2012). Soil evaporation was correlated to soil moisture at the topsoil (0-10 cm). It peaked twice during the seasonal cycle: Once during the wetting period in the fall, and again during drying season in spring. These periods were characterized by superficial

The Yatir Forest Site: Ecohydrology of Yatir – a forest growing in the desert

Naama Raz-Yaseef

soil moisture and high radiation. Summer was too dry and winter was too cold to generate significant evaporation fluxes. Surprisingly, low evaporation fluxes were measured throughout the dry summer period. Perhaps even more surprising was the conclusion that ~50% of the daily flux was due to re-evaporation of moisture condensed onto the soil at night (measured as negative water fluxes from atmosphere to the soil). In contrast to soil evaporation, tree transpiration (Tt) was associated with soil moisture at a 10-20 cm depth layer (the depth of maximum root density), and peaked only in late spring (~1.5 mm d^{-1}), after the accumulation of moisture from the few larger storms that infiltrated below the topsoil layer. Moisture at this depth was maintained for much longer periods than at the surface, often with carry-over between hydrological years. Ultimately, the ratio Tt/ ET, the major link to forest productivity and survival, was more strongly associated with the fraction of precipitation from larger storm (>30 mm), than with total annual precipitation.

These results are significant because climate change scenarios for the Mediterranean often predict drying but also increasing storm intensity. Our findings indicate that the latter effect (intensity) can at least partially compensate for the former (drying) (Fig. 3).

References

Raz-Yaseef, N., Rotenberg, E., Yakir, D., 2010a. Effects of spatial variations in soil evaporation caused by tree shading on water flux partitioning in a semi-arid pine forest. Agricultural and Forest Meteorology 150 (3): 454-462.

Raz-Yaseef, N., Yakir, D., Rotenberg, E., Schiller, G., Cohen, S., 2010b. Ecohydrology of a semi-arid forest: partitioning among water balance components and its implications for predicted precipitation changes. Ecohydrology 3: 143-154.

Raz Yaseef, N., Yakir, D., Schiller, G., Cohen, S., 2012. Dynamics of evapotranspiration partitioning in a semi-arid forest as affected by temporal rainfall patterns. Agricultural and Forest Meteorology 157, 77-85.

Contact:

Naama Raz-Yaseef
Climate and Carbon Sciences Program, Earth Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, CA.
NRYaseef@lbl.gov

The Yatir Forest Site: Backing up the flux measurements in the Yatir Forest

José M. Grünzweig

Ecosystems in dry regions are generally low in productivity and carbon storage, but the Yatir forest seems to defy such assumptions. This was checked quantitatively by eddy covariance measurements over 10 years. But, eddy flux measurements have their own difficulties and uncertainties and must be backed up and constrained by additional measurements, and ultimately by "carbon accounting".

Figure 1. Subsampling stem sections and branches for moisture content during a field campaign aimed at creating site-specific allometric equations for *Pinus halepensis* (picture courtesy: Avi Bar Masada).

Carbon stocks meet carbon fluxes: Much effort was invested in Yatir to add this perspective, by aerial photography (Bar Massada et al., 2006), and by estimating carbon stocks both below and above ground. As it turned out, planting a *Pinus halepensis* forest in an overgrazed, semi-arid shrubland increased the soil organic carbon stock by 75% over a period of 35 years (Grünzweig et al., 2007). Adding the tree and understory carbon inventory (using site-specific allometric equations; See Figure 1) to soil organic carbon, obtained by coring, produced estimates of the ecosystem carbon stock. In total, those in the forest were 2.5 fold the carbon stock in the shrubland. Aerial photography suggests a near linear increase in aboveground tree carbon stock over time (Bar Massada et al., 2006), which allowed us to estimate meaningful average annual increases of 180 g C m^{-2} yr^{-1} over 35 years. These estimates are consistent with the recent NEE measurements of just over 200 g C m^{-2} yr^{-1} with large inter-annual variations (Grünzweig et al., 2003; Rotenberg & Yakir, 2010).

No nutrients to the rescue: Such a large increase in carbon stocks would suggest the need for a similar increase in nutrient stocks, mainly nitrogen. However, nitrogen stocks did not change significantly due to afforestation. Consequently, the ecosystem C/N ratio increased markedly from 7.6 in the native shrubland to 16.6 in the forest, suggesting an increase in nitrogen use efficiency by the ecosystem (Grünzweig et al., 2007).

No water and no decomposition: Biogeochemical mechanisms enabling the rise in carbon storage include low decomposition rates due to recalcitrant pine litter and dry conditions (the volumetric water content of the upper 40 cm of the soil profile is below 20% over 75% of the year and below 12% over 65% of the year). ^{13}C isotopic analyses indicated a small isotopic signal introduced by relatively ^{13}C-rich pine biomass (-23 to -24‰) as compared to ^{13}C-poor

The Yatir Forest Site: Backing up the flux measurements in the Yatir Forest

José M. Grünzweig

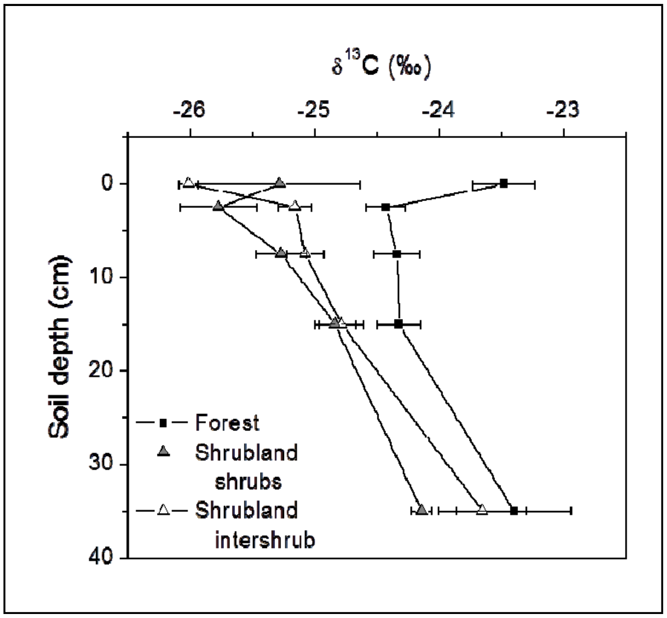

Figure 2. Small isotopic signal of pine biomass recorded throughout the litter layer (0 cm depth) and soil profile (0-50 cm depth). This relatively ^{13}C-rich signal allowed us to calculate the addition of new organic carbon and of decay of old shrubland-derived carbon in the soil (from Grünzweig et al., 2007).

shrubland vegetation (-26 to -29‰), leading to a distinct pine signal especially in the litter and the upper soil layers (Figure 2). This helped us to show that soil organic matter (SOM) derived from pine inputs decays at low rates, likely as a consequence of protection within organo-mineral complexes. Low decay rates of litter and SOM were also confirmed by relatively low soil-respiration rates as determined by measurements of CO_2 efflux from the soil surface (Grünzweig et al., 2009). And, soil respiration rates were low despite high root production (Grünzweig et al., 2007), and relatively high belowground NPP (root production, exudation, micorrhiza etc.; Gelfand et al., 2012) and belowground carbon allocation (~40% of GPP; Grünzweig et al., 2009). Therefore, in the light of the total carbon budget, we concluded that the high carbon sequestration of the Yatir semi-arid pine forest reflects its relatively high productivity, moderate nitrogen requirements and low heterotrophic carbon loss rates.

