CARBON SEQUESTRATION AND WATER LOSS IN SEMI-ARID FOREST ECOSYSTEM

Eyal Rotenberg, Kadmiel Maseyk, Naama Raz Yessif, Ruth Ben Mair and Dan Yakir

Department of Environmental Science and Energy Research, Weizmann Institute of Sciences, Rehovot 76100, Israel

ABSTRACT

We present a quantitative examination of pine forest functioning in semi-arid conditions based on measurements of carbon, water and energy fluxes in a 40 years old Aleppo Pine forest in southern Israel. The ecosystem activities showed a strong seasonal cycle with net ecosystem CO_2 exchange (NEE) during the winter reaching values <-0.12 mg C m^{-2} s^{-1} (uptake) and continued activity throughout ~6 rainless months (including uptake spikes after sunrise), with soil moisture down to 3% (v/v, top 10 cm), under vapor pressure deficit, and with sensible heat fluxes reaching 800 Wm^{-2}. Maintaining continuous activity during the summer stress period enabled rapid ecosystem recovery both after the first rain event in the fall, and following short-term relaxations of stress conditions during the dry period. Eight years annual average NEE was 2.13 t C ha^{-1} (213 g C m^{-2}) and the gross primary production (carbon uptake, GPP) was 8.18 t C ha^{-1}. Although this forest grows at the dry and hot timberline, NEE is only about 0.3 t C ha^{-1} lower than the average reported for the global FluxNet system. This reflects moderate NEE during the short wet season (monthly average NEE of -100 g C m^{-2} s^{-1} during peak activity period) combined with low rates of ecosystem respiration (<18 g C m^{-2} s^{-1}) during the extended dry season. Tight water budget was reflected in leaf-dominated evapotranspiration (ET) and high annual scale water use efficiency (***W*** = GPP/ET) of 3.4 mg C g H_2O^{-1}, with winter ***W*** higher by ~2.5 than the summer values.

Results from the studied site indicate that afforestation activities in the semi-arid region have the potential to capture a relatively large amount of carbon and play a significant role in mitigating the CO_2 effect on climate, because semi-arid regions cover almost 20% of the land surface. The results may become increasingly relevant also to currently wetter regions, due to observed and predicted drying trends.

INTRODUCTION

A global effort has been underway over the past decade to study different aspects of carbon, water and energy exchange between the land biosphere and atmosphere (Baldocchi et al., 2001). It is currently based on over 400 FluxNet stations in diverse climatic and ecological conditions (http://www.fluxnet.ornl.gov/fluxnet/index.cfm). Ideally, flux measurement sites should be distributed over the entire range of climate on land, but the majority of measurement sites are currently located in temperate to cold climate conditions in North America, Europe, and Japan.

This is particularly significant when the measurement network is regarded not only as a monitoring system for carbon inventory, but also as an experimental setup used for improving our understanding of processes underlying ecosystem functioning and its response to change (e.g. Melillo et al., 1995; Osmond et al., 2004; Pielke et al., 1998).

To extend the climatic range of flux measurements and add to the very limited information on forest performance under dry conditions, a flux-measurement site was established in the 2800 hectare *Pinus halepensis*, afforestation system (Yatir) at the transition between the Mediterranean region and the northern edge of the Negev desert in Israel. This is, most likely, the hottest and driest forest flux measurement site in the global network, with the midday summer average temperature above 30 ^{0}C; an annual rainfall of about 284 mm (40 years mean) over only five to six winter months; a ratio of precipitation to potential evapotranspiration of ~0.18; and the annual mean Bowen ratio above 5.

Research sites at both the cold and hot extremes of forest survival are important for comprehensive understanding of ecosystem response to change. While cold forests are active (e.g. high CO_2 assimilation) when temperatures warm up, semi-arid forest activity is triggered when the temperature drops and water availability increases. Such forests are particularly sensitive indicators to environmental and climatic changes. Forest functioning under dry conditions may become increasingly relevant to currently wetter sites according to some future climate change scenarios (e.g. Geider et al., 2001), as well as according to current trends in precipitation observed in regions such as the Mediterranean region (Alpert et al., 2002).

