Thematic week: Water and Land

Thematic axis: Land Use Planning, Forest Cover and Afforestation

Títle of the presentation: Water yield depends on the water and carbon trade-off in forest ecosystems.

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Abstract:

The cycling of water and carbon between vegetation and the atmosphere is an essential biospheric process with feed-backs to the physical system at various spatial and temporal scales (Claussen 1998; Houghton *et al.* 1998; Waring and Running 1998; Prentice *et al.* 2001). A key element of the water/carbon cycles comprises the fixation of atmospheric carbon dioxide (CO_2) by photosynthesis and its release by autotrophic and heterotrophic respiration. Net ecosystem exchange (NEE) is the net uptake or release of carbon by terrestrial ecosystems.

The terrestrial water cycle includes the precipitation that enters vegetation from the atmosphere and its recycling to the atmosphere by evapotranspiration (evaporation from wet surfaces and transpiration through the stomata) and runoff to lakes or oceans. The partitioning of incoming precipitation into evapotranspiration and runoff is determined in part by climate (Monteith and Unsworth 1990) and in part by factors such as Leaf Area Index (LAI), canopy structure and hydraulic properties of the vegetation and soil. The carbon and water cycles are tightly coupled because stomatal responses simultaneously control transpiration and CO_2 uptake and because microbial decay is strongly constrained by soil moisture conditions, as both too much and too little water reduce microbial activity.

Key words: water cycle, carbon uptake, water use efficiency, maintenance and formation cost of living tissues.

1. Introduction

Forest and water related issues are of utmost importance; forests are crucial to the sustainable management of water ecosystems and resources and, at the same time, water is a key factor for the sustainability of forest ecosystems. This interrelation is nowadays even more enhanced in a context of global change with increased temperature, uncertain future rainfall, and uncertain effects of changes in land use**;** last but not least there will be an increasing growing demand for water from our society. Despite this, water and forest management objectives still are commonly dealt in a sectorial way, without considering the interrelated implications between these two key ecosystems and resources. In addition, despite a significant advance in scientific understanding of forest and water interactions based on almost a century of research in forest hydrology, uncertainty, and in some cases confusion, persists because of difficulties sometimes in translating research findings between countries and regions, between different geographic scales, between different forest types and species, and between different forest management regimes. There has also been a failure to effectively communicate results to policy makers and planners and to challenge entrenched views. Therefore, there is an urgent need to (i) improve the understanding of the bio-physical interactions between forests and water in different situations and contexts and recognizing concrete caveats with respect to uncertainties in our knowledge about the interactions; (ii) to develop effective and efficient models for managing forests and water resources with an integrated approach.

Carbon assimilation and water use are tightly coupled. Water availability is known to be the main limiting factor to global plant photosynthesis (Nemani *et al.* 2003), in particular in arid or semi-arid ecosystems within Mediterranean climate regions. Our understanding of the potential of terrestrial net primary productivity is not complete without a clear understanding of the main limitations on leaf photosynthesis (Kosugi, Shibata & Kobashi 2003). However, despite recent advances, the vulnerability of Mediterranean vegetation to climate change is not completely understood. One main source of uncertainty lies in our incomplete knowledge of the processes behind leaf level responses to drought (Flexas *et al.* 2007; Warren & Adams 2006).

Most studies focused on the effect of soil water stress on leaf photosynthesis have been restricted to laboratory experiments, or isolated leaf level measurements over short periods. This makes it difficult to scale results to trees in woodland conditions over entire seasons and years. On top of this, only a few studies have used quantitative analysis to separate the different limitations to photosynthesis (Wilson *et al.* 2000), and even fewer have considered the effect of internal conductance (Grassi & Magnani 2005).

