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Strategies for Improving Water Productivity and Quality of Agricultural Crops in an Era of Climate Change

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1. Introduction

Climate change is one of the most serious problems facing the world today. The recent Intergovernmental Panel on Climate Change reports confirmed that climate change will have a significant impact on global surface temperature. The projections of IPCC are that the rise of the mean temperature will be as high as 6.4°C by 2100, while the concentration of CO_2 will be 1.3 times higher than it was 20 years ago. Furthermore, the number of extreme events, including heat waves, storms and flooding will increase (IPCC, 2007).

Climate change scenarios for Europe are that global warming resulting from anthropogenic greenhouse gas emissions (mainly carbon dioxide and methane) will lead to substantial temperature increases in Northern Europe during winter and in Southern Europe during summer. The especially vulnerable for future European summer climate would be the countries in South-East European and Mediterranean areas. Predictions of different scenarios of climate are that due to the expected increase in temperature and decrease in precipitation, drought would start earlier and last longer in these comparing to other European areas (Beniston et al., 2007). Some scenarios also predict the higher incidence of heat waves and extreme temperature in South East than in Central Europe (Hirschi et al., 2011).

Agriculture is highly sensitive to climate change and especially, to drought. The increase in temperature can increase duration of the crop growing season in regions with a relatively cool spring and shortened the season in regions where high summer temperature already limits production. Therefore, in the areas of water scarcity, the irrigation is necessary for successful agricultural production. Currently, due to the climate change impacts many countries are faced with the increased competitions for water resources between different sectors (agriculture, industry or domestic consumption). The clean freshwater becoming a limited resource and its use for crop irrigation is in competition with the demand for household consumption, as well as with the need to protect the aquatic ecosystems. Therefore, the challenge is to minimize the use of water for irrigation. Another problem is that water in many countries is seriously contaminated with either inorganic or organic pollutants, mainly from intensive animal production and urban areas. Uncontrolled use of contaminated waters (chemically or microbiologically) could have serious environmental and health implications. It is obvious that saving clean water, increasing agricultural productivity per unit of water ("more crop per drop") and producing safe food are becoming of strategic importance for many countries (Luquet et al., 2005).

The aim of chapter is to provide an overview of some of the current challenges and opportunities to minimize the problem of agricultural production under water scarcity. The focus will be on the two approaches: use of the deficit irrigation methods and use of genotypes with increased drought resistance and water productivity. Furthermore, the problems of the use contamination of water for irrigation will be briefly reviewed, as well the novel technologies by which low water quality could be used to improve water productivity and to ensure food safety and quality. The special emphases will be on the current efforts to create genotypes resistant to drought and thus to reduce the existing gap between potential crop yield and crop yield in drought conditions.

2. Climate change impacts on agriculture

Climate change models for Europe highlight a particularly worrying trend in terms of rising temperatures and decreasing precipitation. The mean annual precipitation will increase in Western and Northern Europe (from 5 to 15%) and decrease in Central, Eastern and Mediterranean Europe (from 0 to 20%), while the change in seasonal precipitation will vary substantially from season to season and across different regions. Besides the projected increase in the yearly maximal temperature, it is also expected a large increase in yearly minimum temperature across most of Europe. The increase of minimum year temperature in many areas is connected with an increase of temperature during winter period (Kjellström et al., 2007). Due to the effects of the summer temperature increase and reduced precipitation, the number of extreme events (heat waves, drought, storms) will also increase.

Although agricultural production is highly dependent on climate factors, the climate change is expected to affect agriculture very differently in different parts of the world. Furthermore, the climate change could produce positive or negative effects on agriculture depending on the region. The final effects on crop productivity and food safety depend on current climatic and soil conditions, the direction of change and the availability of resources and infrastructure in specific region or country to cope with predicted change in specific (Parry et al., 2004).