References

Bar Massada A, Carmel Y., Even Tzur G., Grünzweig JM and Yakir D (2006) Assessment of temporal changes in aboveground forest tree biomass using aerial photographs and allometric equations. Canadian Journal of Forest Research 10, 2585-2594.

Gelfand I, Grünzweig JM and Yakir D (2012) Slowing of nitrogen cycling and increasing nitrogen use efficiency following afforestation of semi-arid shrubland. Oecologia, 168, 563-575. doi: 10.1007/s00442-011-2111-0

Grünzweig JM, Lin T, Rotenberg E, Schwartz A and Yakir D (2003) Carbon sequestration in arid-land forest. Global Change Biology 9,791-799.

Grünzweig JM, Gelfand I, Fried Y and Yakir D (2007) Biogeochemical factors contributing to enhanced carbon storage following afforestation of a semi-arid shrubland. Biogeosciences 4,891-904. doi:10.5194/bg-4-891-2007

Grünzweig JM, Maseyk K, Hemming D, Lin T, Rotenberg E, Faloon and Yakir D (2009) Water limitation to soil CO_2 efflux in a pine forest at the semi-arid 'timberline'. Journal of Geophysical Research 114, G03008, doi: 10.1029/2008JG000874.

Rotenberg E and Yakir D (2010) Contribution of semi-arid forests to the climate system. Science 327, 451-454 doi: 10.1126/science.1179998.

Contact:

José M. Grünzweig
jose.gruenzweig@mail.huji.ac.il

The Yatir Forest Site: The nitrogen perspective

Ilya Gelfand

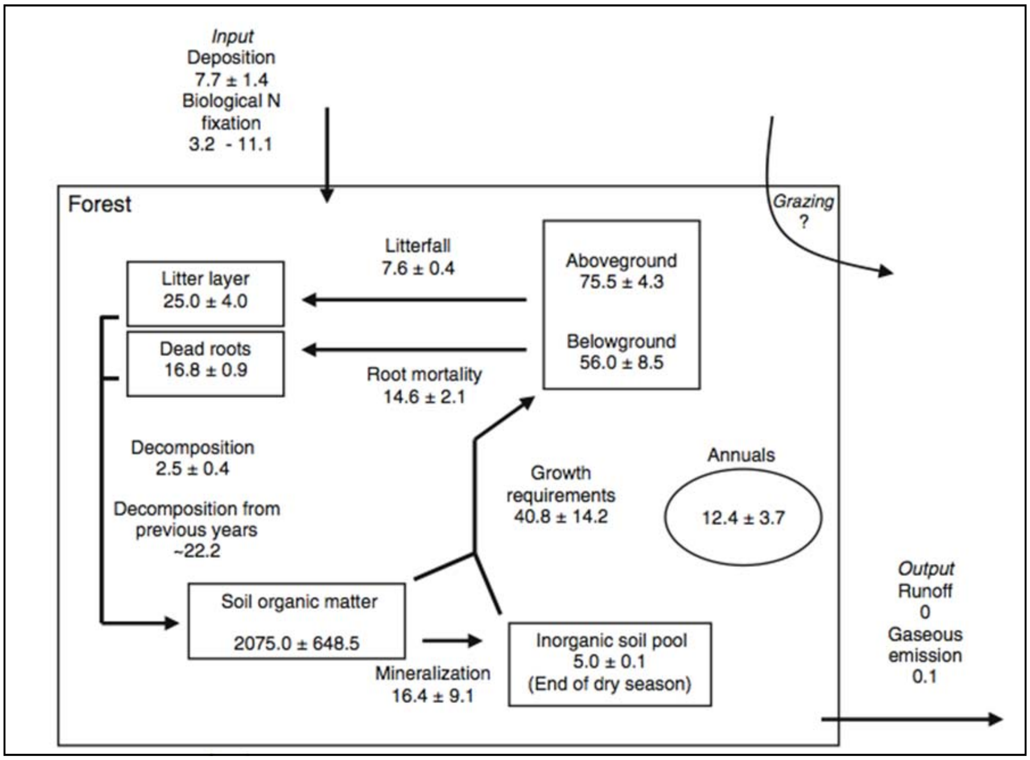

Figure 1. The Yatir forest nitrogen budget with pools in Kg N ha^{-1} and fluxes in Kg N ha^{-1} y^{-1}.

Obvious expectations, not so obvious observations: Observing large increases in C storage, (see 'Backing up the flux measurements in the Yatir Forest, this newsletter), in the forest, compared to the background shrubland, got us thinking that there must also be significant changes in the ecosystem nitrogen budget. We therefore embarked on an attempt to construct the complete N budgets of both the forest and shrubland ecosystems (Fig. 1). Combining field (Fig. 2) and laboratory measurements and incubations, we estimated the size of the major N pools, the flux rates between these pools, and ultimately, the nitrogen use efficiencies of the systems (Gelfand et al., 2012). In contrast to our initial hypothesis, we found little differences in the overall, ecosystem N budget between the Yatir forest and the surrounding shrubland. Yet, we also observed a range of internal adjustments in the forest N cycle (specific fluxes, pool, retention time) that clearly supported the increase in C sequestration potential, even without a net change in total input/output.

Delay with an advantage: The larger canopy surface area in the forest vs. the shrubland enhanced, slightly, the capture of ammonium, seen first in dry deposition, and later when rain arrives in wet deposition. Ammonium accumulated in the soil was further enhanced because of the long seasonal drought, which slows microbial activity, and thus nitrification. When the first rains of the wet season arrive, the microbial communities recover. But, apparently, the microbes that oxidize ammonium to nitrite (NO_2^-) recover faster than the microbial community that oxidizes nitrite to nitrate, an uncharacteristic (i.e. rare) accumulation of nitrite is observed. The slower microbes soon catch up and nitrite gives way to the more typical nitrate (NO_3^-) peak (Gelfand et al., 2008). Interestingly, the delayed appearance of nitrate, the main plant nutrient, improved the synchronization between the time of peak availability of this major nutrient and the time of maximum plant photosynthetic activity in the developing active season.

Quality vs. quantity: With a large increase in carbon accumulation but no change in the nitrogen budget, the forest must have changed its nitrogen use efficiency (NUE), as well as its C/N ratio, compared to the shrubland. Indeed, above ground NUE almost tripled (235 vs. 83 kg dry mass kg^{-1} N), and the forest C/N ratio doubled (16 for the forest vs. 8 for the shrubland). Furthermore, the entire ecosystem nitrogen cycling rate markedly slowed down in the forest compared to the shrubland: net

The Yatir Forest Site: The nitrogen perspective

Ilya Gelfand

N mineralization rates in the soil decreased by approximately 50%, decomposition rates decreased by approximately 20%, and a decrease of approximately 64% in NOx loss in volatilazation was estimated (Glefand et al., 2009). While our investigation was by no means exhaustive, the first insights into the N cycle of a pine forest at the dry timberline provide another piece of the puzzle that help explain the observed 2.5-fold increase in the C stock of this ecosystem without the need to invoke any significant changes in the N stocks.

Figure 2. Ilya Gelfand and assistant coring soil in Yatir for nitrogen analyses and for seasonal incubations

References

Gelfand I and Yakir D (2008) Influence of nitrite accumulation in association with seasonal patterns and mineralization of soil nitrogen in a semi-arid pine forest. ***Soil Biology Biochemi*, 40, 415-424**.

