Energy budget in a semi-arid forest: magnitudes, feedbacks, and implications for regional climate

הכול מדברים במזג האויר... כיצד יער, על סף המדבר, משפיע?

The Weizmann Institute of Science

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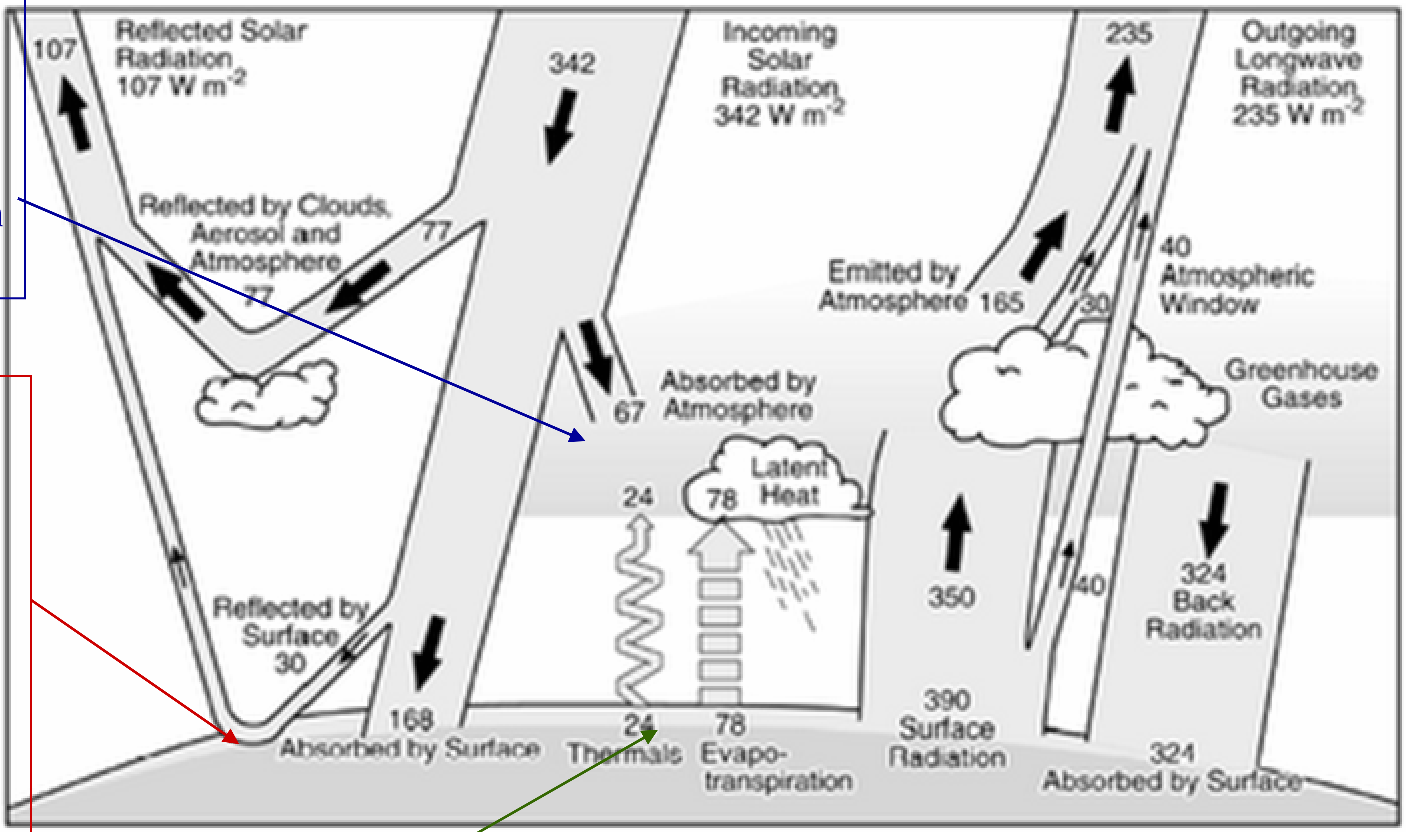
How vegetation cover affects the Earth's surface energy balance

About 2/3 of energy source to the atmosphere comes from the earth surface (the rest comes directly from the sun).

Earth surface average Albedo - 0.15; ranges on land from ~0.45 in white deserts to ~0.05 over a dense canopy.

Lower Albedo means more absorbed S by the surface.



Earth 's radiation balance – annual values; Keihl &Trenberth, 1997

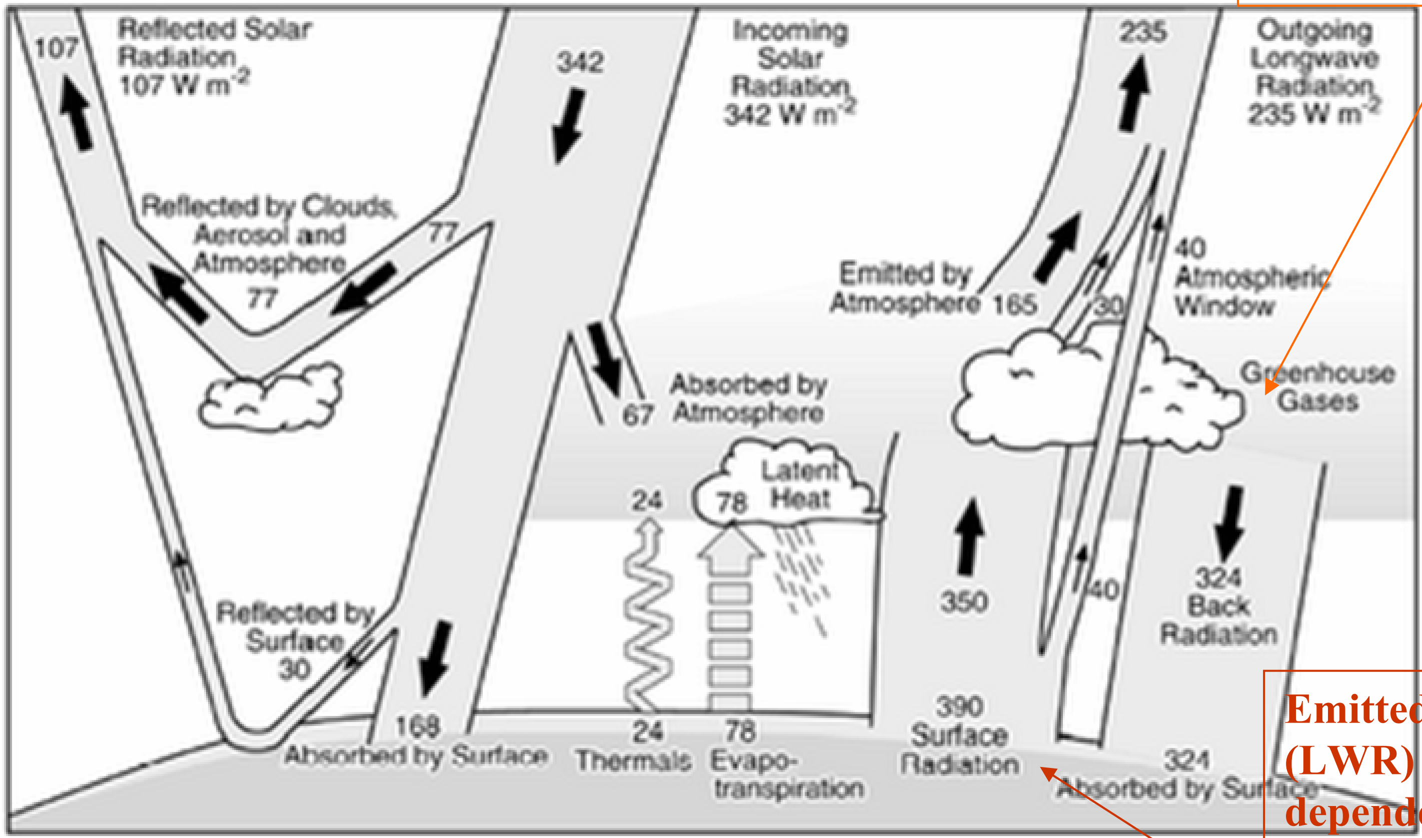
Average Bowen ratio (β) – 0.31; over land it could be higher than 6.

Evaporation enhances the hydrological cycle.

Introduction

How vegetation cover affects the Earth's Radiation Balance

CO_2 uptake by vegetation slows the concentration that rises in the atmosphere, thus lowering downward LWR fluxes.



Emitted thermal radiation (LWR) is strongly dependent on the surface temperature.

Evaporative surfaces (e. g., vegetation) are usually colder than bare surfaces in dry areas.

Other items (not part of this study): the effects on the concentration of trace gases in air (e.g., trephines), the transfer of dust into the atmosphere, the surface drag coefficient, and others.

About 47% of the Earth's surface is defined as dry land

Classification	P/PET[1] (UNEP, 1992)	Rainfall (mm)	Area[2] (%)	Area (Bha)
Hyperarid	< 0.05	< 200	7.50	1.00
Arid	0.05 < P/PET < 0.20	< 200 (winter) or <400 (summer)	12.1	1.62
Semi-arid	0.20 < P/PET < 0.50	200 - 500 (winter) or 400 - 600 (summer)	17.7	2.37
Dry subhumid	0.50 < P/PET < 0.65	500 - 700 (winter) or 600 - 800 (summer)	9.90	1.32
TOTAL			47.2	6.31

