Breckle S.-W. & M.. Küppers (2007): Water conserving plants for agriculture in arid and semi-arid areas. In: Lozán, J. L., H. Grassl, P. Hupfer, L. Menzel & C.-D. Schönwiese. Global Change: Enough water for all? Wissenschaftliche Auswertungen, Hamburg. 384 S. Online: www.klima-warnsignale.uni-hamburg.de

4.9 Water conserving plants for agriculture in arid and semi-arid areas

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***SUMMARY** - Nutrition of mankind relies on very few major domestic plant species conventionally grown in moderate climates. In hot and dry areas or at low water availability such species or varieties become essential that exhibit higher drought and heat resistance. Since their productivity always depends on a combination of highly variable abiotic (environmental, technical) as well as biotic factors, it is the search for the best combination of all of these factors that leads to optimum yield: High water-use efficiency (WUE) and carbon partitioning are species-specific key characters. For the latter it must be taken into account that commercially useful yield may constitute only a small fraction of overall plant-specific biological productivity despite a high WUE. Use of irrigation water in arid areas is unavoidable, therefore irrigation techniques keeping salinity low (by applying leaching and drainage systems) and minimising evapotranspiration are the other pre-requisite for sustaining productivity. An adequate combination of special land use techniques (minimising waste of water) with the cultivation of drought and heat resistant genotypes can potentially result in more productive and yet sustainable agriculture even in hot and dry regions.*

Nutrition of mankind is based on an astonishingly low number of agricultural plants. In the course of a few thousand years of cultivation especially grasses yielded important plants for food: rice, wheat, barley, rye, millet, sugar cane. Including the most important vegetables and fruits the total number of agricultural species will rise to just 100–150, which is relative to 300,000 described flowering plants on Earth a very minor percentage. Of those commercial plants almost none originates from dry areas despite the fact that a large fraction of the land surface is (semi-) arid.

Although first agricultural settlements in the stone age started under the semi-arid conditions of the »Fertile Crescent«, today the largest agricultural productivity is found in temperate regions, likely for two reasons: Here water is locally and reliably available and, secondly, almost no agricultural species have been successfully selected for growth in dry areas. Rising populations especially in areas of critical water availability and long droughts challenge new efforts in agriculture, e.g. concerning new varieties of agricultural plants and improved cultivation techniques. Highly productive, heat and drought resistant plants of low water consumption are an essential prerequisite for future successful agriculture in such areas.

Basic biological requirements of biomass production and yield in commercial plants

Plant growth and productivity depend on a variety of environmental parameters: sufficient plant available water, optimum temperatures, sufficient nutrients, sun light (radiation energy), protection against parasites and herbivores. On the other hand growth is a species-specific characteristic strongly affected by the plant´s life form: For example, despite identical initial biomass of 0.5 g of a beechnut (*Fagus*) and sunflower seed (*Helianthus*), the beech seedling will produce just 5 g after 4 months at an 80 cm deep running tap root whereas the sunflower reaches 3 m height at 6 kg total biomass. While the sunflower dies in autumn beech continues to grow over many decades finally building up tons in biomass. This strongly emphasises the tremendous significance of species-specific investment of assimilates from photosynthesis into plant organs and its potential accumulation over long periods. Because of this the »individual productivity« is much higher in beech, but based on hectar and year it is significantly higher in sunflower.

Of decisive economic interest is, depending on the respective yield type, the production of specifically useful plant parts: Those could be seeds, fruits, roots, leaves, stem wood (in case of trees). However, those are inevitably only a fraction of total biomass production. In the case that assimilates from photosynthesis are immediately re-invested by the plant into new, additional leaves, thus, new productive organs, it will create a large compound interest effect with exponential and, therefore, rapid biomass gain in a short period, even when photosynthesis rates per unit of leaf area are low. If photosynthesis rates are in addition high – as is the case in sunflower – biomass growth will be even more enhanced. Grain yield often is in parallel enhanced – but not necessarily!