Gelfand, I, Feig, G, Meixner FX, Yakir D (2008) Effects of semi-arid shrubland afforestation on biogenic NO emission from soil. ***Soil Biology Biochemi***, 41, 1561-1570.

Gelfand I, Grunzweig JM and Yakir D (2012) Slowing of nitrogen cycling and increasing nitrogen use efficiency following afforestation of semi-arid shrubland. Oecologia, 168, 563-575. DOI 10.1007/s00442-011-2111-0

Contact

Ilya Gelfand
W.K. Kellogg Biological Station,
Michigan State University
3700 E Gull Lake Dr
Hickory Corners, Mi 49060
igelfand@kbs.msu.edu

A Tribute to Shashi Verma

Dennis Baldocchi

This past September, Prof. Shashi Verma retired from the University of Nebraska, Lincoln after a career that spanned the years 1974 to 2012. We want to take this opportunity to profile, Prof. Verma, in the Fluxletter, and reminisce on his many contributions to our field.

Shashi Verma is one of the pioneers of making eddy covariance measurements of CO_2 and water vapor fluxes between vegetation and the atmosphere. He was a mentor to many of us active in the FLUXNET community (e.g. Joon Kim, George Burba, Dean Anderson, and this author). And his developments and findings were fundamental in founding and executing long-term flux measurements across regional and global networks.

I first met Prof. Verma early one morning (by early I mean 5 am), August, 1977. I had just arrived in Lincoln, Nebraska to start graduate work under the tutelage of Prof. Norm Rosenberg, whom we affectionately called 'Doc'. I was told to arrive at the lab early to join the crew on the daily trip to Mead for field research, and to help move irrigation pipe. Having just fled our California walnut farm, where I had been moving irrigation pipe daily for over a decade, I was hoping for better and greater tasks. That morning, as I peered into the truck I saw this young guy—he was a few years over 30, the age of many postdocs—an assistant professor named Shashi Verma. 'Who is this guy?', I thought, as I had expected Doc. I soon found out who this guy was. He proved to me to be a brilliant, insightful, patient, kind, hard-working and innovative scientist.

What I did not anticipate at the time was how he was on the verge of pushing the fields of agricultural meteorology and biometeorology so far forward. At this time, the field of agricultural meteorology was focusing on measuring crop temperature with infrared thermometers and relating these temperatures to crop stress and yield. Shashi was trained as a civil engineer (BS, Ranchi University, India; MS, University of Colorado; PhD, Colorado State University) and was on the verge of bringing his engineering training to agriculture. He knew it was the flux of heat and matter that controls the local environment and affects water use and primary productivity. So, Shashi was fixed on developing the new eddy covariance method to measure these fluxes directly. This desire led him to work with scientists at Lawrence Livermore National Lab (Gail Bingham) to develop and deploy a new open-path CO_2 sensor to measure crop photosynthesis. He was also at the vanguard by using computers to collect data on magnetic tape. This was a big deal at the time, as the ubiquitous Campbell data-loggers had not been developed, yet. (Rosenberg's data-logger was a DATEX; a huge analog device that punched holes in paper tape to record voltages of solar radiation, temperature and humidity. If the paper tape tore you could tape it together.

Over the course of the next five years Shashi and his students would produce some of the first eddy covariance measurements of carbon dioxide and water vapor flux over crops, like soybeans and sorghum. In the meantime, he was also a pioneer in conducting comparative flux measurements; a way of using micrometeorology flux measurement technology to ask and answer scientific questions. In the early 1980's he had a project working with geneticists to develop better crops to feed the world. One idea involved changing the morphology of soybeans -- to examine how creating soybeans with hairy and narrow leaves affected their mass and energy exchange. By measuring fluxes over two comparative fields simultaneously, Verma was able to deduce impacts

Tribute to Shashi Verma

Dennis Baldocchi

of these morphological changes relative to co-occurring weather.

After my cohort graduated, Shashi started down a new path of research on methane fluxes, with the new Campbell tunable diode laser spectrometer. With his student Joon Kim and colleague Dave Billesbach, Verma and company made some of the first season long, eddy covariance flux measurements of methane in harsh wetland environments in Minnesota, western Nebraska and Saskatchewan, Canada.

One of the great things about Shashi as a mentor is that you could go to his office and ask any question any time about anything science related. I don't recall ever being rebuked, or ever having left his office without the answer. Another great thing about his mentorship is that he gave his students the resources to do the work. Maybe it was a different time, but we never worried about funding or instrumentation to do the work or go to meetings to present the work. He also taught us how to be careful scientists and the importance of calibration—the mantra in my lab today is 'calibrate, calibrate, calibrate'. In those early days he'd calibrate the eddy covariance system every 3 hours. He'd zero the psychrometer system hourly, and he had us go through every line of computer code and repeat the calculations by hand to make sure the code was correct in computing fluxes! And when it came to writing up the work, he was there with constructive criticism. Not being the best writer, my manuscripts would come back all red, with suggestions for improvements, better ways to think about the sentences and the material we were presenting.

On leaving Nebraska, I had many opportunities to continue working with Shashi. In 1984, he came to Oak Ridge with his 'new fangled' CO2 sensor and we made the first measurements of CO2 exchange over a deciduous forest. That work was so new that we produced 5 peer reviewed papers with 3 weeks of measurements. Our next chance to collaborate was in 1993-94 in Canada during the BOREAS experiment. Later in our careers we had the pleasure of meeting at least once a year at scientific meetings, like Ameriflux or the AMS AgForest Met conference. Then, we had much fun sitting together, visiting, going to dinner and talking about life in general, family and science.

Shashi Verma is a modest individual, who has had a distinguished career. Among his honors, he is a fellow of the Agronomy Society of America, recipient of the American Meteorology Society Award for Outstanding Achievement in Biometeorology and Charles Bessey Professor of Natural Resources.

In closing, I'd like to remark on his scientific pedigree. He was a student of the late Jack Cermak, an engineer at Colorado State University, who was noted for wind tunnel studies of wind flow in urban settings. What I did not know about was who his scientific grandfather and great grandfather were. During the BOREAS project, where we worked together again in Canada, I was sitting in the Toronto airport waiting for a flight home. Wilf Brutsaert, the engineering professor at Cornell, known for his book on Evaporation, walked up to me and said: 'you are Shashi Verma's student....you are related to Ted von Karman, two degrees removed', and walked away; von Karman was the the fluid mechanics professor at Cal Tech, best known for the von Karman constant ($k = 0.40$). I asked Shashi about this encounter and he could not verify this genealogy. More recently, I was at a meeting in Lausanne, Switzerland and sat next to Prof. Brutsaert on the bus to a field trip, so I asked him about this genealogy. He said Bill Sears was a student of von Karman. Jack Cermak was a student of Sears at Cornell, followed by Verma.

So in closing, we thank you for your contributions to science and your fine mentoring and we wish you a happy and healthy retirement and much fun and time with your son and his family in Texas.

35 years of urban climate research at the 'Vancouver-Sunset' flux tower

Andreas Christen, Tim Oke , Sue Grimmond , Douw Steyn and Matthias Roth

The 'Sunset' neigborhood in Vancouver, BC, may be the most extensively studied area in urban climatology. Since 1977, about 50 papers have been published that focus on flux measurements, land-atmosphere exchange, and models developed using data gathered on and around the 'Vancouver-Sunset' micrometeorological tower. This newsletter contribution aims to provide a brief history of this unique flux tower, show how selected developments in urban climatology were linked to work at this site, and highlight some of the ongoing research on urban trace-gas flux measurements to validate fine-scale emission models.

