Securing water for trees and people: possible avenues

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Securing Water for Trees and People: Possible Avenues

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In the context of water scarcity, threats on forest survival in drier areas, and thus of inevitable trade-off between man and nature for the use of water, this section addresses three main questions of importance for foresters and land-use planners:

a) Can vegetation (upper- and understorey) management techniques in existing forest ecosystems reduce water stress for trees?
b) Can vegetation management and land-use planning increase the availability of blue water and green water for other uses than the forest?
c) To what extent and in what conditions can green water be directed to tree plantations?

Forests are needed for securing the provision to society of diverse goods and services, such as soil protection and water quality, which are both related to the canopy structure. Physiologically speaking, tree canopy and fine roots are the most active parts of trees, and thus any management regime of forest ecosystems must be based on a deep understanding of the functioning of both components and their responses to different silvicultural treatments. Sapwood is also essential as it relates roots to canopy and is highly dependent on silviculture.

In most cases, the structure of Mediterranean forests is influenced by a dense population of trees with moderate or small diameters. For centuries, exploitation has left behind stunted stems with a strong resprouting capacity in some cases. Under critical environments, this is at the origin of the very dense populations of small trees with very low growth rates due to: i) the lack of water availability combined with a high potential evapotranspiration characteristics from the Mediterranean climate; and ii) the higher respiration rates per unit of biomass or wood volume associated to the coppice structures as compared with the respiration rates of more “mature” population structures.

At the same time, it is now well accepted (see sections 2.1, 2.2) that forests are net water consumers. Most experimental studies have shown the high transpiration levels of forest ecosystems and the direct effects of forests on the reduction of water yield and stream flows. In energy limited continuous cover forests, – forests in which water availability is higher than potential evapotranspiration (PET) – the annual transpiration is very close to this PET, while in water limited forests, as it is the case in most Mediterranean forests, the annual transpiration can account for a high fraction of annual rainfall. Up to 90% has been recorded in *Quercus ilex*.

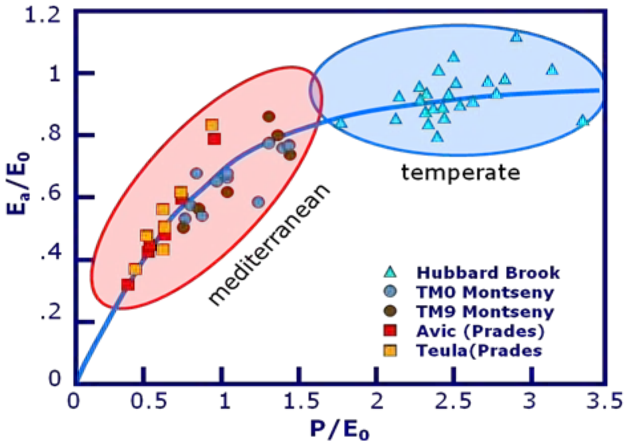


Figure 40. In Mediterranean forests with an effective rainfall lower than the potential evapotranspiration, the actual evapotranspiration is only a fraction of potential evapotranspiration; in other words, the forests grow under water-limited conditions. In boreal or temperate forests where precipitation is higher than the potential evapotranspiration, the actual evapotranspiration equals or is very close to the potential evapotranspiration. These environmental characteristics are the bases of important differences in the ecophysiological responses of water-limited and non-water limited forests. Source: Piñol, J. et al. 1999.

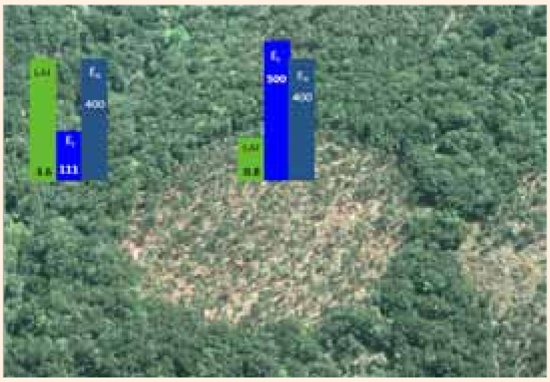
Two questions thus arise: i) Can adequate forest management and planning techniques reduce the water stress undergone by trees and contribute, at least, to the survival of forest stands? ii) Can adequate forest management and planning techniques be useful to reduce water use by forests and/or enhance water-use efficiency (less water is used to produce biomass)? Answering these questions is not an easy task. Some understanding of the water requirements of the tree for different functions and how the water limitations can affect these functions is needed. It is well known that the amount of water directly involved in photosynthesis is almost negligible and that most of the water is transpired through the stomata at the leaf level. Nevertheless, the role of this transpiration is crucial for the tree. The water transpired is the vehicle that carries nutrients on from soil, and the loss of this water through the stomata is the mechanism for up taking carbon by leaves, among other important physiological roles.