Yatir

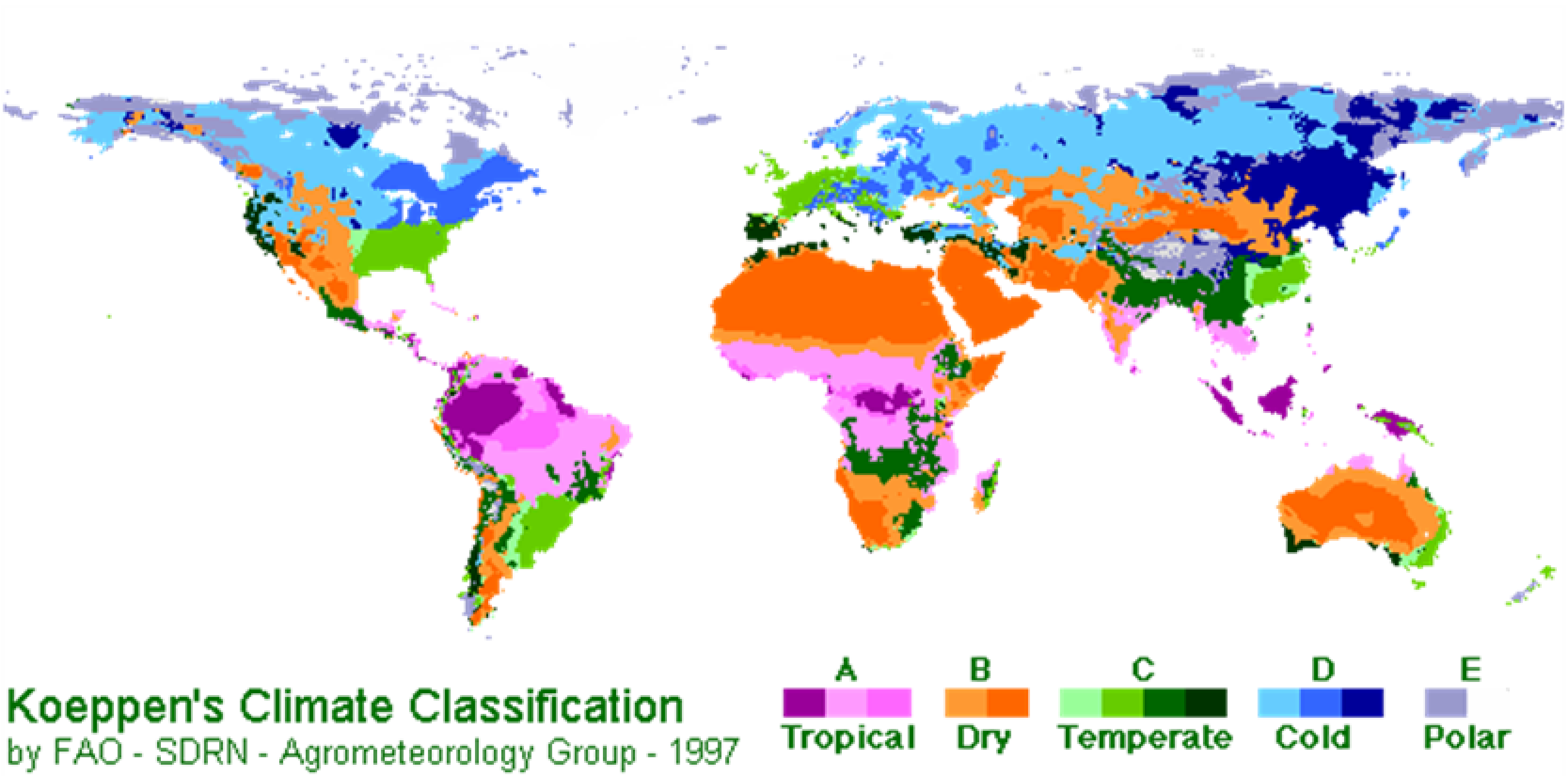
Lal. R., 2003

[1] Precipitation/potential evapotranspiration

[2] Percentage from the Earth's land surface area

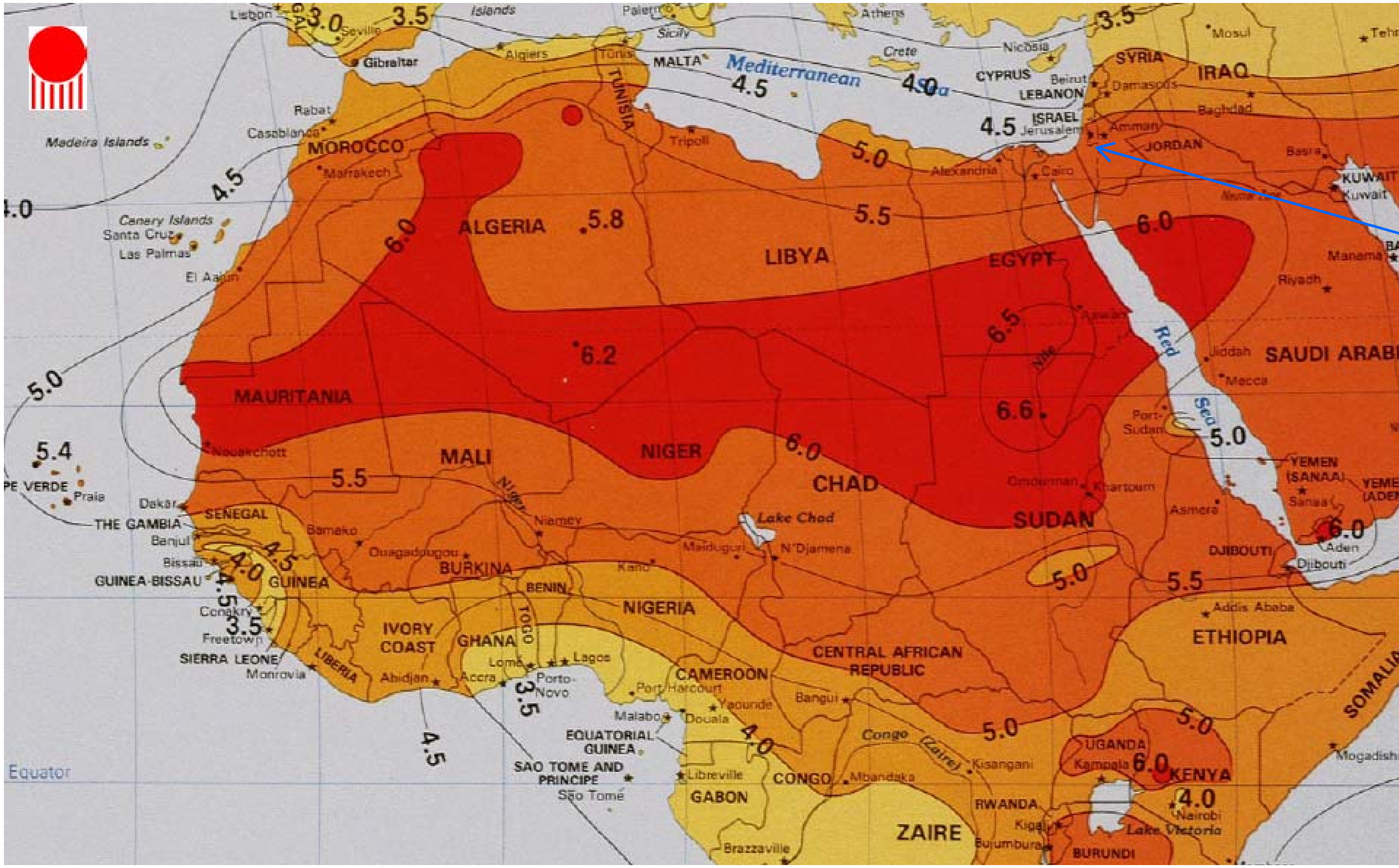
By some estimations, current desertification processes added ~ 0.04%Y^{-1} of the land surface (3 times the size of Israel) to the planet's arid area.

World's main climatic zones



Most of the Earth's dry land areas are around the subtropic climatic zone that receives a high solar radiation load and has a high air temperature.

Annual insolation map of North Africa and the Middle East.
Dry lands are confined to areas where ~Eg > 5 KW_hrs $m^{-2}d^{-1}$



Yatir's Eg = 5.7 KW_hrs $m^{-2}d^{-1}$ e.g., ~240 Wm^{-2}

How changes in land use may effect the climatic conditions in semi-arid land - the "Charney effect"

"A 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.."

"Thus, The Desert feeds back upon itself…" Charney, 1975

Charney et al. 1977 expands this hypothesis to other deserts.

Note that from ecological considerations, desertification is a feed-forward process.

Arguments against the "Charney effect":

It has never been validated where a large albedo change has been acquired on a large surface area (e.g., Lake Nasser; Le Houerou, 1993)

Measurements setup at Yatir

Energy fluxes:

Sonic anemometer, at ~9m' above the canopy, measures exchange, sensible, and latent heat fluxes between the forest and the atmosphere.

Two sets of radiation instrumentations, at 15 and 2 m.a.g., are used for measuring the downward and upward fluxes above and below the canopy.

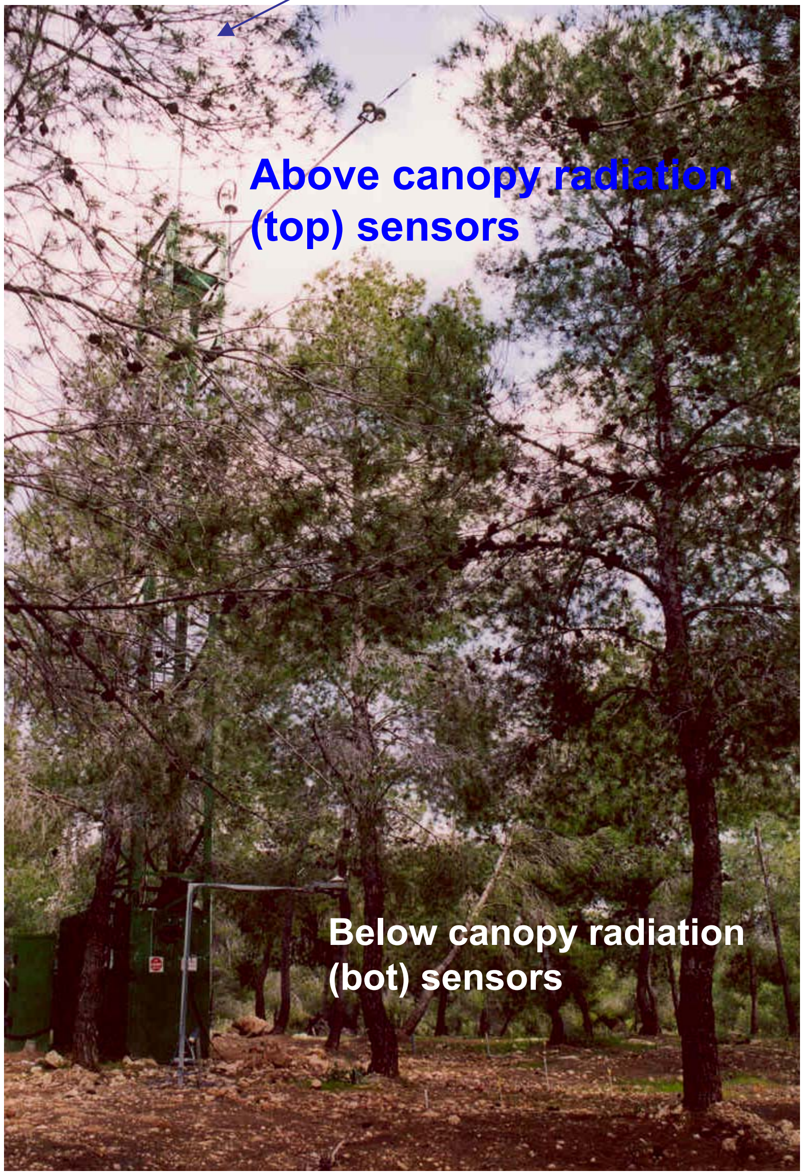
With the sensors in place:

*** Radiation originates from the sun (shortwave radiation, SWR).**

*** Photosynthetic active radiation (PAR, 0.4–0.7 μm).**

*** Thermal radiation (longwave radiation, LWR).**

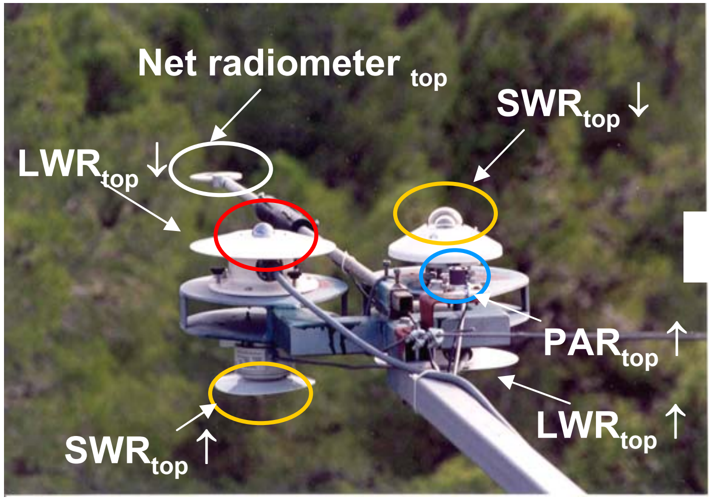
And instruments are available for measuring the meteorological and soil conditions.



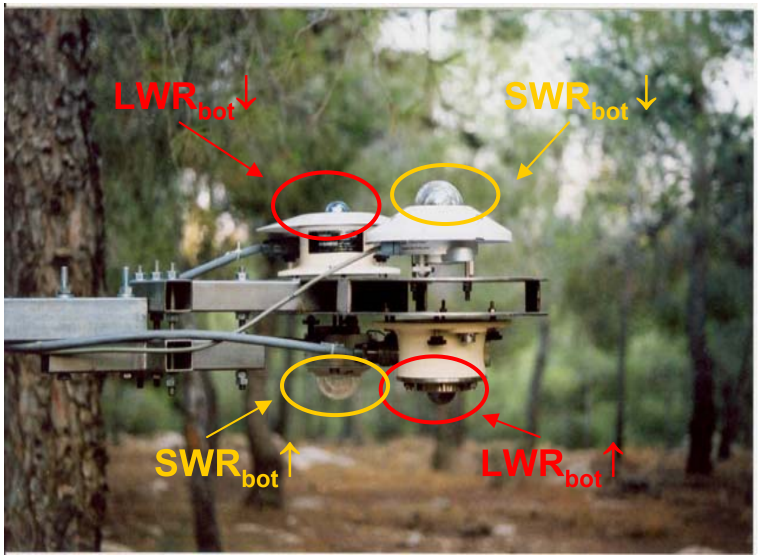
Methods

Instruments for measuring fluxes

- **Eddy covariance system** (3D wind anemometer and IRGA) **measures fluxes of sensible and latent heat** (and water and carbon fluxes).
- **Errors of the covariance fluxes are ~7% at daytimes and 12% at night.**



- **Radiation sensors above the canopy (top sensors)**
- $S_{top}\downarrow + L_{top}\downarrow = R_{top}\downarrow$
- $S_{top}\downarrow - S_{top}\uparrow = Sn_{top}$
- $L_{top}\downarrow - L_{top}\uparrow = Ln_{top}$ **and Ln < o**
- $Sn_{top} + Ln_{top} = Rn_{top}$

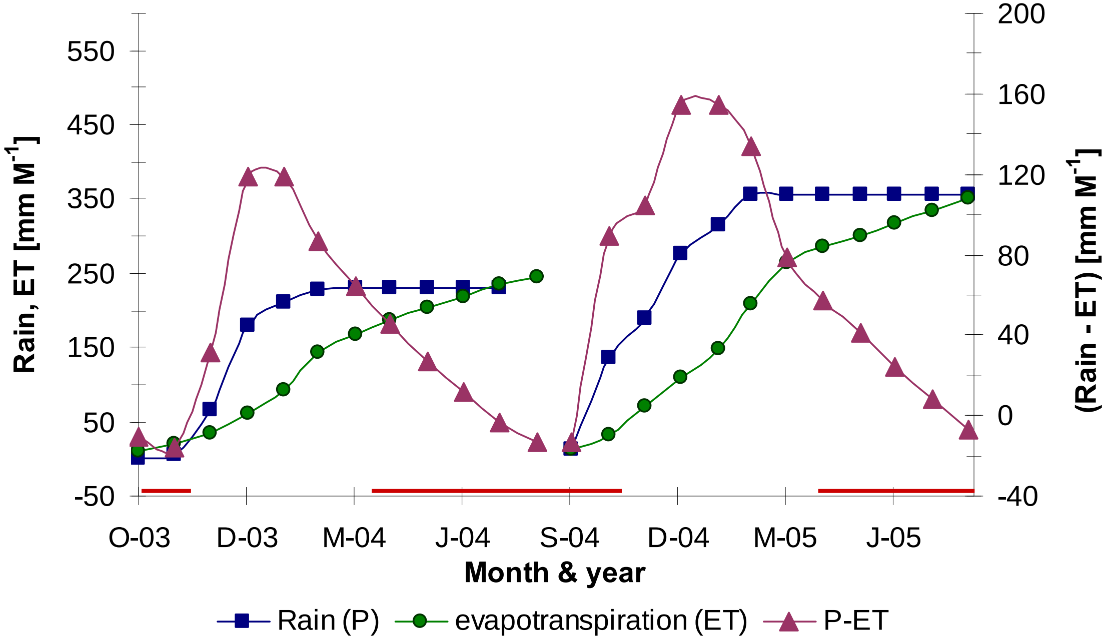


- **Radiation sensors below the canopy (bottom sensors)**

Results

Water was scarce, limiting evaporation and latent heat fluxes for 6 – 8 months a year

The water budget - two yearly cycles:

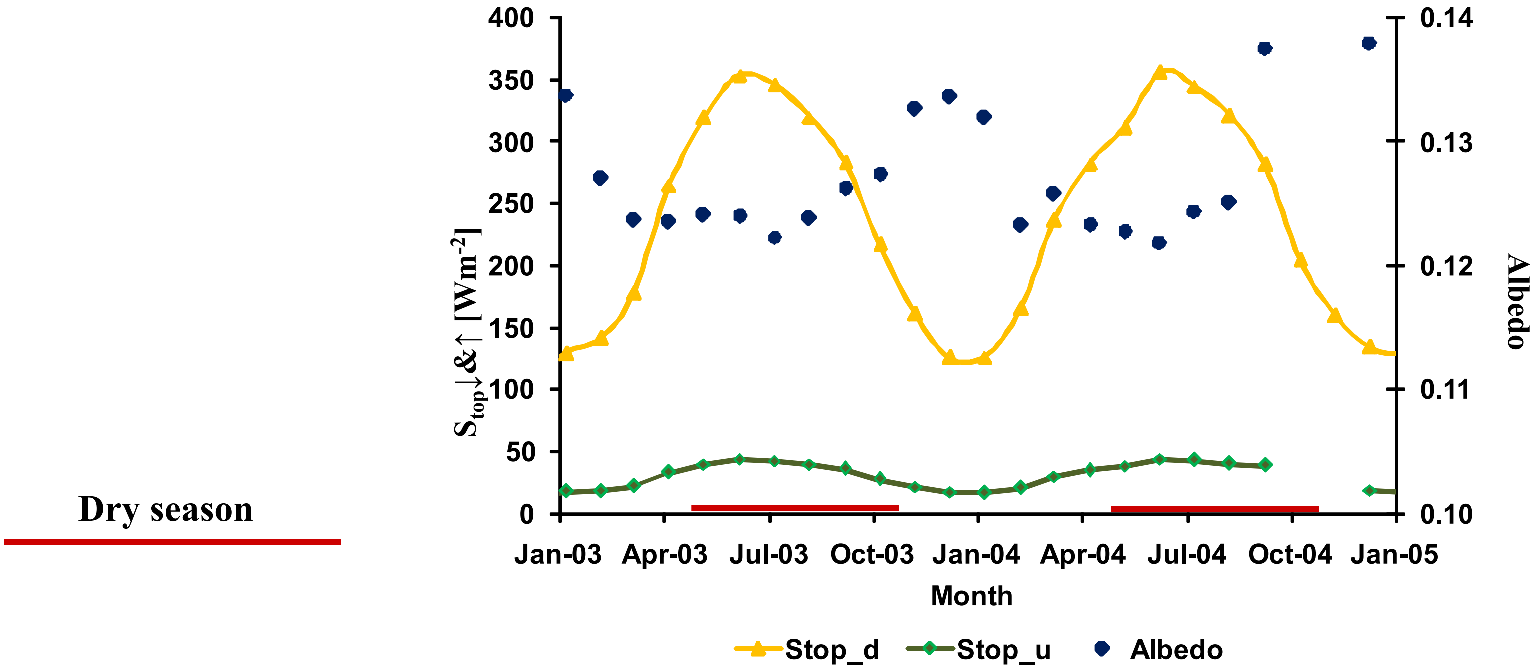


The forest ecosystem uses most of the incoming rain.

Evaporation and transpiration are limited to very low values when energy dissipation from the surface is badly needed.