Establishing an urban micrometeorological tower (1977) One of the biggest conceptual challenges in urban climatology is the spatial heterogeneity of cities. From single lots (roofs, walls, streets, lawns) to the land-cover patchiness in an urban neighborhood (parks, low-density, high-density areas) up to the differences in surface properties between cities and the surrounding area (urban heat island, country breezes etc.) - urban systems are dominated by heterogeneity on many scales, and advection is the norm rather than the exception. From the start it was clear that micrometeorological approaches and theories developed for flat and homogeneous sites would be unlikely to apply *a priori* to the study of urban land-atmosphere interactions. Moreover, it is challenging to separate urban effects from other effects (local winds, land-cover differences, topography, synoptic effects) unless proper experimental control (Lowry, 1977) has been established.

In the 1960s and 1970s the mostly unpublished trials to measure turbulent fluxes above urban surfaces were flawed because micrometeorological methods were applied with instruments situated generally too close (low) to the elements that constitute the urban surface e.g. on rooftops or on small masts *within* the layer that is now recognized as the roughness sublayer (Raupach and Thom, 1981). In the 1970s, there was growing evidence from pioneering work such as the turbulence studies using eddy covariance (EC) instruments mounted on masts during METROMEX in St. Louis, USA (Clarke *et al.*, 1978) and in both Vancouver (Burnaby) and Uppsala by Oke (1978) that micrometeorological methods might work as long as the measurement height was well above the height of the buildings. In other words, in the inertial sublayer above extensive urban surfaces where individual flow-distorting effects of buildings are blended.

Can fluxes be measured successfully using traditional micrometeorological approaches, if we are high enough above the sur-

Figure 1. Then graduate student Douw Steyn (left) and research assistant Brian Guy (right) celebrating having finally completed installation of the complete set of mast mounted instrumentation in July 1978. The set-up included a uvw propellor anemometer (top), a wind profile with cup-anemometers, a yaw-sphere and a Bowen-Ratio system (bottom right), all approaches adopted from work in agricultural and forest climatology.

35 years of urban climate research at the 'Vancouver-Sunset' flux tower

Andreas Christen, Tim Oke, Sue Grimmond, Douw Steyn and Matthias Roth

face? How high is high enough? What are site requirements that would allow this? What would be an appropriate site in the complex setting of a city like Vancouver? Those questions were part of a graduate research seminar led by then Associate Professor Tim Oke at the University of British Columbia, in the mid-1970s. As an exercise, students were involved in the identification of a 'homogeneous' site in Vancouver at which it would be possible to make successful micrometeorological measurements. The criteria developed were: (a) no major changes in building and tree height and density around the site, (b) a relatively flat area, and (c) no significant land-cover boundaries (i.e. a sufficient fetch). One of the sites identified by his students, using maps and air photos was the 'Sunset' residential neighborhood. Follow-up work suggested it might be possible to erect a tower in this area, inside a power substation of BC Hydro, where security was good. Subsequently, after gaining the approval of the city planning authorities and the local residents and with funding from the Natural Science and Engineering Research Council of Canada (NSERC) the 'Vancouver Sunset' tower was established in 1977 (123.0784ºW, 49.2261 ºN). It was one of the first, and now the longest-running micrometeorological tower in Canada in an urban setting. With a height of 30 m this slim lattice structure allows relatively undisturbed measurements to be made at 4 to 5 times the gable height of the surrounding buildings (6-7m).

But the perceived simplicity, was not as straightforward from a practical perspective. It required about ten years to establish confidence in flux measurements at Vancouver – Sunset. During that period a number of the key approaches used today to conduct urban flux measurements were established by research completed at the tower.

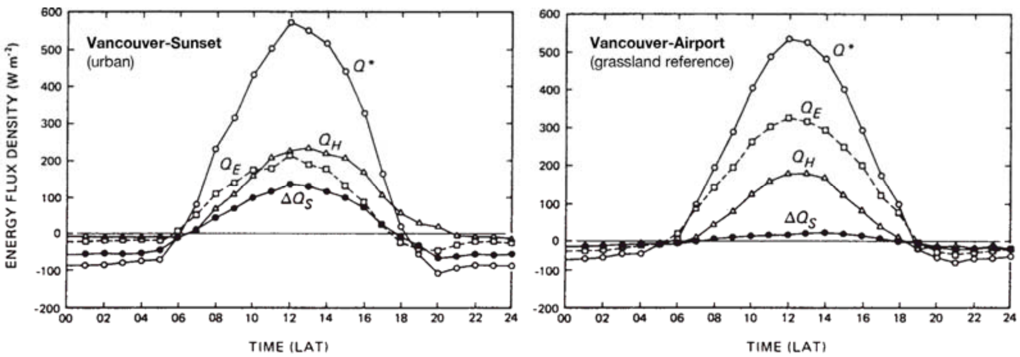

Figure 2. Simultaneously measured averages of energy balance terms measured / estimated at the urban flux tower 'Vancouver Sunset' compared to 'Vancouver-Airport' which served as a rural reference. Shown is a 30-day ensemble average (from Oke 1987 based on Cleugh and Oke, 1986; reproduced with permission).

Pioneering research on the urban energy and water balances (1977 - 1987) In the late 1970s, there was essentially no experimental evidence concerning the magnitude of, and controls on, the energy and water balances in cities. Urban weather and hydrology models assumed that cities are largely impervious and extremely dry. During the first decade, retrieving energy and water balances and the diurnal and seasonal changes in their component fluxes was at the center of the research program at Vancouver-Sunset.

How do we measure integrated turbulent fluxes of sensible and latent heat from an urban surface? What are the proper methods to do that? The first experiments applied instrument systems used over agricultural and forest stands, including the Bowen ratio energy balance (BREB) approach (Kalanda *et al.*, 1980) and aerodynamic methods using gradients of air temperature, humidity and wind and the net all-wave radiation (Figure 1). Oke and McCaughey (1983) compared the summertime energy balance fluxes measured in 1980 using the BREB approach at Vancouver-Sunset, to a simultaneously operated system over a grassland site outside the built-up area of the city. The surprising results during the fairly dry summer season showed that evapotranspiration was about

35 years of urban climate research at the 'Vancouver-Sunset' flux tower

Andreas Christen, Tim Oke, Sue Grimmond, Douw Steyn and Matthias Roth

40% higher over the city (where lawns were irrigated) than the rural values, or at least about equal during cloudy days. Unfortunately, despite using high-quality instruments, calibrations, tests and the installation of multiple reversible Bowen ratio profile systems, the gradients recorded were often extremely small, and at or below the resolution of the instruments.

The first studies to apply EC included measurements with a yaw-sphere thermometer system. The system measured turbulent sensible heat fluxes from wind and temperature fluctuations with a pressure sphere anemometer and a fine-wire resistance thermometer, respectively. It was built at UBC in the laboratory of Dr. Andy Black in Soil Science, and tested over an extensive grass site (Yap *et al.,* 1974; Yap and Oke, 1974). It was first used at 'Vancouver-Sunset' in July-August, 1978 in the study of Steyn (1980). Steyn's work at the tower also included the first analysis of surface roughness using morphometric analysis and turbulence spectra for the wind components. The yaw-sphere-thermometer system was superseded by a commercial Campbell Scientific CA27 1D ultrasonic-anemometer and thermometer system in summer 1983 (Cleugh and Oke, 1986). Net all-wave radiation was measured directly, while storage was estimated and the latent heat flux was solved as a residual. Figure 2 shows the diurnal course of the energy balance terms in summer 1983 compared to simultaneously measured values at a rural grassland site within 7 km distance.