Afforestation has been suggested as an important approach to increase carbon sequestration in the terrestrial biosphere (e.g., Canadell and Raupach, 2008). The results from this semi-arid site offers quantitative information on the little explored potential of afforestation in the vast climatic transition zone between the sub-humid and arid climates (Grünzweig et al., 2003; Paul et al., 2002; Warren et al., 1996), with implications both for carbon cycle and for wood productions, with the latter often a critical component for human habitation in these areas (e.g. Clarke and Noin, 1998; Mainguet, 1994). Afforestation in dry regions is also associated with changes in surface albedo (from 0.13 - 0.35 for bare soil to 0.05 - 0.20 in forests; (Campbell and Norman, 1998), and surface Bowen Ratios, both of which can influence regional climate (Charney, 1975) and environmental conditions (Baldocchi and Meyers, 1998) if applied on a large scale.

METHODS

The Yatir afforestation system is located at the transition between the Mediterranean region and the northern Negev desert, on a hilly (undulated) area at an elevation of 600 to 800 m a.s.l. An instrumented tower is located at the center of the forest (31^0 20' 49.2'' N; 35^0 3' 7.2'' E). Trees within the tower footprint are mainly *P. halepensis* (above 90%) planted during the years 1965-

68. The forest density is currently ~ 300 trees/ha, with leaf area index (LAI) of about 1.5. During the measurement period, the average tree height was 10-12 m, with mean Diameter at Breast Height (DBH) of 17 cm. Understory vegetation consists of dwarf shrubs and herbaceous species, which constitutes only a minor portion of the total biomass. The forest was planted on about 0.20-1 m deep soil. The climate at Yatir is semiarid, with yearly average (1964 - 2009) rainfall (P) of 284 mm, ranging from ~ 140 to 490 mm. The rainy season starts in mid October and ends in mid April (6 months), but its duration can vary. The water table at the Yatir area is at 300 m deep.

Annual mean air temperature during the period surveyed was 18.2 ^{0}C, and the long term annual mean relative humidity (RH) was 54 %. Potential evaporation (PET) rate at a nearby open space station using standard Penman-Montieth equation is on average around 1600 mm y^{-1} (Z. Zimal, IMS, pers. comm.), thus having a long-term mean aridity factor (P/PET) of ~ 0.18.

The method for measurements gathered at the instrumented tower erected in the geographic center of the Yatir forest follows the European methodology (Aubinet et al., 2000), and uses Unitus software (University of Tuscia, Italy). The system centers on a 3D sonic anemometer (Omnidirectional R3, Gill Instruments, Lymington UK) and a close path Li-Cor 7000 CO_2/H_2O gas analyzer (LI-COR Inc., Lincoln, Nebraska, USA). Together they measure the evapotranspiration (ET, mm m^{-2} s^{-1}) rate and the net ecosystem CO_2 exchange (NEE) between the forest ecosystem with the atmosphere, and also the energy fluxes of latent (LE) and sensible (H) heat (Wm^{-2} s^{-1}). Measurements of air temperature and relative humidity, wind speed, air pressure and precipitation (Campbell Scientific Inc, Logan, UT, USA) were carried out below the sonic at 15 m height. Radiation fluxes of solar, thermal, and net radiation (Rn) were measured by two CM21 sensors for solar radiation (Kipp and Zonen, Delft, The Netherlands) and by two PIR sensors for the thermal radiation (Epply Lab., Newport, USA). In seven locations around the tower, soil heat flux units (SHF) measured heat fluxes (Gs, HFT3 soil heat flux plates flux, Campbell Scientific). Rain fall data represented here were taken from the standard station located at the KKL forest house, 1.5 km to the southwest of the meteorological tower.

Gross primary production (GPP) is calculated as the sum fluxes of NEE and ecosystem respiration, Re. As stated, NEE is measured directly but Re is modeled from nighttime measured NEE (nighttime NEE = Re at night) and the correlation between sporadic daytime respiration measurements of the ecosystem components and the environmental conditions at the same times (Afik, 2009; Maseyk et al., 2008). ET is assumed to be correlated with T, the stem flow fluxes, with T measured at representative trees in this ecosystem, and T about 60-70% of ET (Schiller et al., in prep.).