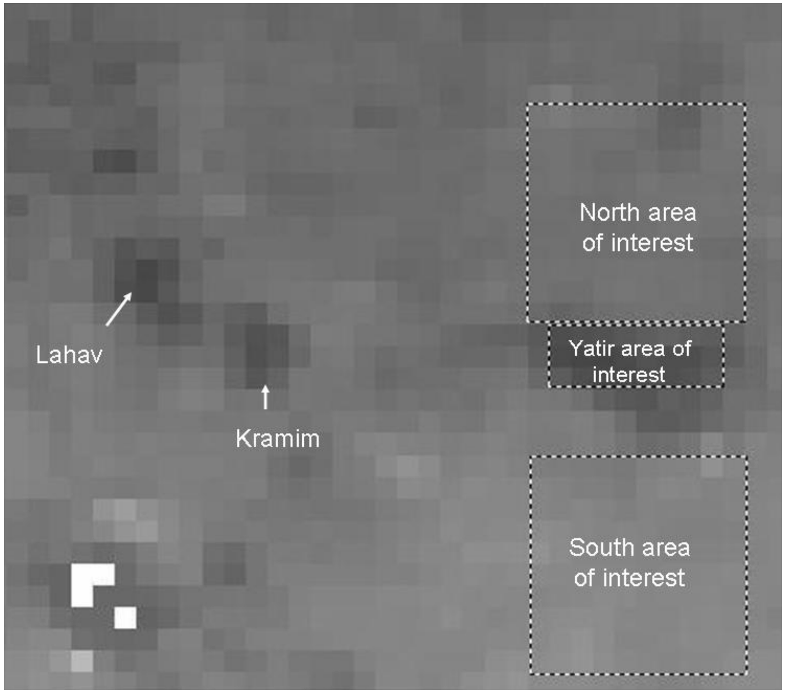
Yatir is among the sunniest forest ecosystems on Earth

- **Annual global radiation (insolation; $Eg=S_{top}\downarrow$) is ~7.5 GJ $m^{-2}y^{-1}$ (238 Wm^{-2}; Annual average).**
- **Annual albedo is ~0.12.**



Results

The forest has lower albedo; thus it absorbs additional solar radiation.



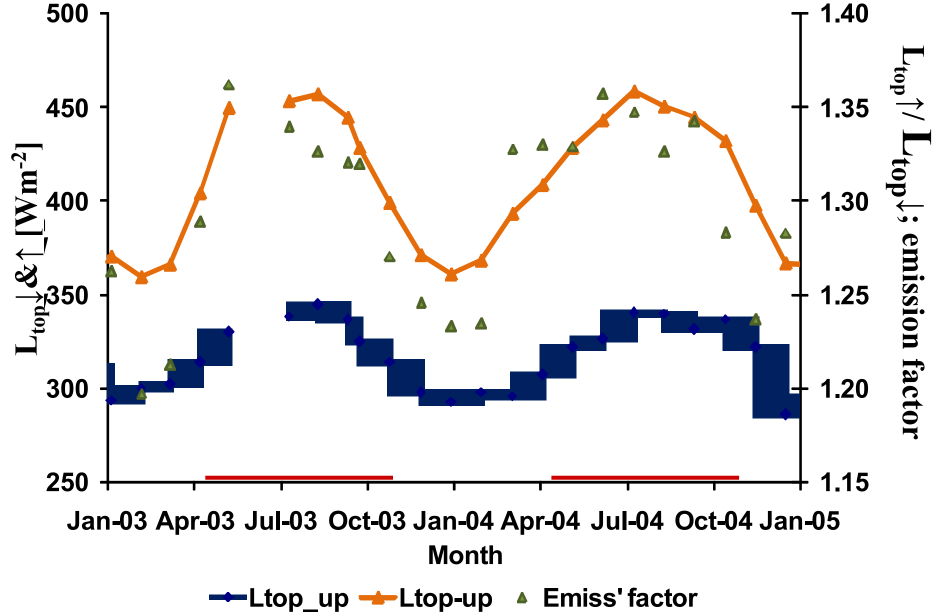
Albedo is about 0.1 lower than the surroundings; it absorbed ~10% more solar radiation than the shrubland.

(MODIS image - M. Sprintsin).

Long wave radiation fluxes (L) above the canopy

- Upwilling LWR fluxs ($L_{top}\uparrow$) are high, whereas downwilling fluxes ($L_{top}\downarrow$) are similar to the global average.
- Not as commonly said, less heat is lost ($L_{top}\downarrow$-$L_{top}\uparrow$) to the atmosphere in winter than in summer.

Winter nights are colder simply because air is colder.



Monthly average of the LWR fluxes above the canopy. Colors on x axis - blue for winter (wet season) and yellow for the dry season.

Results

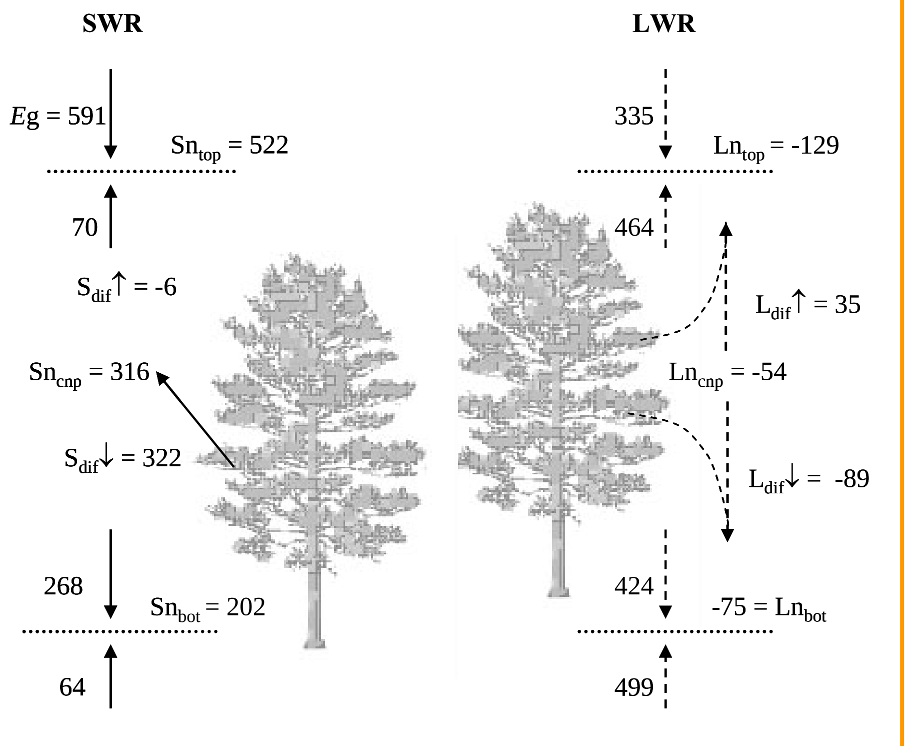
Inside the forest - distinct radiation regime and micro-climatic conditions

♠This radiation measurements setup enable separating between fluxes from- and to- the canopy and soil.

Two findings:

♠Although it is open canopy (covered less then 60% of the surface area), about 80% of the net radiation is absorbed annually by the canopy media.

And,



Average summer day time fluxes at the forest ecosystem

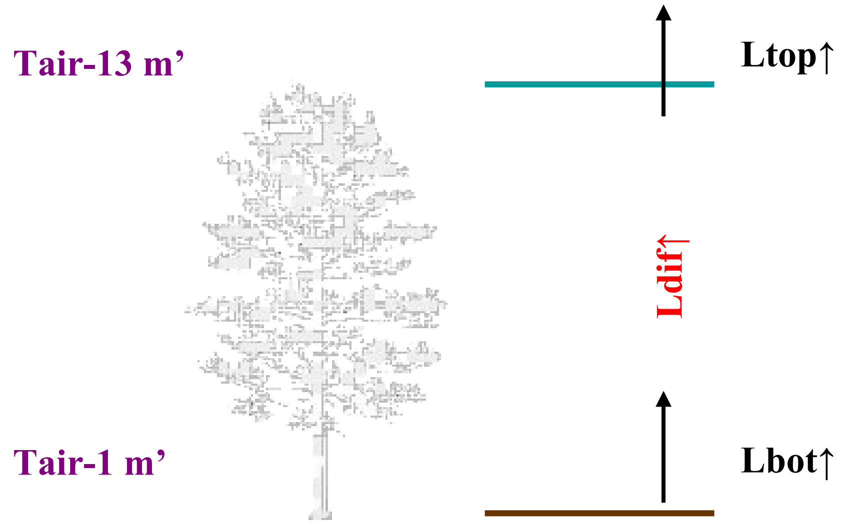
Results

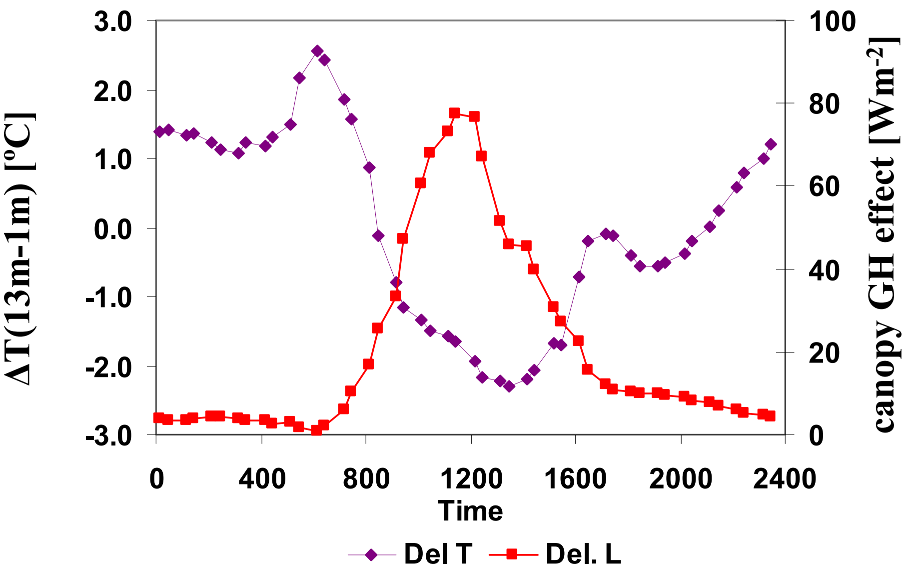
Strong 'canopy green house' effect during the dry season

♣ Strong upward $L_{dif}\uparrow$ was observed, e.g., upward LWR flux from the soil is much stronger than the LWR flux to the atmosphere.