In most Mediterranean forests, potential evapotranspiration is much higher than precipitation – trees cannot achieve the potential rates of transpiration due to the lack of water (Figure 40). In these conditions, the reduction of LAI (e.g. by removing some trees) does not lead to a proportional reduction of transpiration. The remaining trees can use much of the water not used by the cut trees (see Box 10). Nevertheless, despite this lack of apparent response in the amount of water transpired, there are some positive side effects as the thinning improves the survival of the remaining trees.

In Mediterranean conditions, the reduction of LAI (e.g.: through thinning) does not reduce the total transpiration since the remaining trees use much of the water not used by the cut trees. As a consequence, the remaining trees have a better survival.

If a less dense population transpires the same amount of water, each tree transpires a higher proportion of water, which can result in less water stress experienced by trees during extreme drought conditions. The problem can be addressed as a cost-benefit analysis between the reduction of tree density and the increase of survival capacity of the remaining trees in future severe drought conditions. To carry out the correct analysis, one has to know how much water a tree of a given species uses to survive, and how this water is used by the tree.

Box 10. Experimental manipulation in the *Quercus ilex* forest of Prades, Spain. The forest has a coppice structure with a very high density of resprouts, which was reduced in different intensities in replicated experimental plots. Source: Gracia et. al. 1999.



The figure on the left shows the result of applying one of these thinning intensities on the transpiration rates (values are the average of three replicates): the leaf area index was reduced from 3.6 in the control plots to 0.8. The transpiration on a leaf area basis (EL) increased from 111 l/m2 of leaf/year to a value of 500 l/m^2 of leaf/year. Nevertheless, the transpiration on a ground area basis (EG) remained constant at a value of 400 liters/m2 of ground/year, which represents 84% of the total precipitation in that particular year.

Two years later, a very dry period of more than eleven months with less than 300 mm of cumulated rainfall caused an intense dieback of an important fraction of the trees in the control plots. The trees in the thinned plots (left) which transpired the same amount of water but distributed among a reduced number of trees, kept the water potential in better conditions than the trees in the control plots; also, no dieback was observed despite the almost total recovering of the previous values of leaf area index (see also Box 11).

The ratio between water used *per* actual or new produced biomass is easier to understand with an example related to the forest in figures in Box 10. Four years after thinning, the density of trees on the experimental plot was 2,000 trees/ha with a basal area of 36.4 m^2/ha. From the annual precipitation of 580 mm, the trees transpired 490 mm or 84% of total rainfall. The average tree in this population transpired 2,450 liters of water. Box 11 summarises the amount of carbon required to maintain the leaves in the canopy, the wood and bark from stems, coarse roots and branches, and the fine roots. This maintenance requires some carbon, which is respired to provide the energy needed to repair or replace the molecules of different compounds needed to keep the functionality of leaves, fine roots and the living cells present in the remaining tissues of the tree.

In addition, some new leaves and fine roots have to be formed to replace the losses and to grow. In the formation of new tissues and the maintenance of the previous formed, the carbon fixed in photosynthesis is involved (carbon represent the 50% of the dry weight of the plant) and this carbon is fixed at the cost of a huge amount of water transpired (see section 3.2). The data in Box 11 summarise the amount of carbon required by the mean tree in the population to maintain and form the different components of its structure, as well as the water required to fix this carbon. It is evident that

Box 11. Water used by a *Quercus ilex* tree

The table below summarises the use of water in the thinned plot of Box 1 four years after thinning. The tree density is 2000 trees/ha. LAI (3.10) was almost totally recovered (see the picture on the right in Box 10). In these conditions, from the total annual precipitation (580 mm) the trees transpired 84% or 490 mm; or 2,450 liters of water per tree on average.

The table compares the cost of maintenance and formation of leaves, fine roots and wood and bark components of branches, stem and coarse roots both in terms of carbon and in terms of transpiration needed to fix this carbon. On an annual basis, the forest transpired 301 liters of water per each gram of carbon fixed.