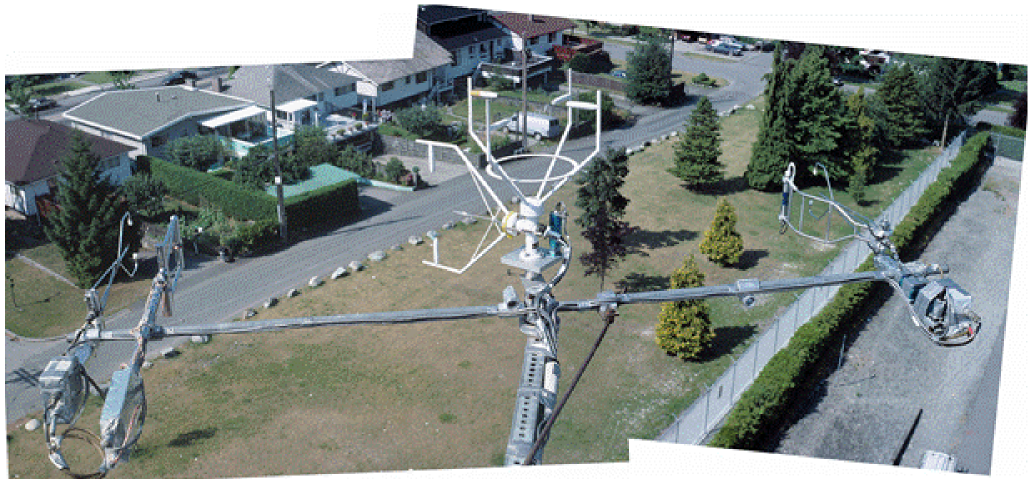

Figure 3. Instrumentation at 27.5m on the 'Vancouver-Sunset' tower in 1989 used by then graduate student Matthias Roth to study turbulence spectra, scalar and momentum fluxes and dissimilarity of turbulent exchange mechanisms. Left is a EC system composed of a 1-D sonic anemometer (CSI CA27T) and Krypton hydrometer (CSI KH20), in the center is a 3-D sonic anemometer (Kaijo Denki DAT-310 TR-61C) was used to retrieve all 3-D turbulence statistics, and at the right is another 1-D sonic anemometer (CSI CA27T) combined with a Lyman-alpha hygrometer (ERC BLR) (Photo: M. Roth)

Most early energy and water balance measurements were conducted in the dry summer season. The first work in other seasons was carried out in winter to spring 1987, and showed that latent heat flux was the most important turbulent flux of the energy balance in the wet wintertime (Grimmond, 1988, 1992). Winter and summer data from the tower were also used to develop an urban evapotranspiration-interception model based on the urban energy balance that considered storage heat flux, aerodynamic and surface resistances and drainage (Grimmond, 1988; Grimmond and Oke, 1991).

Unlike the case of agricultural or forested surfaces, where the use of heat flux plates and temperature profiles was established, the complexity of the construction materials and the structure of an urban surface inhibited direct measurement of the storage heat flux density. Alternatively, different parameterizations were developed. Initially Oke *et al.* (1981) developed a model with a linear relationship between net radiation and storage. It was an area-weighted average of the equivalent relations of several urban surfaces (grass, concrete, tar-

35 years of urban climate research at the 'Vancouver-Sunset' flux tower

Andreas Christen, Tim Oke, Sue Grimmond, Douw Steyn and Matthias Roth

mac, etc.). To account for the phase lag that exists in the diurnal course of each surface relation, Oke and Cleugh (1987) developed, and Grimmond *et al.* (1991) applied, the Objective Hysteresis Model (OHM) to the urban area. This simple approach has proven to be very practical to apply in connection with field observations, as it agrees well with other methods that often require much greater input (Roberts *et al.*, 2006), and has been incorporated into simple urban energy balance models.

The last term of the urban energy balance, the anthropogenic heat flux, (*i.e.* the heat released by human activities, including combustion, electricity, human metabolism) is inaccessible to direct measurement. But a detailed inventory of sources around the tower site was compiled by Grimmond (1988). Her results suggested values of about 8 W m^{-2} on the annual average.

By the end of the 1980s the methodology to measure turbulent fluxes was established, which greatly advanced capabilities to quantify, study and model the energy and water balance of the urban surface. The studies and subsequent models developed at 'Vancouver Sunset' demonstrated that urban areas are not comparable to the dry 'urban desert' postulated in early writing and models and that urban vegetation and irrigation can play a crucial role in energy partitioning (Oke, 1989).

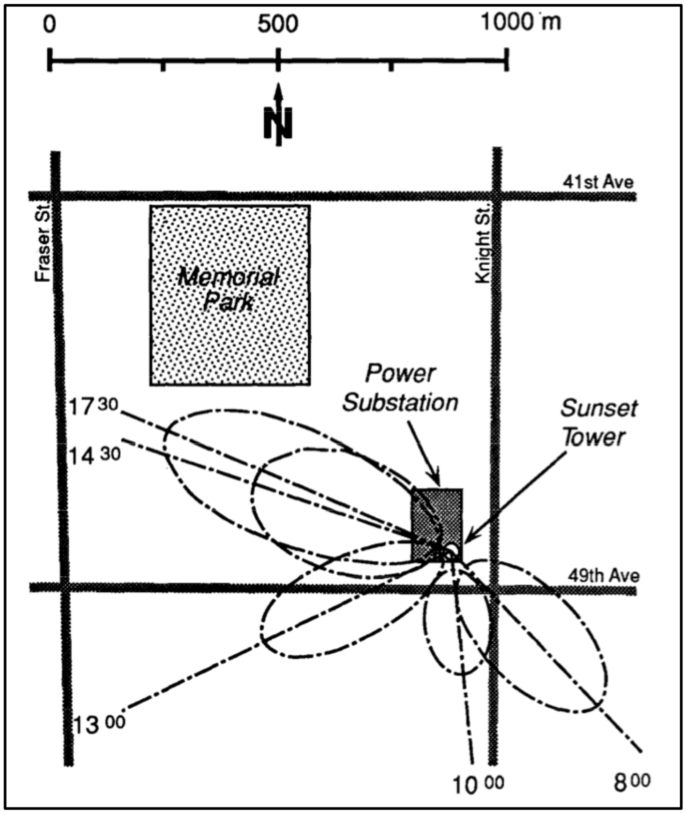

Figure 4. 0.5 level isopleths of the turbulent source areas at 'Vancouver-Sunset' for August 19, 1986 calculated by SAM (from Schmid, 1990).