We call this the *canopy green house effect* which, at noontime, could get above 100 Wm^{-2}.

♣ Not like in well-watered tree ecosystems, where the temperature under the canopy at noon is warmer (by up to 3°C) than above.

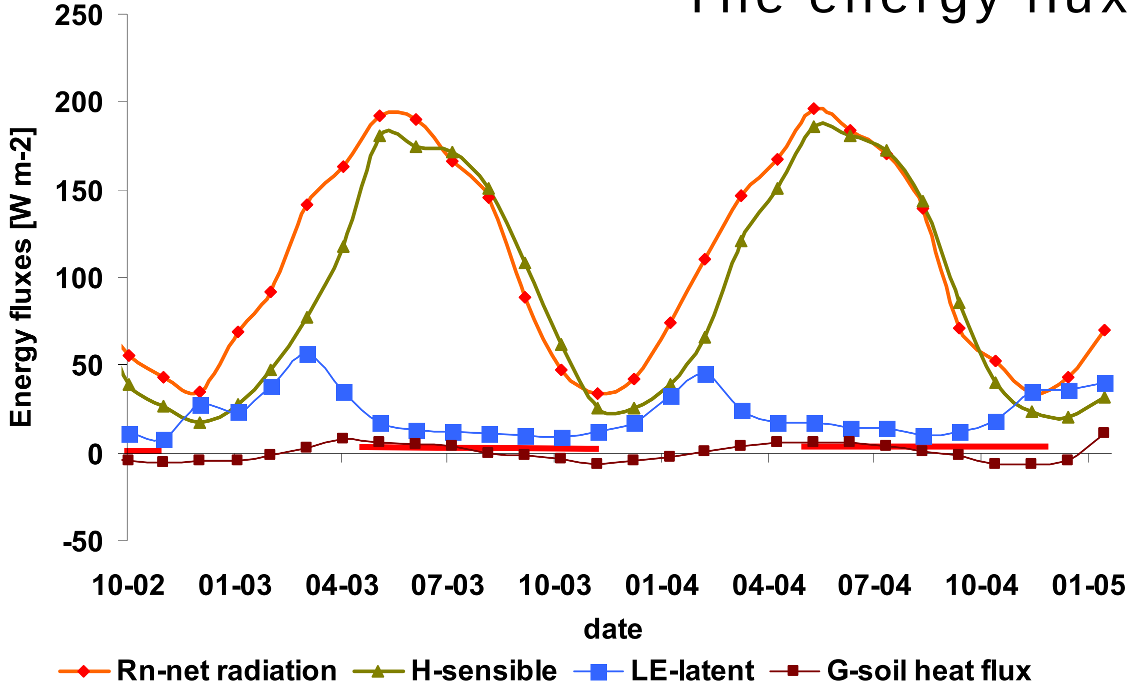




Daily pattern of temperature and $L_{dif}\uparrow$ (average and quarterlies) in the canopy media – Aug. 03.

Results

The energy fluxes above the canopy



Monthly average of exchanged energy fluxes between the forest and the atmosphere

♣Sensible heat flux (H) has a similar magnitude of net radiation (Rn) for most of the dry season.

♣ The forest ecosystem is able to dissipate large sensible heat due to its huge surface area, which is highly coupled with the air: the soil surface, the foliage (needles), and the woody parts (together are >4 times larger than the soil surface area).

♣Temperature of the ecosystem is lower than the soil although it traps more SWR radiation; this is the "canopy radiator effect".

Global impact on climate by dry land afforestation

The balance between carbon sequestration cooling and albedo heating effects

- Carbon sequestration by the canopy reduces the CO_2 concentration in the atmosphere, thus cooling the Earth's surface.
- In calculating this cooling effect, one should consider its global effect on atmospheric CO_2 concentration since air is a well-mixed media.

  Calculation of the radiative forcing (RF) effect due to CO_2 uptake is done according to Myhre (1998), assuming airborne fraction of ½.
- 7 years average measurements of carbon uptake by the forest yields a value of ~2.3 TC ha y^{-1}, similar to long-term (40+ years) uptake by this forest (Bar Massad, 2006).

- Given the annual average solar irradiance ($S_{top}\downarrow$=238 W m^{-2}) of Yatir, a 10% reduction in albedo means an additional radiation absorption of ~24 Wm^{-2}!
- The parallel heating effect is calculated for the whole Earth surface assuming the absorbed heat is mixed all over (e. g., Betts, 2000).

- Our calculation shows that after 30-50 years, the carbon uptake cooling effect is the dominant process (Rotenberg & Yakir, Submitted).

The global impact on climate by dry land afforestation

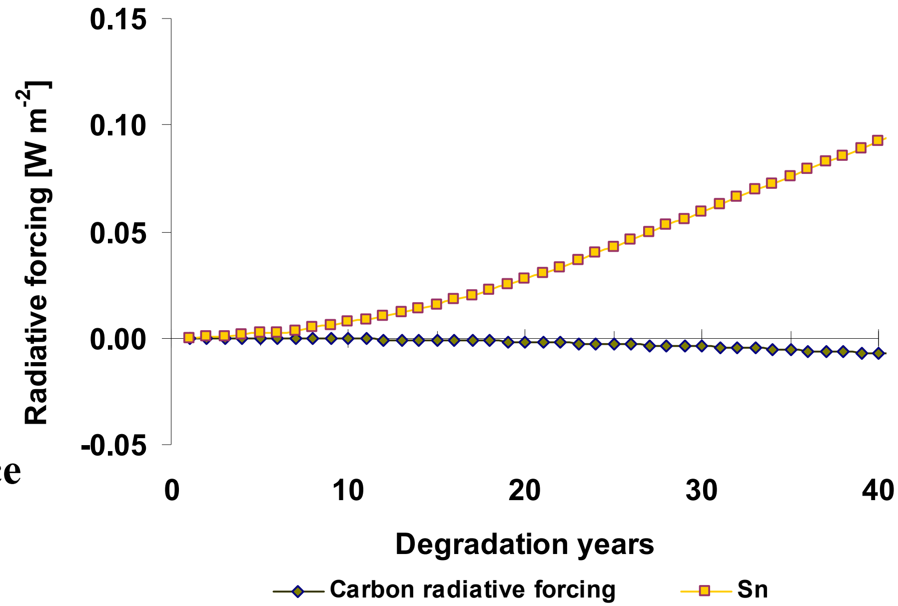
- **Yatir probably stands at the forests dry and hot timberline; even slightly compatible condition could reduce the albedo effect while enhancing the carbon uptakes, reducing that time lag.**
- **The potential of carbon uptake by large-scale afforestation activities:**

If ~10% of the semi-arid zone and part of the adjacent dry land areas (~3.5 Bha) is transformed from carbon neutral (most areas are considered as carbon sources, Lal, 2003) to forests with carbon uptake similar to the Yatir forest; it will capture ~0.8 $GTCy^{-1}$, almost 1 'stabilization wedge' (Socolow and Pacala) for probably >50 years.

- **Note, any afforestation activities should consider a broad range of aspects such as the effect on water yield, biodiversity, social, economic, and other aspects.**

The (current) effect of desertification on Earth radiation forcing

- By definition, desertification is a process that occurs in dry land climatic zones (Le Houerou, 1996), proceeding at a rate of ~6 Mha y^{-1}.
- Following desertification, albedo increases (less SWR absorption; Smith, 2002) and CO_2 is released to the atmosphere (enhanced GHG effect; Lal, 2003).
- Under the assumption of gradual albedo changes of 0.1 in 25 years and carbon losses of 22 TC ha (Lal, 2003), in 50 years, the current radiative forcing effect on Earth following 40 y of land degradation (70th until today) is negative at ~0.085 Wm^{-2} (probably not included in the IPCC-07). During the same period, the RF effect due to CO_2 increases in the atmosphere is (positive) 0.6 Wm^{-2}.



Global radiation forcing on the Earth's surface by land degradation at a rate of 5.8 Mha y^{-1}.

The effects of afforestation on local and regional conditions in a dry land environment –

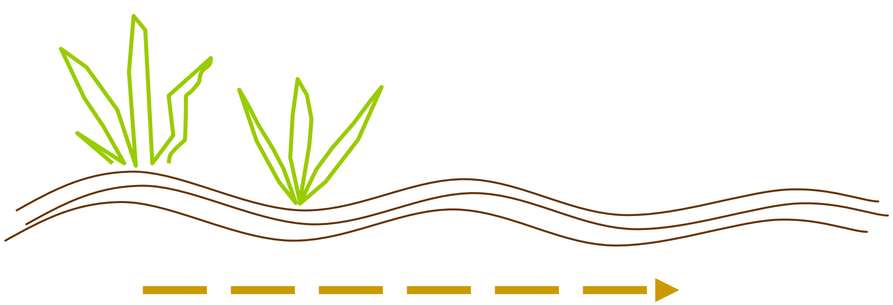
The effect of the forest on LWR emission

- Preliminary measurements show that the forest ecosystem surface temperature at summer noontimes is colder than bare soil outside the forest by up to 20 °C (the 'radiator effect').
- This temperature difference equals lower emitted thermal radiation from the forest by ~100 Wm^{-2}.
- Since the forest canopy also absorbs more solar radiation, the net absorbed radiation (Sn and Ln) by the forest is higher by ~200 Wm^{-2}; a difference of ~40% between the two ecosystems.
- Remote sensing data show (Smith, 2002) that *annual* Ln over savannas or grasslands is lower by ~25 Wm^{-2} or more than over deserts, similar to Sn reduction for the same land cover change (The two processes act in the same direction, increasing radiation absorption for higher vegetative cover in drylands).