Concerning drought and temperature resistance of plants their ecophysiology is most important. A key parameter is water-use efficiency (= WUE) calculated as photosynthetic productivity per simultaneous water consumption: How many molecules of water are transpired when one molecule of CO_2 is assimilated in photosynthesis? It is difficult to precisely determine this

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parameter for it strongly depends on time-scale (whether integrated over an hour, a day, vegetation period or a year) and, secondly, of complexity (whether looked at a single stomatum, leaf, total plant or 1 ha of cultivated or forested land); unfortunately also the significance for the optimisation target of a high WUE varies with these scales, so that changes in scales and up-scaling (leaf, total plant, planted area) become highly important: Those are simultaneously a plant-inherent and a farming technological phenomenon, often neglected but offering a large potential for optimisation, which is by far reaching further than tested molecular-biological chances of improvements.

To illustrate this we composed, deduced and estimated (mean) values from the literature. The molar water-use efficiency of leaf photosynthesis in the very moment of diurnal carbon gain (»instantaneous WUE« in mol CO_2/kmol H_2O) amounts approximately 5 in beech and 2 in sunflower. Obviously, sunflower transpires water in the light phase of the day much more consumptive than beech (data from Fredeen et al. 1991 and Stickan et al. 1991).

Leaves like other organs also consume assimilates in respiration. WUE on the leaf level integrated over the day as a whole (in beech 4, in sunflower 1.5) or over the entire growth season (beech 3.4, sunflower ca. 1; after Fredeen et al. 1991 and Schulze et al. 1986) must be, therefore, lower; additionally periods of suboptimal climatic conditions (e.g. cloud cover) lower this value.

When in the next consecutive step scaling up to the whole plant carbon losses from respiration of non-green tissues (e.g. in twigs, stem, roots) further diminish the value. This new molar efficiency of water use – which is the (annual) biomass production per consumed water of the entire plant individual – is also called »transpiration efficiency« (= W). In an 8-year-old beech (Lyr et al. 1992) it amounts to 3.6 mol CO_2/kmol H_2O (dry matter converted into CO_2 equivalents), in sunflower 2.4 (young plants) and 1.0 (when flowering; after Larcher 2001).

Naturally a high-performance commercial plant should exhibit an extraordinarily high WUE and W; additionally it should allocate a very high fraction of assimilated carbon into its commercially usable parts. However, fractions of fruits, leaves, shoot axes and roots of total dry matter differ both species- and site-specifically, and they indicate »standing crop« only. The true investment of assimilate into a certain plant part (»carbon partitioning«, CP) is very difficult to quantify and therefore almost never given in the literature (but see e.g. Küppers 1994, Timm et al. 2004 for non-commercial plants); it is the annual balance of assimilate flows from and into certain organs expressed as % of total annual plant carbon gain from photosynthesis. It may result in entirely different allocation values than those deduced from »standing crop« dry matter partitioning, since it accounts for respiratory carbon losses, accumulation of biomass at constant investment (e.g. during stem formation) or high losses in biomass due to high turnover rates of certain organs (e.g. leaf production after litter fall, fine-root production). In deciduous woody plants the true assimilate investment into leaves amounts 10–20% (e.g. Küppers 1985) while their dry matter fraction is only 1–2%. In the woody trunk of trees up to 70% of »standing crop« biomass have been accumulated while in herbs the main shoot often contains much less biomass than leaves and roots. Plants growing in dry areas have to invest a much larger fraction of their annual carbon gain into a far-reaching efficient root system. The ratio of above- to below-ground biomass in plants from steppes and deserts is, therefore, strongly shifted towards their root systems. They grow slower since the totally leaf-dependent »compound interest effect« is much lower in their cases. In *Table 4.9-1* examples of total phytomass production per ground area, the so-called net primary production (= NPP; respiratory losses accounted for) are given.

Commercially only a certain plant part or organ is of interest for harvest which is, in general, only a small fraction of total plant production. This fraction is

Table 4.9-1: Annual net primary production (after Jones 1992, Larcher 2001) per ground area in t/(ha·year) and root-to-shoot ratios (in kg/kg of »standing dry matter«, from several sources).