Turbulence and source areas (1985 - 1995) The successful measurement of turbulent fluxes inspired discussions on whether the turbulent exchange of heat and mass above the urban surface can be described using standard surface layer scaling, specifically the Monin-Obukhov similarity theory (MOST). Previous work on turbulence and dispersion over extremely rough urban surfaces had focused on the transfer of momentum, but Roth *et al.* (1989) presented the first detailed analysis of the turbulence transfer (integral statistics and cospectra) that included fluctuations of temperature and water vapor. Roth and Oke (1993) and Roth (1993) gathered extensive measurements of velocity and scalar fluctuations, using a 10Hz - 3D sonic anemometer linked with thermocouples and fast hygrometers on the tower (Figure 3). They demonstrated that many aspects of the turbulent transfer can be successfully analyzed within the Monin-Obukhov scaling framework in the urban inertial sublayer. They also identified a number of fundamental differences from theory including increased efficiency of the turbulent transfer of momentum and sensible heat. Another interesting finding was that the dissipation of turbulent kinetic energy was smaller than predicted. A possible explanation was that transport processes of TKE were more relevant so close to the roughness elements. Finally, the source patterns for water vapor were patchy compared to the more uniform distribution of sensible heat sources and this caused the latent heat fluxes to disagree with MOST predictions (Roth, 1993).

The biggest remaining challenge in the interpreta-

35 years of urban climate research at the 'Vancouver-Sunset' flux tower

Andreas Christen, Tim Oke, Sue Grimmond, Douw Steyn and Matthias Roth

tion of the flux measurements at 'Vancouver-Sunset' was the question of whether the results reflect a representative sample of the urban surface. To study the spatial heterogeneity of the energy balance terms, a temporary mobile tower roved to 5 different locations around the fixed 'Vancouver Sunset' tower in order sample the radiative and turbulent fluxes at different locations (Schmid *et al.,* 1990). Some sites were near parks, while others were at mid-block. At 4-5 times the height of the buildings, net all-wave radiation proved to be relatively uniform and compared well with the tower signal (1-5%) whereas the sensible heat fluxes within the neighborhood varied by 25 - 40%.

Pioneering work on turbulent source areas was conducted at the Vancouver Sunset site (Schmid *et al.,*1988, Schmid and Oke,1990) based on the ideas of Pasquill (1972) and Gash (1986). Interest centered on the extent to which local measurements of a turbulent flux are representative of the surrounding area. The very patchy suburban surface around the site made it necessary to find if observations provided a sample that could be considered spatially representative. The source area model SAM (and later FLUX-SAM) was developed using a probability density function plume diffusion relation. It made it possible to map the extent of the ellipsoid source area (sometimes called a 'footprint') of a flux measurement made at a given height (see Figure 4). The technique has become a standard protocol to assess the representativeness of turbulent flux observations over all types of surface. It further allowed a source attribution of the signal. For example, Grimmond (1988) used source area estimates and overlaid them with a GIS of the nature of the tower surroundings to match the results given by a storage and an anthropogenic heat model.

Figure 5. Surface characterization of the Sunset neighborhood in a 2 x 2 km area derived from high-resolution LiDAR data. LiDAR can be used to characterize the built form (e.g volume, height and type of houses) as well as the characteristics of the urban vegetation (e.g. tree heights, LAI). Overlaid is the long-term cumulative turbulent source area climatology and the two major arterial roads E 49th Ave (21'000 veh. day^{-1}) and Knight St. (48'000 veh. day^{-1}). The long-term 80% source area covers an area of about 1 km^2 and 1400 houses (LiDAR data from Goodwin *et al.*, 2009 and source area climatology from Christen *et al.*, 2011).

Monitoring long-term energy and water balances (since 2000)

Recent advances in instrumentation and data processing enabled the collection of long-term datasets to study the seasonal variability of the energy and water balance partitioning at 'Vancouver Sunset'. From 2001-2002, and again from 2008-2011 long-term flux measurements of the energy and water balance terms were conducted. A specific technical goal of the latter period was to support modeling efforts to incorporate the effect of vegetation into the Canadian Urban Flow and Dispersion Model (CUDM). The tower also contributed to an observational dataset to evaluate long-term hydrology models (e.g. Järvi *et al.*, 2011). Additionally to the flux tower a detailed hydrological / bioclimatological set of measurements was collected including metering of water used for lawn irrigation, 8 homes and gardens wired up with soil sensors and leaf-level conductance measurements on urban trees. To provide

35 years of urban climate research at the 'Vancouver-Sunset' flux tower

Andreas Christen, Tim Oke, Sue Grimmond, Douw Steyn and Matthias Roth

comparisons with the urban site, a rural reference site was established. Table 1 shows a comparison of the energy balance terms over the full annual cycle between the urban and rural site. Notable are the seasonal differences in the partitioning of turbulent fluxes. An interesting feature is the 'over closure' of the annual energy balance at the urban site - the residual term at indicates a missing source of about 15 W m^{-2} (because storage should approximately vanish over an entire year). This missing source matches relatively well more recent estimates of the annual average anthropogenic heat flux density of 13 W m^{-2} in the source area (Van der Laan et al., 2010).

Measuring and modelling greenhouse gas exchange (since 1993)

With cities being the land-surface ecosystem that emits the largest fraction of greenhouse gases (GHG), attention has also been given to the measurement of GHG emissions into the urban atmosphere, with the goal to estimate local or regional emissions and what controls them. The first concentration measurements of CO_2 at Vancouver-Sunset were made as early as June 1993, using a differential infrared gas analyzer (Licor 6262) with inlets at two heights on the tower. Reid and Steyn (1997) established that although emissions are highest during the day, the substantial depth of the mixed layer and the regional boundary layer dynamics caused lowest concentrations in the afternoon, and elevated concentrations (up to 80 ppmv) during the night. The observed CO_2 concentrations nicely matched a simple local 2-D boundary layer model and allowed inference of an approximate source strength profile for the area upwind of the tower.

The first full year dataset of directly measured CO_2 fluxes on the 'Vancouver-Sunset' tower was gathered in 2001-2002 with a closed path CO_2/H_2O analyzer (Li-6262) and a 3D sonic anemometer (Gill Instruments, R2A) (Walsh, 2006). It became obvious that what was previously considered a relatively homogeneous urban surface for the turbulent fluxes of sensible and latent heat, was actually a highly patchy and irregular arrangement of emission sources of CO_2 which inhibited a straight-forward 'ecosystem-level' quantification of the exchange. Two arterial roads cross at a busy intersection only 180 m from the base of the tower. About 1400 detached homes are located within the 80% long-term source area (Figure 5), of which about 93% are heated by natural gas. Additionally areal and diffuse emissions originate from highly managed urban green space (respiration) and human metabolism. Trees (17.1 stems / ha) and lawns with an overall urban leaf area index of 1.8 m^2 m^{-2} uptake a minor fraction of the CO_2. Walsh

Table 1. Daily totals of the energy balance terms measured over an unmanaged grassland site South of Vancouver ("rural", Westham Island) and simultaneously on the urban flux tower Vancouver-Sunset ("urban") - β is the Bowen-ratio. Data from October 2008 to September 2009. Both sites were equipped with a similar EC system (CSI CSAT3 and Li 7500) and with similar 4-component net radiometers (Kipp & Zonen CNR-1) (Data from Christen *et al.* 2010).