	Biomass	Annual production	Annual respiration (gC/tree)		
	kg/tree	kg/tree/year	Maintenance	Formation	Total Cost
			grams of Carbon /tree/year		
Leaves	2.72	1.13	3536	833	4,,369
Bark and Wood*	91.00	2.10	739	1,544	2283
Fine roots	0.40	1.30	514	956	1,469
TREE			4,789	3,332	8,121
			liters of water/tree/year		
Leaves			1,065	251	1,316
Bark and Wood*			223	465	688
Fine roots			155	288	442
TREE			1,442	1,004	2,446

*(including coarse roots)

To maintain and form leaves, the average tree (see table above) requires the leaves to transpire 1,316 liters of water to fix 4,369 grams of carbon, making foliage the most expensive water component of the tree. Bark and wood requires 688 more liters of water and the fine roots, which are renovated several times per year, 442 liters. In total, 2,446 liters of water is transpired per tree annually. The maintenance cost requires 1,442 liters of water per tree or 288 mm in total. Given that transpiration represents 84% of annual precipitation, the 288 mm of transpiration represents 343 mm or 64% of the total annual rainfall.

just to maintain the tissues present on the tree, 1,442 liters of water are required (equivalent to 68% of the annual rainfall); this maintenance does not compensate the leaves and fine roots losses which have to be replaced with the formation of new ones.

Keeping trees alive, even without biomass increment, may result in a huge cost in water, in particular for evergreen species common in the Mediterranean.

These results, however, must not be generalised. Water-use efficiency can differ among tree species (see section 3.3): different tree structures or population densities that can be modified by pruning, thinning or other silvicultural practices can modify the resulting values; however, this example shows the enormous amount of water involved in the functionalism of a forest. It also makes evident the severe risk that the reduction of precipitation projected by most Global Circulation Models in southern Europe, North Africa and other areas in the world represent a threat to the survival of some forests, at least

Box 12. Water used by a *Pinus sylvestris* tree.

The following table summarises the use of water of the average pine tree in a forest with a density of 800 trees/ha, with a basal area of 36 m2/ha and a LAI of 1.4, lower than *Q. ilex* LAI in the forest of Box 11. In these conditions, from the total annual precipitation (634 mm) the trees transpired 68% of precipitation or 430 mm; or 5,378 liters of water per tree on average (in this case the average tree is 24 cm in DBH, bigger than the holm-oak trees in Box 11). The table compares the cost of maintaining and forming leaves, fine roots as well as the wood and bark components of the branches, stem and coarse roots both in terms of carbon and in terms of transpiration needed to fix this carbon. On an annual basis, the forest transpires 350 liters of water per each gram of carbon fixed.

	Biomass	**Annual production**	**Annual respiration (gC/tree)**		
	kg/tree	kg/tree/year	Maintenance	Formation	Total Cost
			grams of Carbon /tree/year		
Leaves	3.25	1.06	2,600	781	3381
Bark and Wood*	326	2.90	9,403	2,131	11,534
Fine roots	0.13	0.45	104	328	432
TREE			**12,107**	**3,240**	**15,347**
			liters of water/tree/year		
Leaves			911	274	1185
Bark and Wood*			3,295	747	4,042
Fine roots			36	115	151
TREE			**4,243**	**1,136**	**5,378**

*(including coarse roots)

To maintain and form leaves, the average tree (see table above) requires the leaves to transpire 1,185 liters of water to fix 3,381 grams of carbon. In these trees, bark and wood are the most expensive components due to the bigger proportion of sapwood when compared to holm-oak. These tissues require 4,042 more liters of water and the fine roots – which are renovated 3.4 times per year – 151 liters. A total amount of 5,378 liters of water is transpired per tree annually. The maintenance cost requires 4,243 liters of water per tree or 339 mm. Given that transpiration represents 68% of annual precipitation, the 339 mm of transpiration represent 498 mm or 78% of the total annual rainfall.

with the structure they have at present. This threat is particularly severe for those forests living in environmental conditions, in which the annual rainfall is lower than the PET – as it is the case for Mediterranean forests previously discussed. In these water limited conditions – especially in those areas in which climate models project severe reductions of precipitation – it is crucial to analyse the cost in terms of water of the forest and evaluate the physiological benefits of reducing the density of tree populations. This task is particularly urgent in Mediterranean species with a very high density of resprouts. Some recent observations make evident the dieback of various tree species in some Mediterranean forests after just three consecutive dry years with rainfall far below the average.

Nevertheless, there is still some room to mitigate water loss from forests through silvicultural practices, although there remains a great need for research in this area. A few examples of potential applications of new research findings are given below.