Despite this lack of knowledge, most of the characteristic traits of Mediterranean vegetation are derived from the water limited growth conditions. At a regional scale, the ratio precipitation/potential evapotranspiration has low values in Mediterranean ecosystems, often below one, which makes one of the main differences with temperate ecosystems. Values of actual/potential transpiration obtained in different experimental watersheds make evident the fact that in Mediterranean ecosystems actual transpiration never reaches the potential values which makes one of the main differences with temperate ecosystems. Even more, Mediterranean climate is characterized by the driest period of the year being during the summer season.

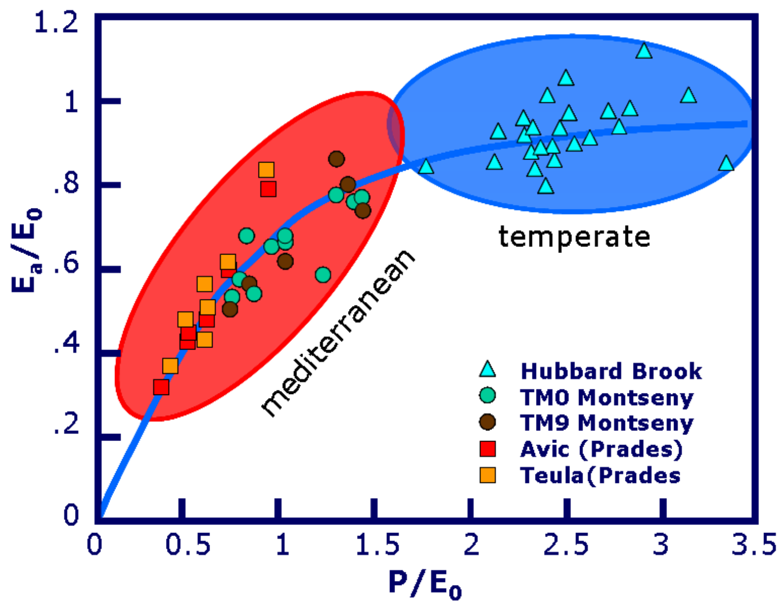

Figure 1. At a regional scale, the ratio precipitation/potential evapotranspiration has low values in Mediterranean ecosystems, often below one, which makes one of the main differences with temperate ecosystems. Values of actual/potential transpiration obtained in different experimental watersheds have been plotted against the ratio precipitation/potential evapotranspiration. In Mediterranean ecosystems actual transpiration never reaches the potential values.

As a consequence, trees are strongly limited by water and it has been experimentally proved hat the reduction of tree density leads to a higher transpiration rate by the remaining trees which is translated in an almost constant amount of water used by vegetation despite their population density. Some characteristic traits of Mediterranean forests as leaf area index, canopy structure and productivity are strongly dependent on water availability, no matter what the trees population density is.

2. The trade-off between carbon uptake and water use.

To best understand the role of water as limiting factor it is crucial to understand the trade-off between carbon uptake and water use. Water use efficiency is a variable used to express how much carbon is fixed in photosynthesis per unit of water lost. Water use efficiency in Mediterranean forest is about 5 mmols of C/mol of H_2O or, in other words, to fix between 2 and 3 g of C, plants have to transpire 1000 g of water so, between 300 and 500 the carbon weight. The cost of carbon uptake in terms of water is very high. The crucial question in this point is how much it costs to maintain the forest structure. This question is of interest because the answer will give us an idea about how limiting the water availability could be both in present and future conditions for the survival of Mediterranean forests.
In the experimental evergreen oak Forest of Prades (Tarragona, Spain) the averaged water use efficiency is 3.68 mmols of C/mol of water or in other words, to produce 1 kg of

	Formation	Maintenance	Total	Water mm
Leaf Biomass	189	844	1033	281
NPTissues	146	204	350	95
Fine Roots	184	95	279	76
Total	**519**	**1143**	**1662**	
Transpiration (mm/y)	**141**	**311**		**452**
Precipitation (mm/y)	**178**	**392**		**570**