	Net all-wave radiation Q^*		Sensible heat flux Q_H		Latent heat flux Q_E		Residual $\Delta Q_S - Q_F$	
	Rural	**Urban**	**Rural**	**Urban**	**Rural**	**Urban**	**Rural**	**Urban**
Spring (MJ m^{-2} day^{-1})	9.10	8.94	2.64	6.07	5.16 β = 0.5	3.04 β = 2.0	1.30	-0.17
Summer (MJ m^{-2} day^{-1})	13.44	12.53	4.40	9.56	8.39 β = 0.5	3.31 β = 2.9	0.65	-0.34
Fall (MJ m^{-2} day^{-1})	3.75	3.38	0.77	2.51	3.18 β = 0.2	2.06 β = 2.0	-0.20	-1.19
Winter (MJ m^{-2} day^{-1})	0.28	-0.01	-0.46	1.01	1.33 β = -0.3	1.10 β = 0.9	-0.59	-2.12
Yearly total (GJ m^{-2} y^{-1})	**2.41**	**2.15**	**0.67**	**1.75**	**1.65**	**0.87**	**0.09**	**-0.47**

35 years of urban climate research at the 'Vancouver-Sunset' flux tower

Andreas Christen, Tim Oke, Sue Grimmond, Douw Steyn and Matthias Roth

(2005) presented her dataset as ensemble fluxes coming from eight different wind sectors, of which the two sectors containing the intersection often measured fluxes greater than 60 µmol m^{-2} s^{-1}. The highest ensemble annual emissions were estimated to be 10.0 kg C m^{-2} y^{-1} (from the SSE sector) and the lowest were 2.0 kg C m^{-2} y^{-1} (from sectors, with no arterial roads, in the WNW area).

Direct measurement of CO_2 fluxes were re-established from 2008 to 2012, using a 3D ultrasonic anemometer (CSI-CSAT3) and an open path analyser (Li-7500). Continuous measurements since 2008 show a similar spatial behavior with little inter annual variability. Consistently, highest annual ensemble fluxes are found from the SE sector with the intersection (13.0±0.3 kg C m^{-2} y^{-1}) and lowest from the NW sector that contains no arterial roads (3.0±0.3 kg C m^{-2} y^{-1}). The two other sectors contain one arterial road segment each, at about the same distance from the tower. The NE sector with a road segment that has 48,000 veh. day^{-1} shows higher fluxes (6.7±0.1 kg C m^{-2} y^{-1}) than the SW sector with a segment of 21,000 veh. day^{-1} (4.4±0.2 kg C m^{-2} y^{-1}). The diurnal course of the fluxes is in-line with traffic counts, and there is on average a 25% reduction observed on weekends compared to weekdays. If the monthly ensemble averaged fluxes are shown against heating degree days (sum of temperatures below a 18ºC threshold, when heating systems are usually turned on), a clear relation can be discerned (Figure 6, see also Christen et al. 2011).

The spatial heterogeneity of CO_2 sources is a challenge to the usefulness of these direct flux measurements and calls for detailed modeling of the processes contributing to emissions and uptake in the turbulent source area of the tower. A highly detailed LiDAR scan, flown in 2007 over the source area of the tower (Figure 7), has become an important data-source to model GHG emissions at fine scales. The LiDAR scan describes the detailed characteristics of urban building structure and vegetation characteristics (Goodwin *et al.*, 2009). The data were used to inform building energy models and classical ecological models in order to quantify in detail the carbon cycle for a ~4 km^2 area surrounding the tower (Figure 8, based on Christen et al. 2010). Numbers in Figure 8 denote carbon fluxes in kg C m^{-2} y^{-1} (arrows) and carbon pools in kg m^{-2} (boxes). Their corresponding size is proportional to the magnitude of the flux or pool. Fluxes carry carbon in different forms, such as carbohydrates in fuels, or CO_2 between the surface and atmosphere. Fluxes entering the system in Figure 8 from the left are lateral fluxes of imported carbon supplying the neighborhood with fuels, food and materials. Lateral fluxes leaving the system on the right side are exports of carbon in the form of various waste products. Vertical fluxes are shown at the top, and are essentially the CO_2 fluxes measured on the tower, they are a combination of emissions from buildings, traffic, human respiration and the net ecosystem exchange of urban vegetation and soils. The model predicts that 6.7 kg C m^{-2} y^{-1} is imported into the system by lateral fluxes, and about 90% of this carbon eventually leaves the system in the form of CO_2 to the atmosphere (5.9 kg C m^{-2} y^{-1}). Only a small part leaves the system as lateral output in

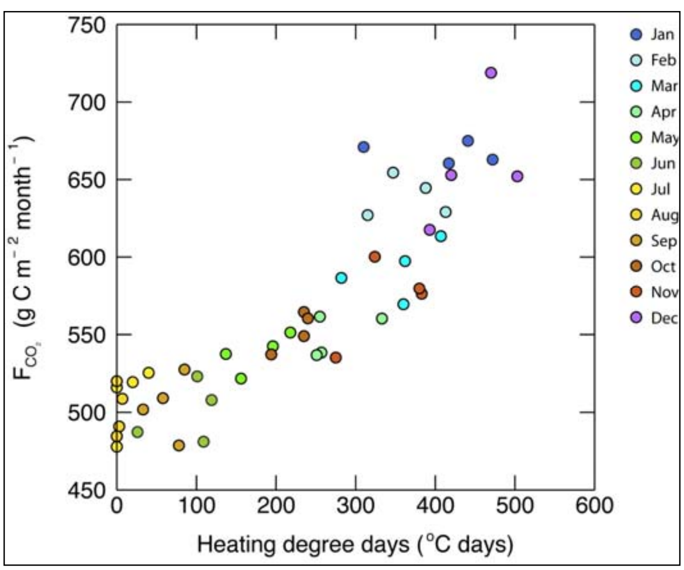

Figure 6. Monthly CO_2 fluxes measured at 'Vancouver-Sunset' (ensemble average from all four wind direction sectors) as a function of monthly heating degree days for the 4-year period May 2008 to April 2012.

35 years of urban climate research at the 'Vancouver-Sunset' flux tower

Andreas Christen, Tim Oke, Sue Grimmond, Douw Steyn and Matthias Roth

the form of waste (0.8 kg C m^{-2} y^{-1}). Readers familiar with similar carbon budgets for forests will recognize that pathways of carbon in an urban ecosystem are linear rather than cyclic and that the 'urban ecosystem' is characterized by a substantial throughput of carbon; most of the imported carbon are fossil fuels (>80%). The local storage of carbon is small. Vegetation and soils are moderate pools and most carbon is stored in buildings – this includes carbon in wooden buildings and furniture. Nevertheless, compared to the fluxes, pools in an urban ecosystem are relatively small.

This carbon cycle model can be also defined in a spatial context because the location of roads (traffic counts) and buildings (heating systems) is well known in an urban area. Christen et al. (2011) used a gridded version of this model at a fine resolution of 50m and overlaid turbulent source areas of the EC system on the tower. In the annual total the modelled fluxes weighed by the turbulent source area (7.42 kg C m^{-2} y^{-1}) matched reasonably well the measured flux of 6.71 kg C m^{-2} y^{-1} determined by means of EC on the tower (given the uncertainty of source area models). This opens up opportunities for flux towers to verify fine-scale pollutant and GHG emission inventories.