Water-use patterns in natural eucalypt forests in which the canopy structure varies greatly between irregular old-growth (with “windbreak” trees) and even-aged regrowth (without windbreaks), offers some hints that water use may be reduced by modifying the canopy structure. Thus it seems possible that internal “windbreaks” within a plantation could create a water-wise forest similar to an old-growth forest. The number and

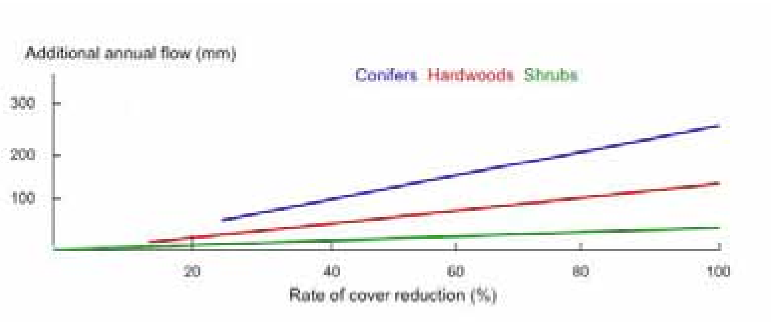


Figure 41. Impact of forest cover reduction (%) on additional annual flow (mm) within the five years following the cut. Source: Bosch and Hewlett 1982.

layout of windbreaking trees required within a plantation to quench thirsty regrowth remains an interesting research question. Careful species selection may be needed to ensure that water savings are achieved with internal windbreaks and ensure that they do not merely simply swap one problem for another. Species differ greatly in their ability to control stomata – with some species maintaining a very frugal water balance while others remain at the mercy of the elements.

One way to modify water use through the structure of the canopy is through the boundary layer that influences how the air near the trees mixes with the upper atmosphere. Even-aged plantations have a very different boundary layer than mixed-species plantations and old-growth forests, which is reflected in their water use. Canopy texture is important because it affects the aerodynamics, especially the turbulence and the boundary layer. Fortunately, it is relatively easy for forest managers to manipulate the canopy texture through species selection and thinning regimes. However, many plantations are relatively small, and edge effects are important. It is clear that unproductive transpiration can be reduced by softening plantation edges through pruning and thinning, by avoiding unnecessary breaks in the canopy and possibly with hedges to create more aerodynamic edges.

There is evidence that mixed-species stands offer hydrological as well as other benefits. Some studies report greater production efficiency (ratio of transpiration:assimilation) in mixed species plantings compared with pure stands. Pure *Acacia mearnsii* achieved 1,406 (± 302) m^3 of water/ m^3 of wood, but improved to 882 (±98) m^3 of water/ m^3 of wood when mixed with *Eucalyptus globulus*. It seems likely that the different statures exhibited by these two species helped to create this effect, as the eucalypt tends to be tall and narrow, whereas the acacia tends to be shorter and broader, offering a mutual benefit: the taller eucalypts provide shelter for the acacia, and the leguminous acacias provide nitrogen for the eucalypts.

In the Mediterranean environment constrained by water limitations, only drastic changes in the forest cover beyond the limits of classical thinnings might result in an increase in blue water.

As mentioned earlier, forests are in general net consumers of water and hence negatively influence the annual water yield, even if their cover may have a beneficial impact on flow seasonality. Hydrological studies have shown that the large watersheds are not suited for investigating the relationships between land use and water yield as well as the experimental paired watersheds because the interpretation of the results raises many problems. Our available knowledge is based on experiments, planned or carried out in small catchments. The forest cover manipulations in the catchment relate to clear or partial cut, afforestation of bare land or fire. A literature review carried out on 94 catchments has shown that the additional flow related to the rate of cover reduction can be significant, but only above a threshold of about 20% to 30%. This additional flow ranged from a few per cent up to 20% of the annual rainfall. The amount of this additional flow was also proportional to the rainfall. The relative flow increase, in regard to the annual rainfall, for different cover types: conifers, hardwoods and chaparrals was respectively in a range of 10% to 20%; 0% to 20%; and 5% (after chaparral removal). For chaparrals, whose occurrence is situated in dry areas (usually below 600 mm), the flow increase would amount only 30 mm even after a drastic modification.

These data suggest that the impact of classical silvicultural treatments like intermediate or moderate thinnings on an increase in water yield is small or non existent. This is even truer in water-constrained environments like in the Mediterranean. These results are also consistent with those discussed above, showing that the surplus of water generated by the thinning in a Holm oak coppice is entirely consumed by the remaining trees. One can conclude that only drastic modifications of the forest cover, such as its partial or full conversion to other land use, may result in a significant increase of water yield.