Table 1. Cost of formation and maintenance of leaf biomass, non photosynthetic tissues and fine roots (gC/year) in the evergreen holm oak forest of Prades (Tarragona, Spain). The rightmost column and lowest rows represents the transpiration required to compensate the cost of each component of the tree. Precipitation required has been estimated assuming the empirical fact that transpiration accounts for 80 per cent of precipitation in this forest

organic matter the trees transpire 150 kg of water. Probably it may be easier to understand if we explore these results from a different perspective. The maintenance cost of leaves, woody tissues and fine roots are, in this forests, 844, 204 and 95 gC·m^{-2} of ground·year^{-1} respectively. That means that to balance the respiratory cost of leaves the trees invest 844 gC·m^{-2} of ground·year^{-1} . Analogously, in the formation of new tissues the forest invest annually 189, 146 and 184 gC·m^{-2} of ground·year^{-1}.

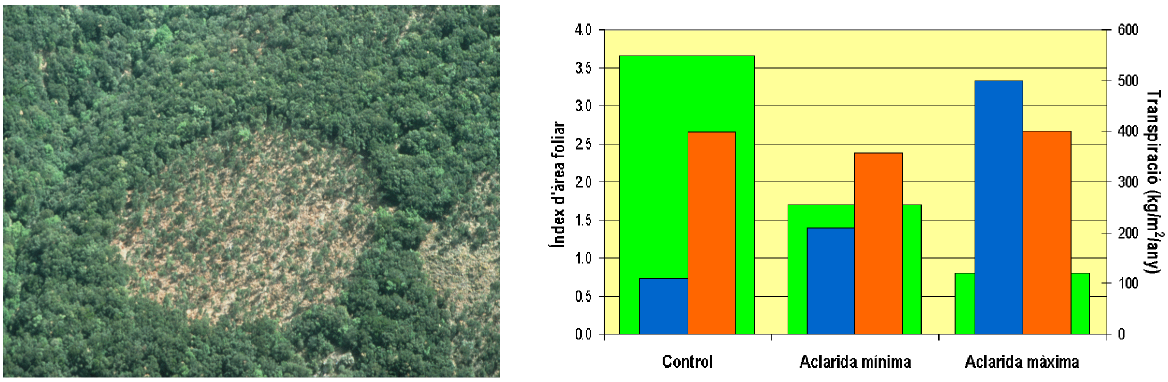

Figure 2. Experimental thinned plot at l'Avic forest (Tarragona, Spain). The tree density in the control forest around the thinned plot is 12629 trees/ha. This high density is at the origin of the forest stagnation. Annual increase of DBH is far below 0.5 mm/year. At different experimental trees density was reduced to 2432 and 1447 trees/ha. This thinning causes the reduction of leaf area index from 3.6 to 1.7 and 0.8 respectively (larger green bars in the histogram). Followinf this LAI reduction the transpiration rates of the forest increases from 111 liters of water/ m^2 of leaf to 210 and 500 respectively (left narrow bars). The total transpiration (liters of water/ m^2 of ground) is about the same in all the cases (right narrow bars).

The photosynthesis needed to compensate this cost of carbon requires a transpiration rate of 452 mm of water per year or taking into account that transpiration represents 80 per cent of precipitation, 570 mm of annual rainfall are needed to carry on the photosynthesis needed to balance the respiratory cost of the forest. In other words, with less of 570 mm of rainfall the forest reduces the formation of new tissues and below 392 mm can not maintain the present biomass. From these data it results evident the conflict between water and carbon and the high cost of carbon uptake in terms of water.

From the perspective of water management it is clear that most of the management regimes that we can adopt do not affect the water cycle. Given the strong water limitation of Mediterranean forests, a reduction, for example, of trees population density has an effect on the water balance of the remaining trees which can improve the amount of water transpired per individual tree or per unit of leaf area but has no effects on water yield has it has been proved experimentally (figure 2).

In other words, the total amount of water uptake by the remaining trees does not differ and Mediterranean forests can transpire up to 80 per cent of precipitation, strongly competing for water.