Increase in greenhouse gases can affect agriculture directly (primarily by increasing photosynthesis at higher CO_2) or indirectly *via* effects on climate (primarily temperature or precipitation). Of special importance is the increase of CO_2 concentration. Over the last century, atmospheric concentrations of carbon dioxide increased from a pre-industrial value of 278 parts per million to 379 parts per million in 2005. Most of the increase in carbon dioxide comes from burning of fossil fuels such as oil, coal and natural gas, and from deforestation. It is also certain that the accumulation of CO_2 and other greenhouse gases will cause a further increase in mean global temperature (IPCC, 2007). As a consequence of increased photosynthesis at elevated CO_2, dry matter production of C_3 plants is expected to increase more than in C_4 plants. C_3 plants are those that use the C_3 carbon fixation pathway in photosynthesis in which the CO_2 is first fixed into organic compounds containing three carbon atoms, while C_4 plants use C_4 carbon fixation pathway for producing compounds containing four C atoms. Reducing stomatal opening and thus transpiration, high CO_2 can have another direct effect on plants, and it could be expected an increase in water use efficiency (WUE) of C_3 and C_4 plants. Kimball et al. (2002) reported several experiments in controlled, semi-controlled, and open-field conditions, which have shown that a doubling of atmospheric CO_2 from 330 to 660 ppm may increase the productivity of C_3 species by an average of 33% at optimal growing conditions. The effects of CO_2 and other greenhouse gases depend also on their interaction with other environmental factors, especially drought. Results for potato showed that elevated CO_2 can only partially alleviate long-term whole plant responses to water stress (Fleisher et al., 2008). These results pointed out that the CO_2 "fertilization" effect cannot totally compensate for the negative effects of other environmental stresses.

In general, the effects of global change on Europe are likely to increase productivity of agricultural plants, because increasing CO_2 concentration will directly increase resource use efficiencies of plants, and warming will give more favorable conditions for plant production in Northern Europe. The sensitivity of Europe agriculture to climate change, especially drought, has a distinct north-south gradient and many studies indicating that Southern Europe will be more severely affected than Northern Europe. The particularly vulnerable to agricultural drought in Europe are Mediterranean and South-East Europe regions. In a lot of the countries of these regions, economic development is heavily dependent upon growth in the agriculture and, therefore, the climate change impacts on agriculture could have significant social consequences (EEA, 2008).

In Northern Europe increases in productivity and expansion of suitable cropping areas are expected to dominate, whereas disadvantages from increases in water shortage and drought will dominate in Southern Europe. The increased crop productivity in Northern Europe will be also caused by lengthened growing season, decreasing cold effects on crop growth and extension of the frost-free period. On the contrary, the expected decrease in productivity in Southern Europe will be the consequence of the shortening of the growing period, with subsequent negative effects on grain filling (Iglesias et al., 2009).

Climate change effects may reinforce the current trends of intensification of agriculture in Northern and Western Europe and extensification in the Mediterranean and South Eastern parts of Europe (Olesen & Bindi, 2002). Furthermore, the area of some of the crop's cultivations in Northern Europe will be expanding, especially for cereals. According to Alcamo et al. (2007) it is expected that increase in wheat yield related to climate change will be from +2 to +9% by 2020 and from +10 to +30% by 2080, while for sugar beet yield increase will be in the range from +14 to +20% until the 2050s. Study for Southern Europe predicted a general yield decreases (e.g., legumes -30 to + 5%; sunflower -12 to +3% and tuber crops -14 to +7% by 2050) as well as increases in water demand (e.g., for maize +2 to +4% and potato +6 to +10% by 2050). The same study showed that the impacts on autumn sown crops are more geographically variable; yield is expected to decrease in most southern areas, and increase in northern or cooler areas (e.g., wheat: +3 to +4% by 2020, -8 to +22% by 2050, -15 to +32% by 2080). Furthermore, predictions are that by 2050 energy crops (e.g., oilseeds such as rape oilseed and sunflower), starch crops (e.g., potatoes), cereals (e.g., barley) and solid biofuel crops (such as sorghum and Miscanthus) will show a northward expansion in potential cropping area, but a reduction in Southern Europe (Alcamo et al., 2007).

2.1 Drought effects

The increase of temperature or drought may have a significant impact on plant growth and productivity. At the whole plant and the crop level, the important repercussions of high temperature or drought stresses are mediated by their effects on plant phenology, phasic development, growth, carbon assimilation, assimilate partitioning and plant reproduction processes. These major effects account for the most of the variation in crop yield caused by drought stress. However, there is a large variability in stress sensitivity at different periods during the life cycle of a given plant or during an increase in stress duration and severity. For crop plants, stresses during the generative phase can have been much more dramatic effects on plant yield than the stress during the vegetative phase (Craufurd & Wheeler, 2009). Table 1 presents an overview of the growth stages that are most sensitive to drought in different agricultural crops.