Most recently, the approach has been extend-

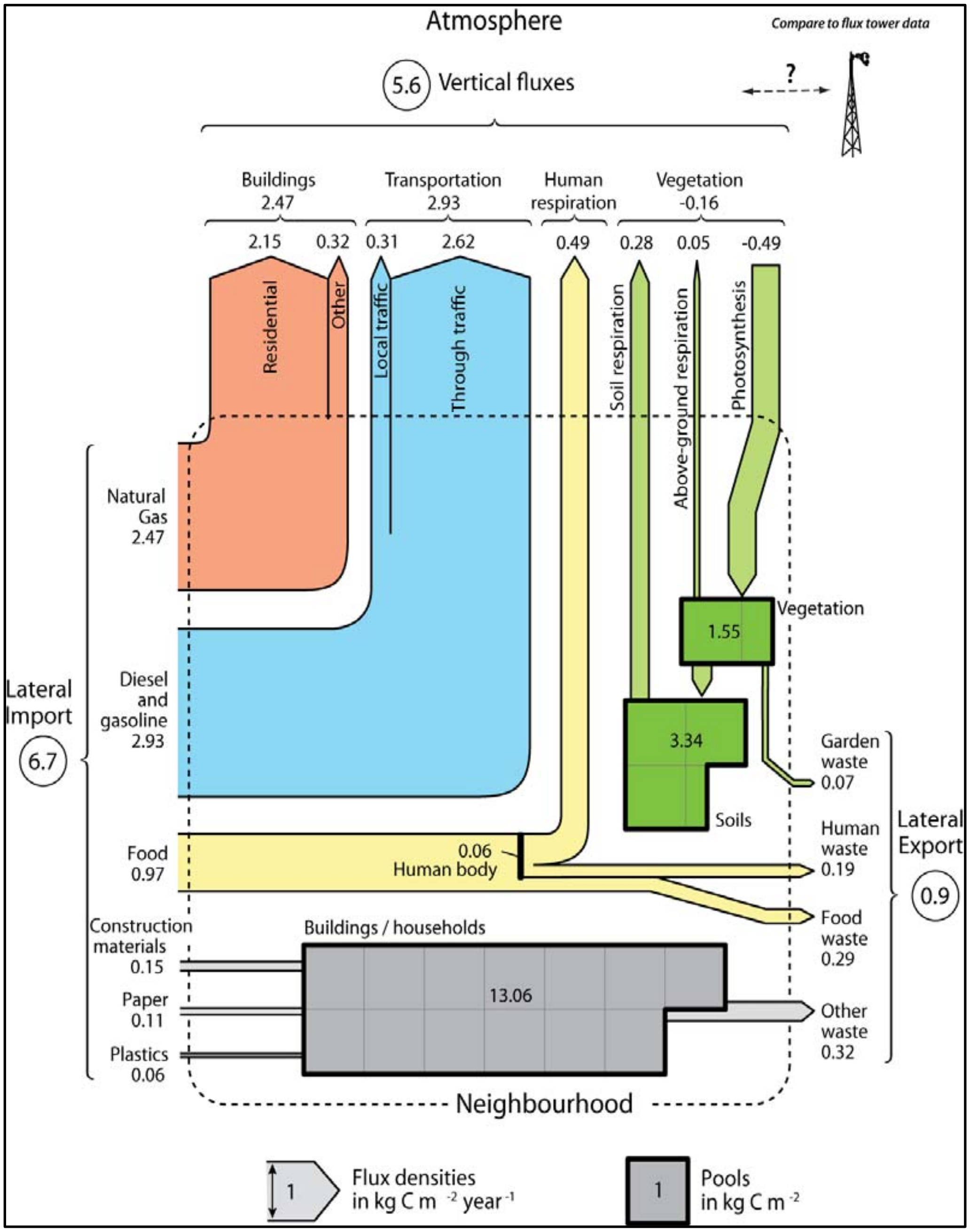

Figure 7. Modeled urban carbon cycle for the Sunset neighborhood. See text for details (modified from Christen et al. 2010).

35 years of urban climate research at the 'Vancouver-Sunset' flux tower

Andreas Christen, Tim Oke, Sue Grimmond, Douw Steyn and Matthias Roth

ed to direct EC measurements of Methane (CH_4) using a open-path CH_4 analyzer (Li7700). Between Feb 2012 and April 2012 an average (net) emission of 17 nmol m^{-2} s^{-1} (23.7 mg CH_4 m^{-2} day^{-1}) was recorded. This flux density matches larger-scale estimates for cities and is comparable to emissions from wetlands. A higher CH_4 flux density is measured during the daytime (maximum ~24 nmol m^{-2} s^{-1}), a lower flux density is recorded in the late night (minimum ~9 nmol m^{-2} s^{-1}). Most of the CH_4 emitted in an urban area can be attributed to incomplete combustion (traffic, space heating / natural gas) and possibly some fugitive emissions of the natural gas network that supplies homes. Uncertain to-date is the contribution of biogenic processes.

Conclusions

Urban flux towers such as 'Vancouver-Sunset' can be a platform to not only quantify the exchange processes over a specific urban area, but more importantly are places to develop, translate and adapt experimental approaches to complex and extremely rough surfaces. The recent advances in the numerical modeling of the urban environment (building energy modeling, GHG emission modeling, dispersion and weather forecasting at increasingly finer scales) require detailed information on flow, turbulence and land-atmosphere interactions in cities. The knowledge and certainty that we can apply theories or use selected parameterizations and simplifications originate from experimental field research on micrometeorological towers in the urban atmosphere. Urban measurements are also needed to test and verify models. As such, results obtained at 'Vancouver-Sunset' are not only of local interest, but have more generally advanced the modeling of weather, climate, hydrology and emissions in the urban environment.

Acknowledgements

The unique measurements at Vancouver-Sunset would not have been possible without the continuous financial support of the Natural Science and Engineering Research Council of Canada (NSERC) continuously since 1977, and more recently the Canadian Foundation for Climate and Atmospheric Sciences (CFCAS) and the Canadian Foundation for Innovation / BCKDF. BC Hydro has provided the University of British Columbia with a long-term permission and commitment that have allowed us to operate this unique research facility.

References

Clarke, J.F., Ching J.K.S., Binkowski F.S., Godowitch J.M., 1978: "Turbulent structure of the urban surface boundary layer", Ninth NATO/CCMS International Technical Meeting on Air Pollution Modeling and its Application, Toronto, ON.

Christen, A., Coops N., Kellett R., Crawford B., Heyman E., Olchovski I., Tooke R., van der Laan M., 2010: "A LiDAR-Based Urban Metabolism Approach to Neighbourhood Scale Energy and Carbon Emissions Modelling". University of British Columbia, 2010 Technical report for Natural Resources Canada, 104pp.

Christen A., Crawford B., Grimmond S., Voogt J., Oke T. (2010): "Year-long urban-rural differences of the surface radiation and energy balance observed in and near Vancouver, BC", *44th Annual CMOS Congress / 36th Annual Scientific Meeting of CGU*. May 31 - June 4, Ottawa, Canada.

Christen, A., Coops N.C., Crawford B.R., Kellett R., Liss K.N., Olchovski I., Tooke T.R., van der Laan M., Voogt J. A., 2011: "Validation of modeled carbon-dioxide emissions from an urban neighborhood with direct eddy-covariance measurements", *Atmospheric Environment*, **45**, 6057-6069.

Cleugh, H., Oke, T.R. 1986: "Suburban-rural energy balance comparisons in summer for Vancouver, B.C." *Boundary-Layer Meteorology*, **36**, 351-369.

Gash J.H.C., 1986: "A note on estimating the effect of a limited fetch on micrometeorological evaporation measurements", *Boundary-Layer Meteorology*, **35**, 409-413.

Contact

Andreas Christen
Department of Geography and Atmospheric Science Program
University of British Columbia
132 - 1984 West Mall
Vancouver BC V6T 1Z2
Canada
andreas.christen@ubc.ca