3. How climate change will impact Mediterranean forest processes?

Temperature change scenarios in the world vary regionally, but show a clear trend towards warming. The pre-industrial atmospheric CO_2 concentration of 270 ppmv has increased up to the present values of 380 ppmv and, very likely, it will continue to increase. Both atmospheric circulation patterns and rainfall patterns show evident changes. In a recent analysis (Schroeter et al., 2005), the average projected temperature increase in Europe ranged from 2.1 to 4.4ºC (according to different climate and socioeconomic projections) with the strongest warming consistently in the high latitudes.

At a global scale, twelve out of the last 13 years (1995-2006) are among the hottest since we have instrumental records. The temperature increment from 1850-1899 to 2001-2005 has been 0.76ºC. In Spain, the increment from 1971 to 2000 has been of 1.53ºC, a much higher value than the 1.2ºC predicted by the climate models (Parry *et al.* 2000). These observations suggest that the problem in the Mediterranean can be much worst than predicted and the temperature can increase 2.5º or even 3.5ºC by 2050.

The effects on terrestrial ecosystems of climates which may differ from present in many respects including changes in water availability and changes in the seasonal cycle of precipitation, changes in the relative phasing of temperature and rainfall, changes in temperature leading to changes in snowmelt and so on. Such changes have implications for the land-atmosphere carbon exchange and evapotranspiration, soil moisture and runoff. The two cycles (carbon and water) are closely coupled through stomatal behaviour, and both can have feedback effects on climate (CO_2 concentration; precipitation patterns and sensible/latent heating).

Some process based models attempt to mathematically describe the processes which govern carbon and water fluxes in forest ecosystems, and thus forest growth or decline. They are complex dynamic simulators, with each process interacting in real time with other key variables. Thus they can be used as excellent tools for the exploration of future forest ecosystem performance under different assumptions of climate change (Haus, 1990, Mohren & Burkhart, 1994). Used in conjunction with management orientated growth and yield models, they can also prove very useful in verifying and backing up the predictions of such models in a changing climate, and suggesting modifications in methodology where necessary.

Predicting the effects of climate change on the future performance of current forest stands can benefit from highly mechanistic process based models which can accurately describe the responses of forest stands under a variety of conditions. The lack of understanding of the effect of water stress on ecosystem function leads to big discrepancies when modelling in these conditions but recent advances allow us to successfully reproduce water and carbon balances during periods of stress. This will be of particular importance for modelling future scenarios, where water stress is expected to increase in Mediterranean ecosystems. Particular attention has to be paid to the modelling of water and carbon fluxes, and in assessing different approaches to modelling the effect of water stress on the photosynthetic apparatus, autotrophic and heterotrophic respiration. It is now widely accepted that climate change will alter weather patterns throughout the world, and changes have already been observed and documented.

For Mediterranean ecosystems, an increase in air temperatures coupled with changes in the distribution of precipitation is expected to lead to a higher rate of evapotranspiration, and increased levels of summer drought (IPCC, 2007). In Mediterranean ecosystems, water is already the limiting factor for growth, and an increase in the occurrence of drought could have a large impact on the growth rates of new and current forest stands. The potential application of empirical models, based on statistics gathered under current or past climatic conditions, for the prediction of the future performance of forest stands is therefore questionable.

Among all bioclimatic regions, the Mediterranean appeared most vulnerable to global change. Most of this vulnerability is associated at the general atmospheric circulation and the role of water as a limiting resource for Mediterranean ecosystems. The Mediterranean regions, roughly located between 35º and 45º of latitude, are just in the frontier with the high pressure area linked to the Hadley cell. Any increase in the atmospheric energy is translated into an enlargement of the Hadley cell and, as a consequence, the high pressure belt moves to higher latitudes in the northern hemisphere and to lower latitudes in the southern hemisphere, reaching the Mediterranean areas. Given that these higher pressures are associated to hot and dry air that has been desiccated when ascending in the low pressure equatorial areas, the temperature increase and precipitation decrease associated to climate change in Mediterranean areas is easy to understand.