RESULTS AND DISCUSSION

Carbon and Water fluxes

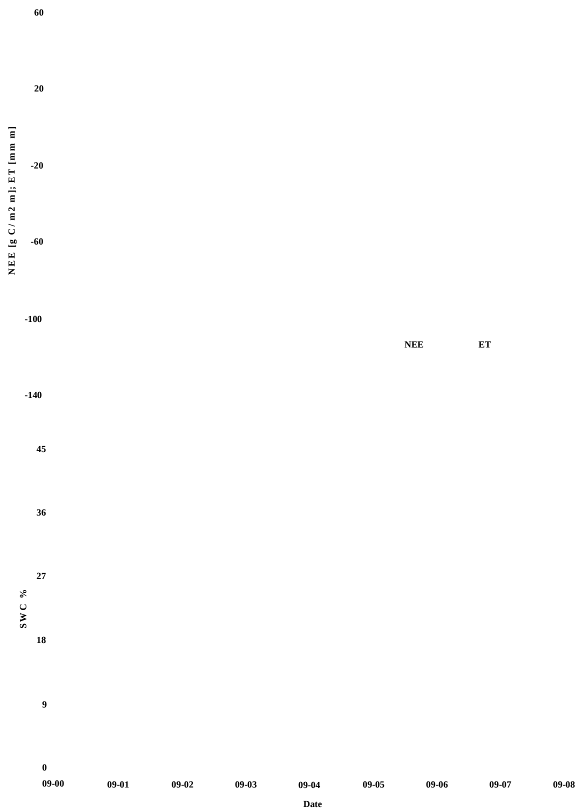

Figure 1: Eight years (2000-2008) monthly values of a) net ecosystem exchange (NEE, [gC m-2 month-1]; Negative values - carbon uptake by the ecosystem) and evapotranspiration (ET, mm M-1); and b) monthly mean of soil water content (SWC, v/v%) at the soil top 0-30 cm layer.

Annual average NEE of the Yatir forest for the eight year ecological study, after corrections for nighttime flux losses, was -213 gC m^{-2} y^{-1} (-2.13 t C ha^{-1} y^{-1}), ranging from -111 to -354 gC m^{-2} y^{-1}, depending on the climatic and the trees' conditions. These yearly corrected NEE values compare well with estimates of long-term ecosystem carbon stock reported previously (Bar Massada et al., 2006; Grunzweig et al., 2007; Grünzweig et al., 2003), assuming these values are near the annual mean value of the forest lifetime. Generally, high uptake occurred during the third in a 3-in-a- row sequence of above average rainy years. This high uptake enabled the trees' leaf area to expand considerably (leaf turn around period at Yatir is ~2.5 years). The seasonal pattern, Figure 1a, shows that most carbon uptake occurred during winter to early spring, months January to April; Leaf-scale measurements of assimilation showed maximal rates at temperatures between about 16 and 19ºC. Hence, temperatures favorable for photosynthetic activity occurred from November through May, and in other times only in the early morning hours or late afternoons. During the intermediate months, when water supply for transpiration was scarce due to low soil water content (Figure 1b), the trees' photosynthetic activities were limited and the ecosystem became mostly carbon neutral (NEE around zero). The forest becomes a small carbon emitter in the summer months, from July through September. In spite of the low precipitation and the dry environment (see below), the Yatir annual average NEE value is only about 30 gC m^{-2} y^{-1}, lower than the annual means found for the all of the flux stations in the Fluxnet (~250 gC m^{-2} y^{-1}, Luyssaert et al., 2007).