Desertification vs. afforestation effect on climate

Charney's (hypothesized) feedback:

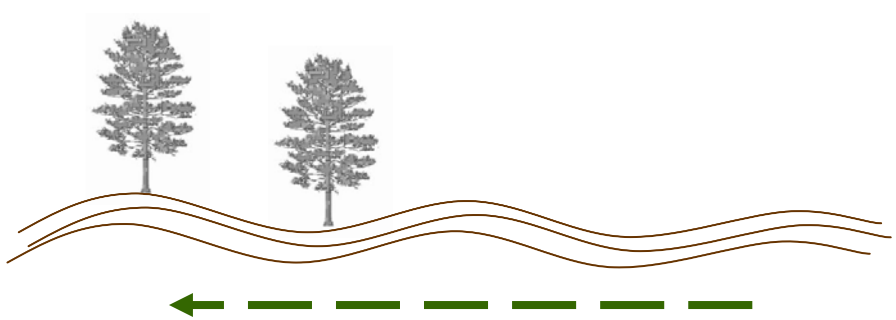
1. Vegetation redaction
2. Albedo (α) $\Uparrow$ and Sn $\Rightarrow \Downarrow$
2. Sensible (H) and latent (LE) heat $\Rightarrow \Downarrow$
3. Cloud cover $\Rightarrow \Downarrow$
4. Stop$\downarrow \Rightarrow \Uparrow$, Ltop$\downarrow \Rightarrow \Downarrow$ and Rn $\Rightarrow \Downarrow$
5. Cloud cover $\Rightarrow \Downarrow$
6. Less vegetation



Affrestation effect (Yatir):

1. Afforestation of low shurbland ecosystem
2. $\alpha \Rightarrow \Downarrow$ and Sn $\Rightarrow \Uparrow$ (+24 Wm^{-2} ann')

   H $\Rightarrow \Uparrow$ and surface temp' $\Rightarrow \Downarrow$ (up to 20°C)
3. Ltop$\uparrow \Rightarrow \Downarrow$ (~25 Wm^{-2},ann')
4. Rn(=Sn+Ln) $\Rightarrow \Uparrow$ (~ 50 Wm^{-2} ann') & H$\Rightarrow \Uparrow$
5. (possible) clouds $\Rightarrow \Uparrow$
6. Comfortable conditions $\Rightarrow$ vegetation$\Uparrow$



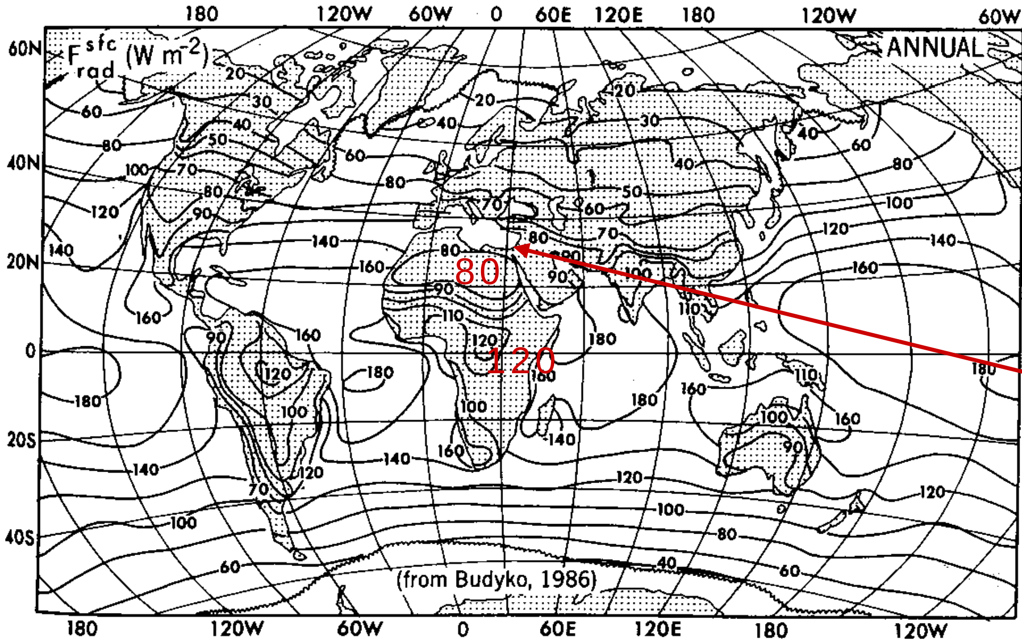
discussions

Global perspective

Forest under dry land climatic conditions changes drastically the magnitude of exchange energy fluxes with the atmosphere.

Models are needed to fully assess the feedback on climate.

Annual net radiation (Rn; Wm^{-2})



Yatir's:

Rn = 115 Wm^{-2}

H = 103 Wm-2

Annual sensible heat (H; Wm^{-2})

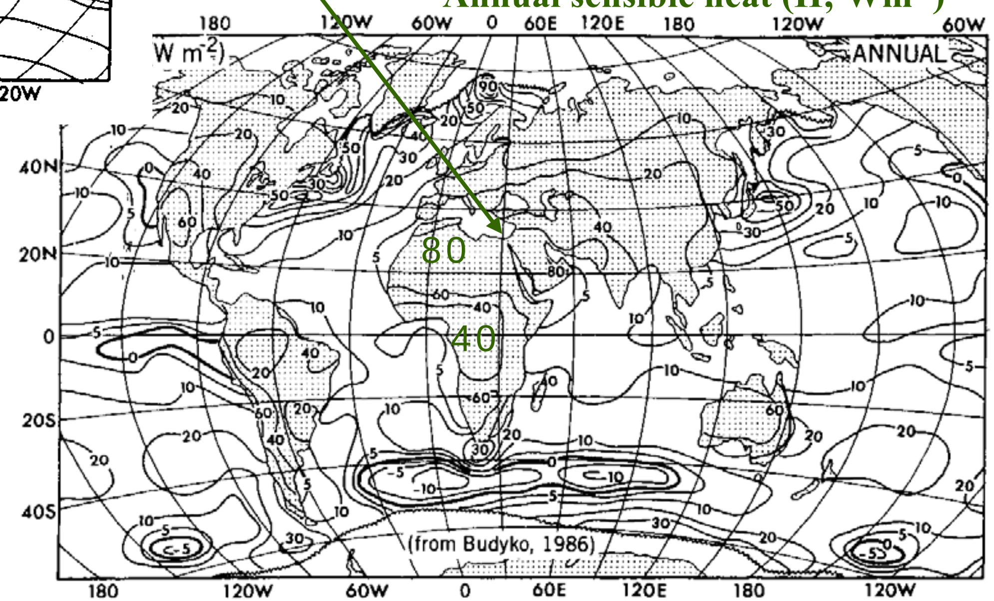


FIGURE 10.8. Global distribution of the sensible heat flux from the earth's surface into the atmosphere in W m^{-2} for annual-mean conditions after Budyko (1986).

Global distribution of net radiation flux at the Earth surface for annual mean conditions (above) and sensible heat flux distribution from the surface in to the atmosphere (right).

Peixoto&Oort, 1991, Fig's. 6.12 & 10.8

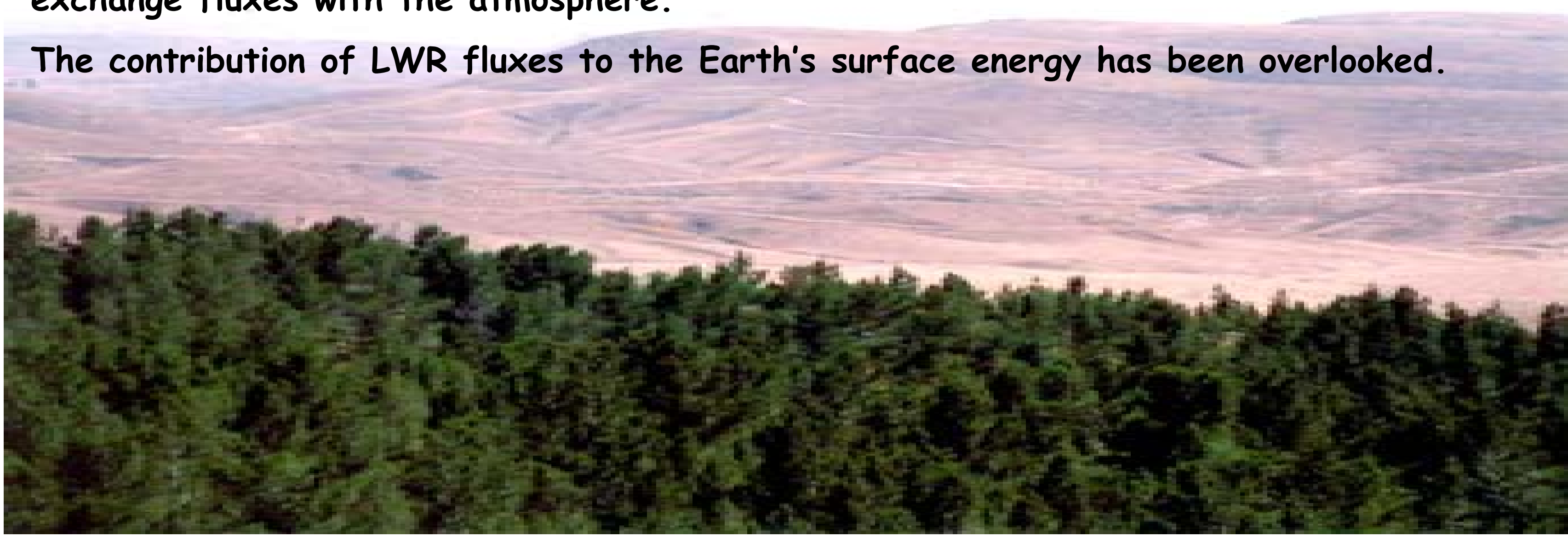
Remarks

- ✓ Sahara (~2% the Earth surface) was a 'green' landscape 11-5Kyr ago (CO_2 of ~280 ppm). Some attributed this (e.g., Renssen, 2006) to higher summer insolation over the Northern Hemisphere (due to Perihelion and axial effects combined with CE), which caused a higher temperature gradient between the Atlantic Ocean and West Sahara, which brings moist air and precipitation.
- ✓ Our observations may also point to the effect of canopy reduction (natural or enhanced by man), accompanied by a reduction of sensible heat and retardation of air circulation as an additional mechanism underlying the desertification process of the Sahara.
- ✓ Thus, different climatic states could possibly exist over land surface at different covers without heating up (or cooling down) the whole planet; it is supported by some climatic models.

Conclusions

- **In dry land regions, vegetation has a strong effect on the exchange energy fluxes with the atmosphere and thus on local climatic and environmental conditions.**
- **Massive afforestation in dry land areas could have a meaningful influence on global climates and in mitigating the increased CO_2 concentration in the atmosphere. However, any such effort should consider other sorts of influences, such as the effect on water yield.**
- **In dry land environments, long wave radiation (LWR) fluxes have effects similar to short wave radiation (SWR) regarding energy dissipation within the canopy and regarding the exchange fluxes with the atmosphere.**

The contribution of LWR fluxes to the Earth's surface energy has been overlooked.