All climate models and socioeconomic scenarios concurred on increasing precipitation over much of northern Europe (between 10 and 40 per cent more rainfall) and decreasing

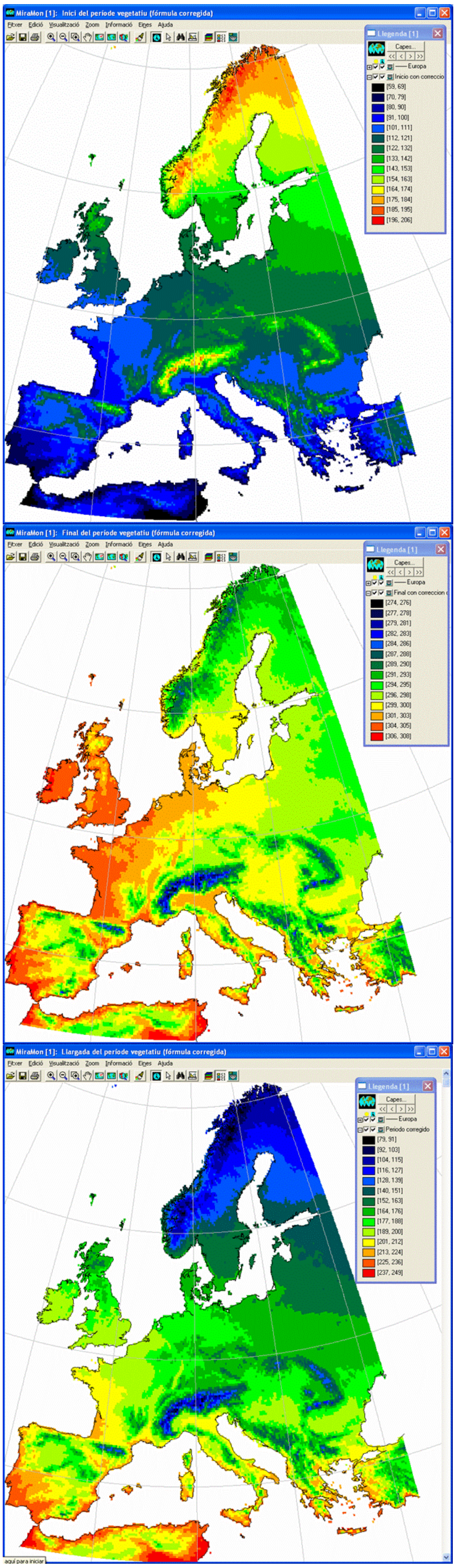

Figura 3. Geographical distribution of the dates (julian day) of start (top), final (center) and total length (bottom) of the growth period in year 2080 of european forests simulatd using the process based model GOTILWA+.

precipitation in the south of Europe (up to 20 per cent drier), particularly in summer. This reduction predicted for south Europe can have severe effects as, for example, the increase of frequency and intensity of the drought periods which in turn will affect water resources, forestry and agriculture. In the Mediterranean region, water scarcity would likely be aggravated by higher extractions per capita for irrigation and tourism (World Tourism Organization, 2003).

Mountain forests in the Mediterranean also seem to be vulnerable because of a rise in the elevation of snow cover and altered river runoff regimes. Mediterranean and Mountains species are disproportionately sensitive to climate change as it has been corroborated with recent observations (Walther G.R. et al. 2002) and projections (Gottfried et al. 1995). In a recent study (Gracia, 2007) simulations of forest growth in Europe with the GOTILWA+ process-based model (Gracia 1999, http://www.creaf.uab.es/gotilwa+/) predicts an enlargement of the length of the growth period by the year 2080 of 50 days for the Mediterranean region (60 in the case of Portugal) and, by contrast, only 33 in the Scandinavian countries. This enlargement of the forest activity will imply a greater water demand while the climate projections predict less precipitation (figure 3).

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