Crop	**Stage of development**
Field crops	
Maize	flowering and grain filling
Wheat	flowering more than yield formation
Rice	head development and flowering
Soybean	flowering and yield formation
Sunflower	flowering more than yield formation
Sugarbeet	first month after emergence
Cotton	flowering and boll formation
Sugarcane	tillering and stem elongation
Tobacco	period of rapid growth
Vegetables	
Lettuce	head development
Pea	flowering and yield formation
Bean	flowering and pod filling
Carrots	root enlargement
Cabbage	head development and ripening
Cucumbers	flowering and fruit development
Potato	tuber initiation and enlargement
Tomato	flowering, fruit setting and enlargement
Pepper	flowering and fruit development
Fruit tree and grape	
Grape	vegetative period and flowering
Citrus	flowering and fruit setting
Olive	flowering and yield formation

Table 1. Stages of plant development that are the most sensitive to drought.

2.2 Water scarcity and contamination

Water is essential for high and stable yield of agricultural plants and in many areas modern farming would be impossible without irrigation. However, only a small proportion of the world cultivated area is equipped for irrigation. According to FAO (2003), more than 80% of global agricultural land is rain-fed and in these regions, crop productivity depends solely on sufficient precipitation to meet evaporative demand and associated soil moisture distribution.

Furthermore, most of the climatic scenarios predicted that climate change will have a range of impacts on water resources. A simulation study done by Eitzinger et al. (2003) predicted that groundwater recharge will be reduced in Central and Eastern Europe. Although there is still a considerable range of uncertainty related to changes in climate variability in future climate scenarios for these regions, the study showed that summer crops will be very vulnerable and dependent on soil water reserves, as the soil water or higher groundwater tables during the winter period cannot be utilized as much as by winter crops and evapotranspiration losses during summer due to higher temperatures could increase significantly.

The Mediterranean and South East European regions are especially vulnerable to water scarcity. They are faced with increased competitions for water resources between different sectors (agriculture, industry or domestic consumption). Climate change projection for the Mediterranean area is a gradual increase of temperature and lower rainfall by the end of this century. Moreover, increased average temperatures will be coupled to an increase in extreme events frequency and magnitude as heat waves.

Investigations of impact of warming climate on the phenology of typical Mediterranean crops indicated an earlier development of crops and a reduction of the length of growing season for winter and summer annual crops, grapevine and olive tree (Moriondo & Bindi, 2007). These responses may allow some crops to escape summer drought stress (e.g., winter crops). However, at the same time the climate change will increase the frequency of extreme climate events during the most sensitive phenological stages and without irrigation this will reduce the final crop yield quantity and quality.

Although drought in South East European region is shorter than in Mediterranean, its impact on agricultural production in South East European region (Serbia, Bosnia and Herzegovina, continental part of Bulgaria, Croatia, Montenegro and Albania) could be also very serious. During summer period growth and productivity of a lot of agricultural plants are in the most sensitive phase to drought, and therefore, the reduction of yield could be significant. In accordance to current agricultural drought effects and prediction of increasing agricultural drought in the future, farmers are forced to irrigate crops. However, the maximal use of water for irrigation usually occurs during 2 or 3 summer months that is a significantly shorter period for crop irrigation than in Mediterranean region, where sometimes the irrigation period is more than six months. Therefore, the mitigation of drought by irrigation is economically more profitable in Mediterranean than in South East European climate conditions.

Together with water scarcity current problem in many areas is also contamination of water resources. In the most of European countries` water for irrigation is abstracted from surface water. The surface water resource may be recipients of treated wastewater and may be polluted from other anthropogenic activities or natural sources (Vinten et al., 2004). The problem is very serious because about 10% of crops are irrigated with untreated wastewater (Anon, 2003) and currently the potential for contamination via irrigation water is further increased worldwide.

Water for irrigation could be contaminated microbiologically or/and chemically. The pathogens, organic and inorganic chemical compounds in wastewater, can induce health risks for workers and consumers, exposed *via* the direct or indirect contact with such waters during field work and ingestion of fresh and processed food (Peralta-Videa et al., 2009).

The wide spectrum of pathogenic organisms in low quality water poses the most immediate and direct risk to public health. The most frequent microbiological contaminants in water are faecal microorganisms, including disease-causing pathogens like *Salmonella*, *Campylobacter*, *Shigella*, enteric viruses, protozoan parasites and helminth parasites (Steele & Odumeru, 2004). The potential risk is transport of pathogenic from water for irrigation to soil or crops. Moreover, the edible portions of a plant can become contaminated by contaminant uptake from soil by the root system and subsequent transport of the pathogen inside the plant. Therefore, irrigation with water contaminated with bacteria can be the starting point of a water–soil–plant–food contamination pathway (Battilani et al., 2010).