	Annual net primary production	***root/shoot ratios***
	In 360 days = 1 year (vegetation period)	
Desert	0.03–0.2	0.02–2
Meadow (temperate region)	5–20	2–5
Sugar cane plantation	25–75	5–20
Temperate deciduous forest	4–25	5–20
	In 120 days (vegetation period)	
Potatoe	15	2–5
Rice	30	15–30
Cereals	20	5–20

frequently quantified by the harvest index (HI) giving the amount of intended harvest product relative to NPP. Depending on the targeted product HI can be entirely different even within the same plant species. If e.g. sunflower seeds are the intended product then HI is 5–10% of NPP, while for oil from these seeds HI is only 1–2%. If total biomass of the sunflower plant is used for silage fodder then HI may reach 92% of NPP. Obviously HI must be exactly defined. In beech HI for harvestable wood is clearly much higher than for beechnuts. However, stem wood can only be harvested once, beechnuts in every mast year, while sunflower – an annual plant – must be newly sown every year.

An important future aspect may be the utilisation of large agricultural areas for production of biological engine fuel (Vorholz 2004). If this pays energy-wise is still to debate. If it is not only used the fraction of a plant organ (e.g. oil production from rape oil), but the total plant biomass is harvested, then HI = 100%.

All parameters looked at so far (WUE, W, CP, NPP and HI) are eco-physiologically important but do not tell us much about potential production of a given agricultural field. Here the hectar-based yield is the appropriate parameter. Grain yield in sunflower amounts to 0.4 to 3.2 t/(ha·year), in wheat to 3.5, rice 4.9 and maize 6.3 t/(ha·year). These data of Loomis (1983) and Schuster (1993) have been obtained at favourable growth conditions.

However, if agricultural production in arid regions is our concern then the amounts of plant available water (and its costs) become the limiting factors. It is NPP and HI relative to the invested volume of water which ultimately control the potential for agricultural success in dry areas. The most important parameter is, consequently, yield of a product relative to volume of consumed water. Here we may observe the paradoxon that a commercial plant or variety of a better W is doing worse than another plant concerning its yield/water consumption, and vice versa. Water consumption consists of two components: evaporation (where the plant is not directly involved) and transpiration (directly from the plant body).

Heat resistance of commercial plants and plant breeding

At high temperatures (above 42–45 °C) NPP and plant growth become strongly reduced by inadequate shifts in metabolic processes, gradual degradation of proteins (including those enzymes that regulate metabolism) and especially through an exponential increase in respiratory losses of CO_2 at declining photosynthesis.

One must consider that not air temperature (e.g. of 42 °C) is decisive but the temperature inside a leaf which may be 10–15 °C higher (if no wind). Limits of heat resistance (see *Table 4.9-2*) are then easily reached. Additionally heat increases water losses from plant and soil and enhances drought effects. Of course cooling effects of transpiration play a certain role but always demand for sufficient available water.

Depending on a commercial plant´s origin one should expect different optimum and tolerable maximum temperatures of metabolic processes and growth, which are closely related to species-specific thermal stability of cell structures (membranes, organelles).

Therefore special attention has been paid to proteins protecting against heat shocks, so-called »chaperones«. They are synthesised when already supra-optimal temperatures further rise rapidly, and they generate heat resistance by protection of enzymes and membranes. In general plant genomes have about 20 genes of chaperones available which are very precisely regulated (Wandtner 2002). In the future such an induced thermo-tolerance may become important in plant breeding by introducing these genes into genomes of commercial plants. However, transpiration cannot be altered this way for it is exclusively driven by physical factors. Here effects of (self-) shading in order to reduce leaf temperatures are a similarly important optimisation target in plant breeding which can e.g. be realised by variation in leaf orientation.

Drought resistance of commercial plants and plant breeding

Besides breeding for better heat tolerance the improvement of drought and salt resistance is similarly important. Over the last decades conventional plant breeding produced a large variety of new rice cultivars (Smil 2000) better coping with the variable environmental conditions of different countries. Nevertheless, again it has become clear that not only new varieties but also improved agricultural knowledge and techniques have strongly contributed to increase harvest yields, e.g. by taking shorter growth periods and better rotation systems (up to 3 harvests per year) into account. For this a larger number of adequate commercial plants will be needed in the future.