Both relative humidity (RH) and leaf to air vapor pressure deficit (D) reflected the dry conditions at the study site. Events of extreme dry condition occurred in spring and in autumn. The lowest RH measured since the station's establishment was 5% and 1/2-hour recordings of RH of ~10% occurred during most of the forest's high photosynthetic activity months. A typical day-to-night temperature range of around 10 °C resulted in high RH values on many nights, thus moderating annual mean values (of 54%). During the day, low RH values combined with high air temperatures led to high D values throughout the year, with values above 3000 Pa during 12.3% of the time. These values are considerably higher than values reported for other Fluxnet forest sites, including semiarid *Pinus ponderosa* forest sites (Law et al., 2000b). Notably, preliminary measurements of the long-wave radiation budget at the forest (not shown) indicated that canopy temperatures can be about 5 ˚C above air temperature over extended time periods. Such results significantly raise the leaf-to-air D well beyond the already high atmospheric values reported above.

The data reported above clearly demonstrate the extreme conditions in which the Yatir forest is growing. The low precipitation, and its distribution, results in low soil water content and severe water stress over much of the annual cycle. Furthermore, the rainfall distribution pattern enhances this effect (Rambal and Debussche, 1995). Clearly, plants under limited water availability and exposed to extreme D must tightly control their water budget to survive. Indeed, these conditions seem to result in special adaptations and patterns of activity that allow the forest to maintain surprisingly high carbon sink levels on an annual scale.

Evaporative water from the ecosystem, the combination of water transpired from the vegetation tissues and evaporation water mainly from the soil surface (ET) mirrored the NEE fluxes (Figure 1a). It peaked toward the end of the rainy season, during the months of March or April, at about 60 mm M^{-1} (month) when there was enough soil water available for the trees to assimilate. At that period, the soil surface was also wet and the energy reaching the ground was enough for extensive evaporation. During the rest of the year, the soil's upper surface became extremely dry (down to ~3%; v/v) halting direct soil evaporation. Water in deeper layers decreased markedly as well (Raz-Yaseef, 2008), reducing T; consequently, CO_2 exchange (NEE) stopped. Thus, because of the high atmospheric water demand toward the end of the summer and until the first seasonal rain, ET decreased to below ~10 mm $month^{-1}$.

Annual evapotranspiration at a given year matches the annual precipitation (Figure 2). The ecosystem's water balance is calculated for the hydrological year, starting on October 1st before the start of the rainy season. Except for the first two measurement years (2000-01 and 2001-02), the ratio of ET to precipitation (P) (ET/P) was 0.8 and 1.1, with low values in wet years (300 mm or more), and high values in drought years (<230). The pattern may be understood to suggest trees' higher water harvesting efficiency in drought years, which decreases in wet years, enabling some water storage for subsequent dry years. (Note that low ET values in the first two years may reflect also technical problems in the early stage of the project, as well as the cumulative effect of the previous five dry years, before 2001). Ignoring the ET values for those two years, for a first approximation, the forest utilizes most of the incoming rain (ET/P>0.9 over the years), leaving only small amounts of water for any others uses.

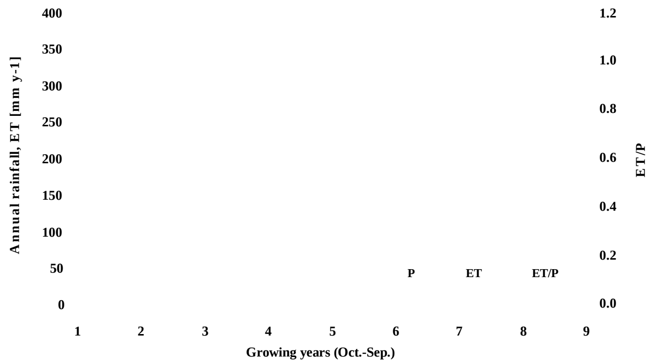

Figure 2: Annual precipitation (P), evapotranspiration (ET) and the ratio (ET/P) for eight years, where year 1 is October 2000 to September 2001. Note ET/P higher than 1, it is below 1 in drought years and above 1 in wet years.

Water use quotient *(W)*

Adjustments in the ratio of plant or ecosystem carbon uptake to water loss, defined here as the water use quotient, ***W***, is one of the mechanisms used by plants to adapt to drought conditions (see Jones, 1992). It is often used as an indicator for plant performance and its response to environmental conditions (Pataki and Oren, 2003; Stanhill, 1986), including increasing concentrations of atmospheric CO_2 (e.g. Drake et al., 1997; Wullschleger et al., 2002). Here we estimate ***W*** from the relationships between GPP and ET.