The question of a drastic change in forest cover, and thus of land use, in order to increase the production of blue water downstream deserves much attention and should integrate all goods and services related to the initial cover. Soil erosion, inter alia, is a major threat in the Mediterranean (see section 1.5) and should not be underestimated. Changing partially or totally the forest cover in a catchment into other land-uses can be also envisaged. It amounts to redirecting green water flow from forest trees to other plant cover: fodder in rangelands, crops in fields, agroforestry systems, etc. It also requires a thorough assessment of the pros and cons.

Box 13. Negotiating a reforestation project in Tunisia

During a 1998 participatory appraisal exercise in the poverty-stricken hilly areas of Zaghouan Governorate in Tunisia, participants from the surrounding douars (villages) expressed serious concerns about the restrictions imposed by a new mechanised reforestation project covering the hilltops of the Sidi Salem forest (410 ha). Before the project, local communities viewed the public forest as their free grazing area, where they also collected fuel wood and medicinal herbs. Reforestation involved bulldozing and replanting the whole area with Aleppo pine in fenced plots. Traditional uses of forest products were banned until the commercial wood had been sold to outside traders after a nine-year rotation period. Local communities, therefore, perceived the programme as a threat to their customary rights.

To address the issue, project staff met with local representatives and the Soil Conservation and Forestry Services. The aim was to identify possible measures that would be technically and economically acceptable to the line agencies, while answering local needs. The joint final proposal included the following measures: i) replacing Aleppo pine with fast-growing fodder and honey producing tree species on gentle slopes so as to reduce the deferred grazing period; ii) extending the firebreak network to make the upper forest zone accessible to livestock; and iii) setting aside the steeper sections for Aleppo pine and covering the rest with fodder species plots.

The agreement also mobilised community participation in the project's implementation through initiatives such as: i) contracting local interest groups to prepare and maintain plantations; ii) establishing pilot plots to test the introduction of local fodder species; iii) creating a local forestry association to be responsible for forest management as required by Tunisian law; and iv) providing microcredit for buying improved stoves that consume less fuel wood.

Following discussions and negotiations on cost-sharing and reciprocal obligations, all activities were integrated into the action plans of the concerned douars and line agencies without any increased costs for the project.

Source: FAO 1997.

Box 14. An example of a payment for environmental services (PES) in a Tunisian watershed

An illustrative example of potential PES scheme can be drawn from the management of the Barbara watershed in north-western Tunisia. Most land is privately owned and cultivated with cereals. In order to protect the downstream water infrastructure, the government gives large subsidies (80% of the investment costs) to protect gullies using acacia plantation and/or check-dams. However, these subsidies are not conditional and the landowners are not compensated for expenses and lost income from grazing resources. Consequently, the survival rate of acacia is quite low. The economic analysis of different land-use alternatives showed that all the protection measures are less profitable for farmers than producing cereals alone; only one cereal with the acacia plantation in gullies seems to be profitable from a national perspective. In order to encourage acacia plantation in gullies, farmers should be compensated for any loss of income incurred (100 TND/ha). This compensation could be covered by the reduced cost of sedimentation (200 TND/ha). The payment by water users could increase the budget available for conservation, contribute to a more efficient use of water and could increase the survival rate of acacia because payments would be conditional to success indicators.

The question of a drastic change in forest cover to increase the production of blue water downstream deserves much attention and should integrate all goods and services related to the initial cover.

Planting trees in a context of overall water scarcity should take into account not only the multitude of marketed and non marketed goods and services that could be provided, but also the large number of stakeholders at local and national levels who could be affected and who have different and divergent perceptions regarding forest plantation and the use of natural resources (Box 13).

Upstream users can benefit from the direct uses of forest plantations, while downstream users of water resources would be affected by the effects of land management change upstream on the quantity and quality of the water reaching the reservoir.

While public administration is more concerned by soil and water resources protection and economic development, the private owner is interested in the short-term private benefits of the plantation. Also, the local population who live in forest areas, especially in southern and eastern Mediterranean countries, would like to maximise its private income for the current use of natural resources in the short term. Another distinction could be made between the upstream and downstream users. Upstream users can benefit from the direct uses of forest plantation, while downstream users of water resources would be affected by the effects of land management change upstream on the quantity and quality of the water reaching the reservoir. This mixed characteristic of forest services and their scale dimension stress the critical trade off between watershed protection and the local benefits for forest owners or local users. The situation is still more complex given that some land-use changes can have non-reversible effects on the development of forests, at least in the short term.