During the 20th century grain yield of wheat – a crop adapted to temperate environments – could be strongly increased, despite constant NPP, by breeding of new varieties of higher HI (which could be achieved by reducing carbon investment into the main shoot, thus resulting in smaller plants). For this success there is also good hope to breed more drought resistant wheat varieties although their grain yields are expected to decrease. In contrast to wheat is the strong increased productivity of maize especially in the USA, which results from new varieties growing at higher plant densities (Grefe 2004); however,

Table 4.9-2: Heat resistance of leaves of higher plants originating from diverse climates (50% injury after half an hour´s heat treatment) (from Larcher 2001).

Tropical trees	45–55 °C
Herbaceous mesophytes	55–60 °C
Subtropical palms	55–60 °C
Grasses from steppes	60–65 °C
Succulents	58–67 °C
Aquatic plants	38–44 °C
C4-grasses	60–64 °C
Broad-leaved-boreal-trees	42–45 °C
Winter-deciduous trees	um 50 °C
Needle-leave-trees from the taiga	44–50 °C

in dry areas not sufficient water will be available to cultivate those. Irrespective of this breeding for altered CP still offers a large potential for improvements. Since the 1930s HI in most maize varieties has been not larger than ca. 0.5 (sugar cane 0.85). Obviously, HI is a relatively constant transmissible value, which, however, declines strongly under all kinds of stress.

As an example of a drought and simultaneously heat resistant plant the millet and other tropical grasses (e.g. *Sorghum bicolor*), C4 grasses, can be seen. It is the most important millet grass and – on global scale – an economically important plant (*Fig. 4-9.1*). It originates from equatorial Africa and is nowadays cultivated in all warm areas. In southern USA the area where it is cultivated has doubled within 45 years; at the same time its grain yield increased 4-fold. This grass species transpires little and can remain in kind of a latent survival state (with no growth) when under extreme water stress, regaining growth soon after rain. In Africa and Asia it produces in the mean 0.98 t of seed/ha, while in the USA – thanks to breeding of new hybrids – this amounts to 4.2 t of seed/ha, on well watered and nourished sites even to 10.0 t/ha.

It might be also useful to look for new wild plants from nature from deserts and arid areas for inbreeding purposes. However, we have to keep in mind, that desert plants have not evolved growth strategies for high productivity, but simply for survival under adverse conditions.

Fundamentals of agriculture in arid regions, irrigation in cultivation and the risk of salinisation

In arid regions huge areas are short of water due to high temperatures and low soil moisture. Because of the very low precipitation and high evaporation rates from soils these are generally and continuously threatened by salinisation. Only solar radiation as a prerequisite for NPP is excessively available. Despite this it is possible to cultivate crops in areas of predictable rain depending on the rainy season (e.g. in central Asia or the Mediterranean region) as it has been done since hundreds of years employing sophisticated methods (»runoff farming« e.g. to feed the Nabatean town »Avdat« in the Negev desert, 300 BC – 100 AD). However, run-off agriculture is very labour intensive at very low harvest yields per hectar, although efficiency of water use can be very high (»lalmi« type of cultivation in Afghanistan). Agriculture in dry areas, therefore, strongly depends on artificial watering.

Nowadays watering systems often reach an effectiveness of much less than 50%, which means that less than half of the invested water reaches the cultivated field or the roots of cultivated plants. In the utopian case China, India and Pakistan – representing half of the Earth´s agricultural area with artificial irrigation – would change from furrow irrigation to sprinkling irrigation or, even better, dripping irrigation, the demand for water of these countries would be more than completely balanced. We can conclude this when looking at required amounts of water for irrigation under the extremely arid conditions of Egypt (*Table 4.9-3*).

In arid areas – as indicated by the geomorphology of endorrheic basins missing an outflow to the ocean (e.g. Dead Sea, Aral Sea, Giant Salt Lake, Lake Tschad etc.) – potential evaporation strongly exceeds precipitation. All minerals imported (by rain, surface flows, leaching of rocks, wind) remain in the area, accumulate and result in natural salinisation. Unfortunately the same is true for irrigated fields. Assuming an annual irrigation of 1 m^3/m^2 (= 1,000 mm) at a NaCl concentration of 300 ppm in the water (which is fairly low: Euphrat 300–900 ppm, Nile: 200–400, Colorado: 600, Arkansas: 3.000 ppm) this will

Fig. 4.9-1: Sorghum bicolor from a field in China (Photo: SWBreckle).

inevitably lead to a gradual salinisation of the irrigated fields (Kreeb 1964). In our example after 10 years 3 kg $NaCl/m^2$ will have accumulated. At a specific soil mass of 1.500 kg/m^3 and a salt accumulation in the upper soil horizon (0–20cm) this results in a salt content of 0.1% after 10 years and of 0.3% already after 30 years. As many developmental projects of the past 30 years have proven, already a salt content of 0.3% will clearly reduce yield, especially when the classical wisdom »no irrigation without drainage« has been neglected for purpose of saving money: This rule will gain further importance when waste water from settlements with a higher salt load will be recycled in irrigation to supplement precipitation.