The results show a clear seasonal trend in ***W***, changing during midday times (09:00-15:00) from ~3.5 mg C g H_2O^{-1} in February (years 2004 and 2005) to ~1.3 mg C g H_2O^{-1} in the following summer and some recovery in November (~1.8 C g H_2O^{-1} in 2005). Notably, the decrease in ***W*** in summer was observed when GPP decreased and approached zero, while residual evaporation driven by high D reduced ***W*** and weakened the overall GPP vs. ET correlation. It is also interesting to note that summer water fluxes were less than half the winter values, even though the ecosystem to air water vapor gradients (D) during the summer might have been be three times higher than in winter. Thus, despite the D effects and consequent decrease in ***W***, plants clearly controlled water loss, and on the whole, decoupled ET from environmental conditions.

Values of ***W*** are calculated and reported differently by different authors; consequently, conducting a comparison is difficult. Plants growing in dry conditions may adapt to maximize ***W***, but the high environmental water demand can compromise this effort. A reduction in ecosystem ***W*** with increasing D was recently reported by Scanlon and Albertson, 2004. Lacher, 2003 reports ***W*** values between 1.3 and 2.1 mg C g H_2O^{-1} (converted from dry matter production values) for coniferous trees. Reichstein et al. (2002) reported GPP-based ***W*** values in Mediterranean forests and macchia between a maximum of 6 and 2 mg C g H_2O^{-1} in winter and summer, respectively. Across evergreen conifers forests, Law et al., 2002 reported an annual ***W*** (as NEE/ET) of 0.8 mg C g H_2O^{-1}, and higher values but minor seasonal changes from 3.1 to 3.0 mg C g H_2O^{-1} in winter and summer, respectively, in a pine forest in Metolius, Oregon (Law et al., 2000a). During the measurement period at Yatir, the estimates of annual ***W*** (***W*** =GPP/ET) ranged between 3 and 4.9 mg C g H_2O^{-1}. Across sites, the comparison of ecosystem scale ***W*** is sensitive to differences in accuracy of NEE and ET measurements, the assumptions behind GPP calculations, and variability in ecosystem parameters such as canopy density (influencing the ratios of soil evaporation to ecosystem transpiration). It is nevertheless significant that despite the dry conditions in Yatir, its ***W*** values are close to the upper values for C3 plants. In the dry summers, ***W*** is low and reflects the water stress that characterizes the forest under such conditions, with GPP near zero and only residual evaporation resulting from the extreme D values. We speculate that the Yatir results, which demonstrate a conservative system maintaining high ***W*** even during mild environmental conditions, reflect interactions with the low hydraulic conductivity in the soil-plant-atmosphere system. This may be part of the overall adaptation to water scarcity at the site.

CONCLUSIONS

1. Eight years mean annual NEE of the semi-arid Yatir forest was -213 gC m^{-2} y^{-1}, and it is only about 30 gC m^{-2} y^{-1} lower then the annual mean found for the global flux stations network (Fluxnet).

2. Mean ratio of ecosystem evapotranspiration to local precipitation, ET/P, is over 0.9, thus leaving only a small amount of water for others uses.

3. Estimates of the eight years' annual ecosystem water use efficiency; ***W*** (***W*** =GPP/ET), ranged between 3 and 4.9 mg C g H_2O^{-1}, with the highest values in the main activity season (January-April). High ***W*** values despite the dry conditions in Yatir are close to the maximum values for C3 plants. Low ET even during the wet season, combined with moderate mean NEE values, resulted in high wet season gross ***W*** values reflecting predominantly the canopy response. The decrease in ***W*** in going into the dry season reflected proportionally greater decline in C uptake than in water loss to evapotranspiration, which was due to the coupled effects of seasonal decrease in soil water content and very high D values.

4. Aleppo pine afforestation shows suitability to the semi-arid conditions, and resilience, resulting in relatively high annual carbon sink. This is potentially significant for C sequestration in the land biosphere if applied on a large scale in the semi-arid regions, as well as for currently wetter regions that are subject to drying climatic trends.

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