Topics for future studies

- ✓ **A comparison study that will include concurrent measurements of fluxes for different biome types (e.g., detailed flux measurements outside the Yatir forest) is needed for more comprehensive assessments of *land use change* effects on the dry land energy balance.**
  For example, at this stage we cannot quantify the diel differences in emitted LWR from the forest versus its surroundings and predict where screen (air) temperature is warmer – inside or outside the forest, or the LUC effect on RH.
- ✓ **Applying regional and global climatic models to fully assess afforestation effects on local, regional, and global climatic conditions as well as on the environment. This includes answering questions such as what size areas, what kinds of biome modifications, landscape patterns, and land changes would clearly influence local conditions (e.g., regarding wind patterns, humidity, air temperature, and cloud cover) and the nature of the influence.**





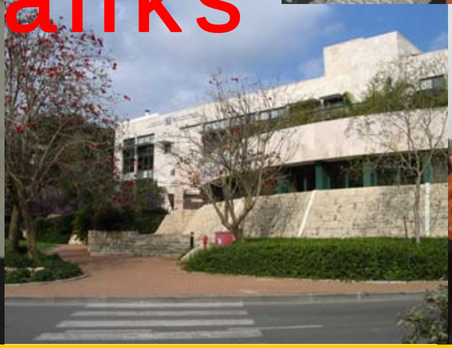




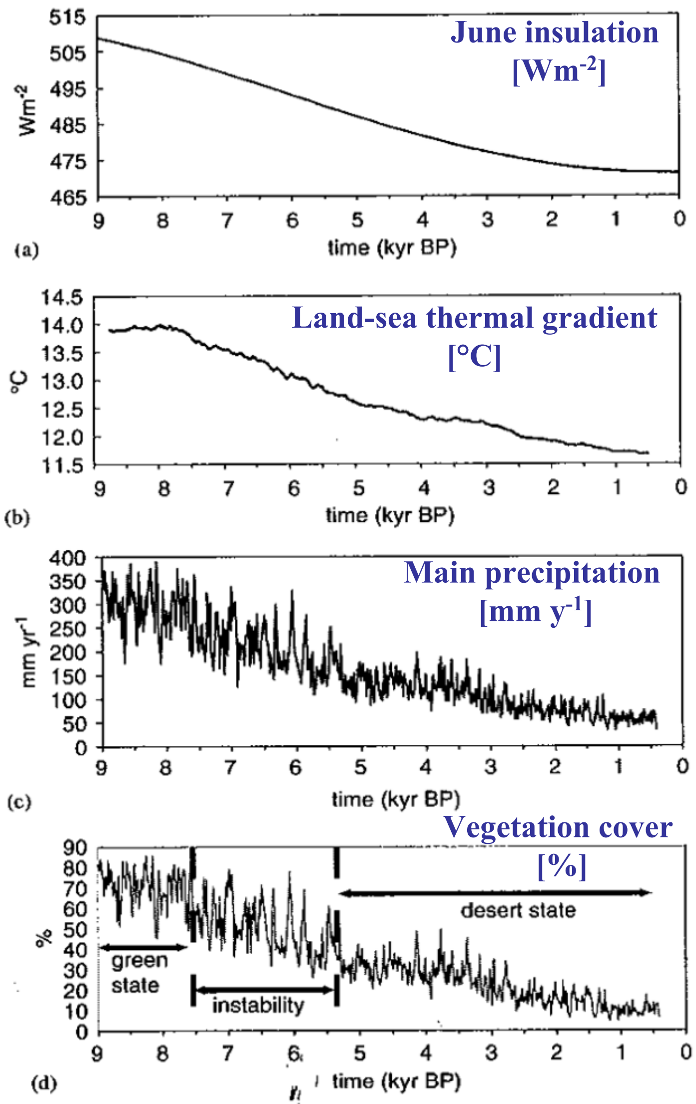



Thanks






Dr. G. Manca with the eddy correlation software, and the technical help of G. Argaman, O. Migdal, N. Kaufmann, Y. Ben Ami, I. Regev, O. Shapira, B. Arad and Y. Freizler

Simulation of climate evolution in Western Sahara of the last 9,000 years….

Rensen et. al., 2006

Insulation (Stop↓)

⇓

Sea-land thermal gradient

⇓

Cloud cover and rain

⇓

Less vegetation cover of the surface

Results from Yatir does not hint for higher air temperature due to more radiation absorption, but rather the enhance air up lift.

The Charney (hypothesized) effect

(follows vegetation cover reduction in the vicinity of arid land)

Initially, the increase in albedo(↑) acts to reduce the absorption of SWR by the ground(↓) and therefore the transfer of sensible plus latent heat into the atmosphere(↓). The resulting reduction in convective clouds(↓) tends to compensate for the increase in albedo by allowing more SWR(↑) to reach the ground, but it reduces the downward flux of LWR even more(↓), so the net absorption of radiation by the ground (Sn and Ln) is decreased(↓). Thus, with or without evaporation, the increase in albedo(↑) causes a net decrease in radiative flux(↓) into the ground and therefore a net decrease in convective clouds and precipitation(↓).

In other words - Desertification leads to warmer surface but colder overlay atmosphere.

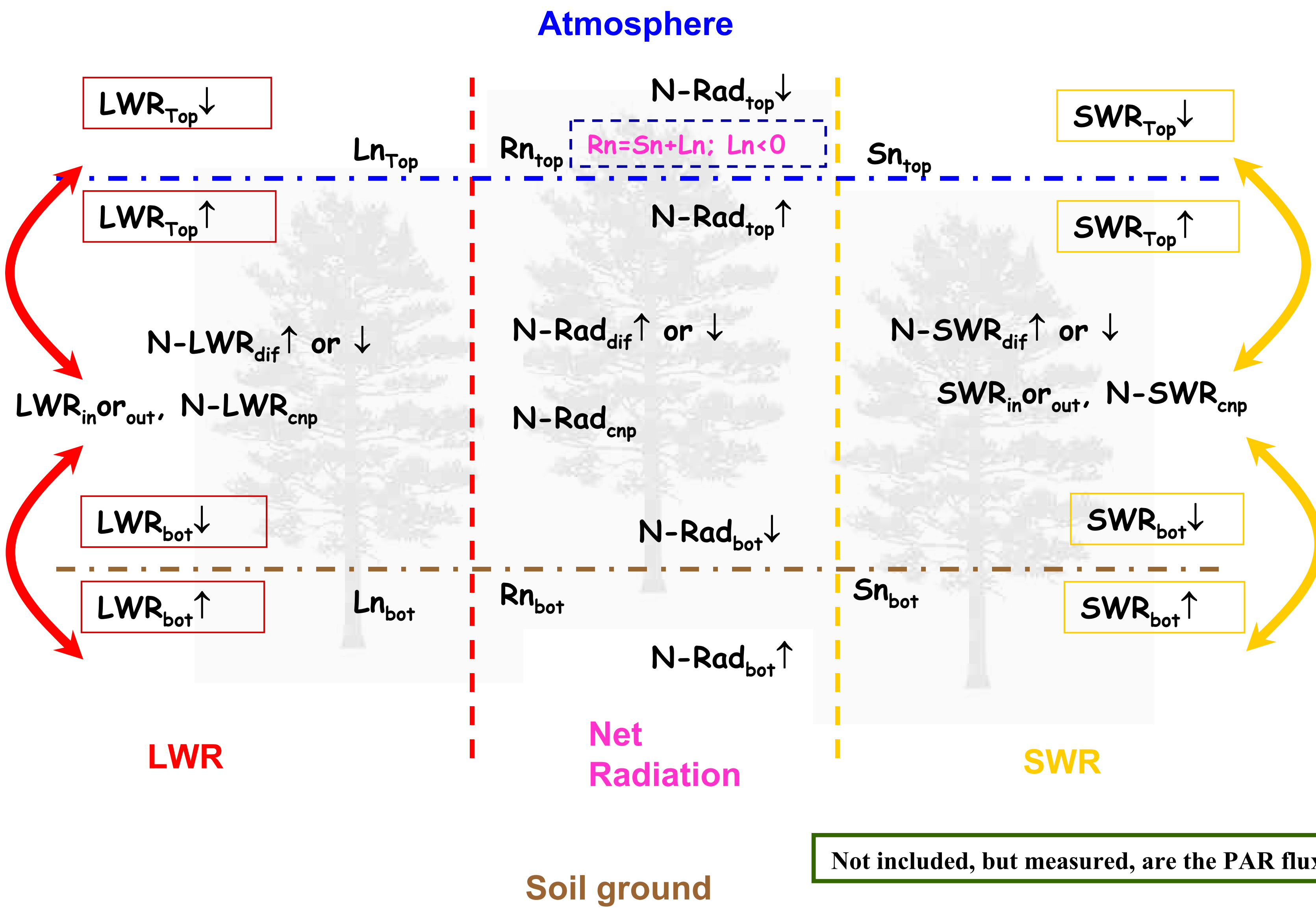
The effect of afforestation in the vicinity of arid land

(Yatir 's outcomes)

..the darker vegetation surface decreases albedo(↓) and acts to enhance SWR absorption(↑). The increase in surface area, coupled with the air, intensifies sensible heat (LE is limited because SWC is low) dissipation into the atmosphere(↑), compensating for the absorbed SWR and even lowering the surface temperature, further enhancing net absorbed radiation by the ecosystem(↑). The *possible* outcome of the huge H is enhanced air circulation(↑) toward the forest and the formation of convective clouds that may reduce SWR(↓) that reaches the ground, which increases downward LWR(↑) and *possibly* more comfortable conditions for forest growth…? That is if the forest area is big enough…

Methods

Terminology and direction of fluxes



Not included, but measured, are the PAR fluxes.

Shortwave radiation sensors

Kipp & Zonen CM21 SWR sensors:

Measure radiation at wave bands of 0.3-~3 μm.

'Secondary' instrument with an accuracy of 2%.

Inter-comparison campaigns for the sensors before and during operation (2002–2005) showed a deviation between sensors within a single sensor accuracy.

Sensitive to rain, water condensation, and dust on the dome.

Foot print cover by the above canopy downward-looking sensor ($SWR_{top}\uparrow$) is ~ 700 m^{-2}.

Longwave (thermal) radiation sensors

Appley's PIR LWR sensors:

Measure radiation at wave bands of ~4-100 μm.