Sophisticated cultivation techniques which minimise evaporative losses of water will strongly help to increase agricultural water-use efficiencies. Below-ground dripping irrigation, concealing the soil with plastic sheets, lava pebbles (Teneriffa) or sand were locally successful. Costs of waste water (if available) used in irrigation could follow economic rules and may then result in entirely different optimisation parameters than just looking at cultivation techniques (e.g. when considering »trade offs«, cost-benefit-relationships, costs of labour, yield quality etc.; Breckle 2003). Also optimised stand structures (shade producing trees, optimised self-shading) strongly help to reduce evaporation (shading the ground produces lower soil temperatures) and transpiration (dynamic light as generated by the plant itself reduces leaf temperatures; Roden & Pearcy 1993) at identical photosynthetic carbon gain (Kirschbaum et al. 1998). Obviously it is highly important to breed commercial plants which – at reduced transpiration (despite higher temperatures), improved WUE and W – produce higher yields at better HIs.

Final considerations and conclusions

Available agricultural technologies have already proven that large amounts of water can be saved in cultivation. Employing adequate plants in combination with technologies drastically reducing evapotranspiration are ways to minimise water requirements at optimal cultivation of commercial plants. Dripping irrigation as controlled by water consumption of the crop itself – like in Israelian farms – or the use of 10 cm high sand beds in which soil capillaries are interrupted (similarly covering the soil with volcanic slag in the banana plantations of Teneriffa) are among such technologies.

Collected water from evapotranspiration – like in special green house cultivation, plantation towers and foil tunnels – may be almost completely recycled for irrigation. In these cases harvest yields relative to water consumption are very high.

Table 4.9-3: Amounts of water (in m^3 per ha = 0.1 mm) consumed in Egypt for watering of several crops cultivated under different irrigation methods (after Springuel 2003).

Crop	*Furrow irrigation*	*Sprinkling irrigation*	*Dripping irrigation*
Wheat	1,850	1,060	
Horst bean	1,240		810
Maize	1,790		950
Sunflower	2,380		1980
Tomato	1,190		950
Grapes	500		380
Citrus	790		400

Future agriculture will be more and more confronted with the demand to increase its production but wiser adapted to diverse site and regional conditions. The potential to breed commercial plants of optimal light use at moderate water consumption is by far not fully utilised. However, our expectations should not be too great since in all cases successful cultivation of (new) heat and drought resistant crops will strongly depend on adequate field techniques. Inherently this requires the choice of an adequate plant variety or race for cultivation, optimal planting density and protection from high radiation in the stand, arrangement in rows, planting of trees for extra shading, introducing herbaceous ground covers, optimal watering by minimising evaporative water losses, the choice of the best growth period (e.g. using plants with short species-specific growth cycles) and site conditions such as slope, water availability, wind exposure etc..

Besides the demand for water any intensified agriculture will require extra fertiliser, especially nitrogen. Without the Haber-Bosch-technique to fix nitrogen from the atmosphere (unfortunately consuming large quantities of energy) agriculture of its present global productivity would not exist. The amount of N in fertilisers produced by industry has already reached the natural level of global N fixation (by nodule bacteria, soil microbes, discharging in lightnings etc.; Smil 2001). Therefore, future agriculture does not only have to consider optimal use of water for cultivation but also, inevitably, use of nutrients at high efficiencies.

A major problem is long transport ways and conduction of water over long distances. Cultivation of drought-, heat- and salt-resistant plants in arid regions will gain more and more importance in the future but it is only one aspect of the story. Agriculture can only be successful in the future when several of the indicated paths will be followed simultaneously ♦