Accuracy of 2-3%, but with no 'official' calibration standard (because of the SWR sensors' accuracy).

Readings are highly sensitive to environmental conditions (wind speed, rain, solar radiations, and others)

At Yatir, the readings are corrected for the effect of SWR on the sensors' output.

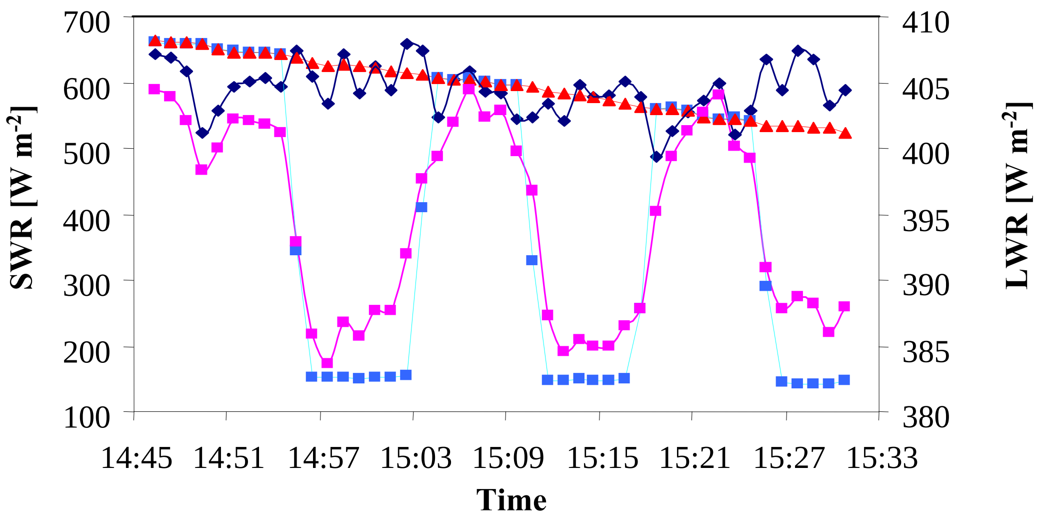
Accuracy of the radiation measurements (SWR and LWR) are lower under field conditions:

Assumed accuracy at Yatir:
Net fluxes ~3-4%
Single flux ~5%

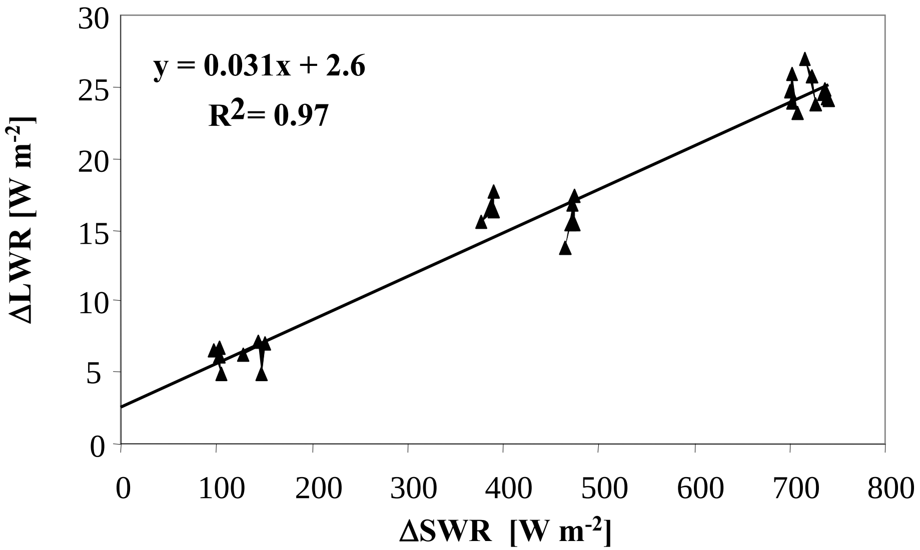
Accuracy of the radiation sensors are higher than the EC fluxes, but they represent a lower footprint area.

The effect of solar radiation (SWR) on LWR sensors' readings

The sensor's silicon dome, which eliminates SWR from reaching the sensing unit, is heated and adds thermal radiation to the atmospheric incoming LWR.



Incoming atmospheric SWR, alternating SWR, incoming atmospheric LWR, alternating LWR

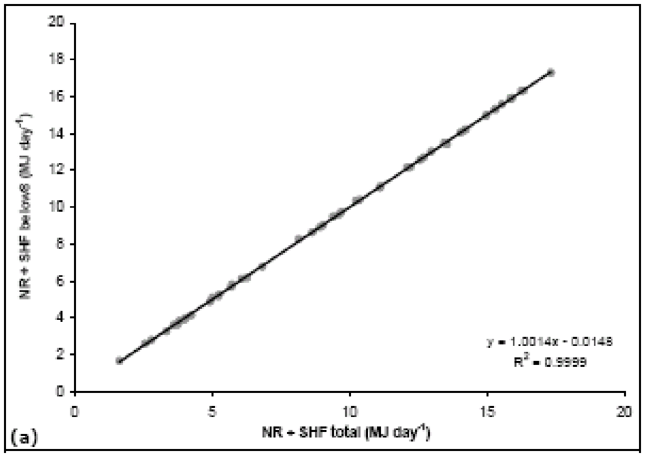


As a result of the dome heating, the measured LWR fluxes were reduced by ~3% of the incoming SWR to the sensor.

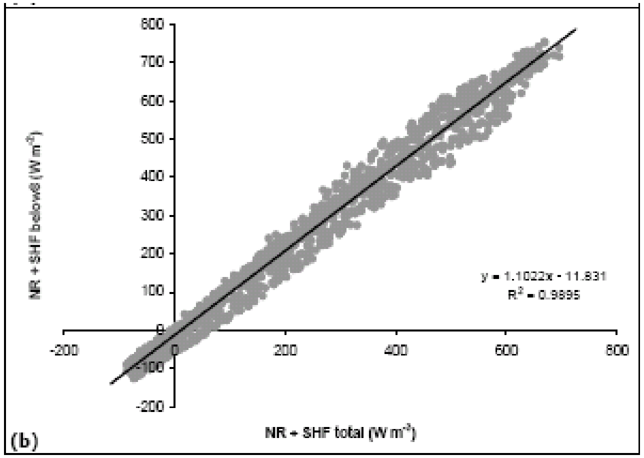
Budget closures as an indication of the quality of the measurements at Yatir

The high rate of energy closure between the available energy (sum of net radiation (Net SWR + Net LWR above canopy) and heat flux in the soil) **and heat fluxes above the canopy** (sensible (H) and latent (LE) heat fluxes) **is an indication of the high quality of the measurements.**

Similarly, high closure was found for the water budget (P with ET) **and was in good agreement with the carbon balance.**



On a deil time scale (24 hours; year 2004) **the energy closure was 1:1** (R^2 = 0.999).



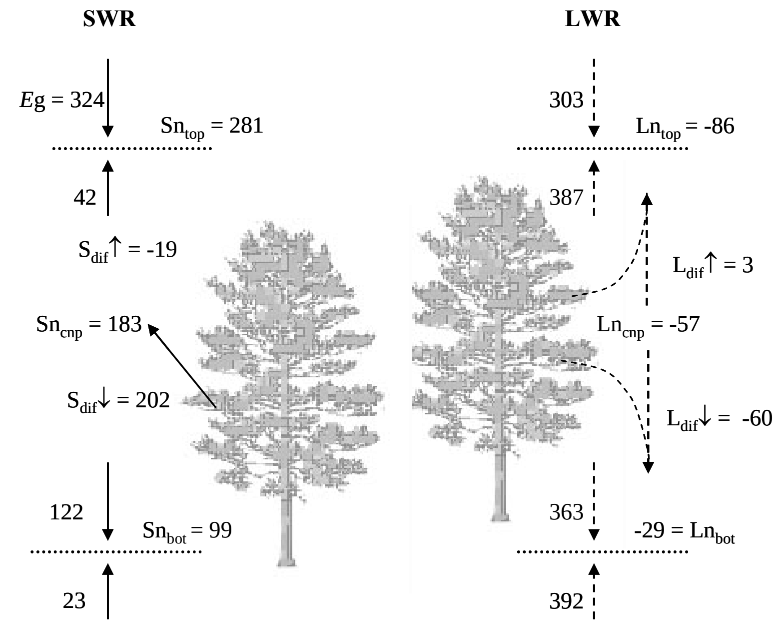
At ½ hours time scale (year 2004), **the correlation slope of the energy fluxes was 1.10** (R^2 = 0.989) **and the deviation was attributed to heat storage by the canopy media space, components that had not been measured at Yatir** (Agam N. unpublished data).

Results

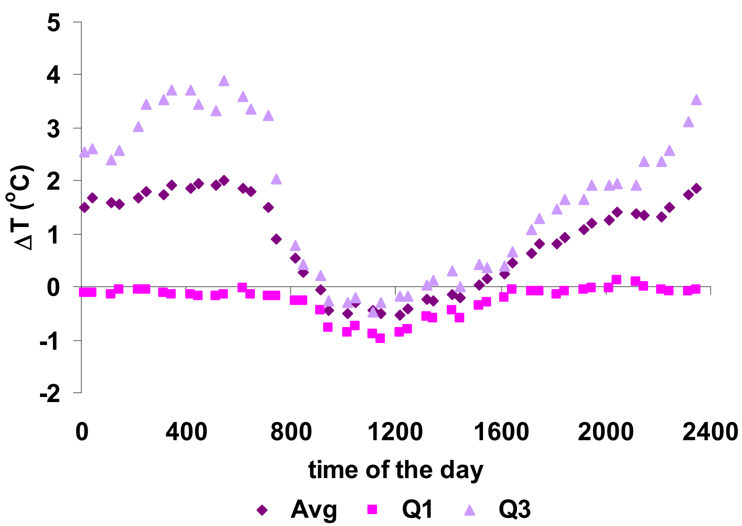
At winter day time…

♣ Low sun angles and more available water for evapotranspiration reduce the intensity of the radiation fluxes within the canopy.

♣ The canopy green house effect almost disappears, and at nights, strong inversion conditions disrupt the accuracy of EC flux measurements (night time ΔT(13 to 1m) could be above 4°C).



Day time average radiation fluxes.



Daily pattern of temperature and L_{dif}↑ in the canopy media – Feb. 04.