Increasing trend of consumption of fresh fruit and vegetables present also a risk factor for infection with enteric pathogens such as *Salmonella* and *Escherichia coli* O157 (Heaton & Jones, 2008). Routes of contamination with enteropathogens may vary. Usually they include application of organic wastes to agricultural land or contamination of irrigation waters with faecal material. If the crops are irrigated with wastewater an increased incidence of enteropathogens in different fruit and vegetables will happen (Steele & Odemeru 2004).

Pathogen survival will depend on the different environments conditions associated with the method of irrigation, e.g. surface irrigation like furrow and sprinkler irrigation, exposure to high temperatures, desiccation and UV-light factors which all lead to a faster die-off of pathogens on the soil surface. Studies on plant nursery irrigation (Lubello et al., 2004) have shown that tertiary treatment technologies like filtration and peracetic acid need to be added to primary and secondary treated wastewater to eliminate the risk posed by waterborne pathogens.

Results of Enriquez et al. (2003) showed that the use of the subsurface drip line could delay the movement of pathogens to the surface and inhibit the further impact on the above ground product. To test the hypothesis that subsurface application of urban wastewater could provide the potato safe for consumption, Forslund et al. (2010) compared different irrigation techniques (sprinkler, furrow and subsurface drip irrigation) for using treated urban wastewater, canal water and tap water. These results showed no significant number of *E. coli* in soil and potato tubers during irrigation. They also pointed out that soil could be a very effective filter barrier for pathogenic in ensuring food safety.

The use of low quality water for irrigation may also introduce hazardous heavy metals into the food chain (Behbahaninia et al., 2009). Heavy metals are dangerous as they tend to accumulate in living organisms faster than they are metabolized or excreted (Järup, 2003). Water filters designed to protect irrigation systems, offers no barriers against heavy metals contamination, except for the fraction of metals bound or trapped into the suspended solids. Several techniques are applicable to remove heavy metals from contaminated water. Heavy metal removal device (HMR) is based on heavy metal adsorption to granular ferric hydroxide (GFH) and HMR application is recommended if severe heavy metal pollution occurs in the irrigation water source, which cannot be sufficiently treated by the gravel filter (Battilani et al., 2010).

As the result of EU FP6 project SAFIR (www.safir4eu.org) new decentralized water treatment devices (prototypes) were developed to allow a safe direct or indirect reuse of wastewater produced by small communities/industries or the use of polluted surface water. The testing was done of a small-scale compact pressurized membrane bioreactor and a modular field treatment system that include commercial gravel filters and heavy-metal specific adsorption materials. These results indicated that decentralised compact pressurised membrane biobooster (MBR) could remove up almost all *Escherichia coli* and total coliforms. MBR from inlet flow also removed arsenic, cadmium, chromium, copper and lead. The field treatment system (FTS) also proved to be effective against faecal contamination when applied with its complete set up including UV treatment. FTS removed arsenic, cadmium, copper, chromium, lead and zinc (Battilani et al., 2010). Using new technology Surdyk et al. (2010) investigated the transfer of heavy metals from low quality surface water to the soil and potato plants in a Serbian field study during 2007 and 2008 seasons. These results indicated that after passing water through the FTS no significant impact of the irrigation water on potato heavy metal accumulation could be detected.

In general, the use of low quality water for irrigation of agricultural plants as a substitute for groundwater and surface water can only be accepted if the health of farm workers and consumers of irrigated produce can be ensured.

3. Agricultural strategies for adaptation to climate change

To avoid or at least reduce negative effects of drought, several agronomic adaptation strategies have been suggested, including both short-term adjustments and long-term adaptations. The short-term adjustments include efforts to optimize production without major system changes. Most of them are already available to farmers and communities. Examples of short-term adjustments include use of varieties/species with increased resistance to heat shock and drought, introducing new crops, changes in sowing dates (Olesen et al., 2007) and fertilizer use, improvement and modification of irrigation techniques (amount, timing or technology), other different soil or crop managements as mulching, crop rotation, intercropping, skip rows, protected cropping (Davies et al., 2011). They are autonomous in the sense that no other sectors (e.g., policy, research, etc.) are needed in their development and implementation.

Long-term adaptations refer to major structural changes to overcome adversity caused by climate change (Bates et al., 2008). This involves changes of land use that result from the farmer's response to the differential response of crops to climate change. The changes in land allocation may also be used to stabilize production, substitution of crops with high inter-annual yield variability (e.g., wheat) by crops with lower productivity but more stable yields (e.g., pasture). Other examples of long-term adaptations include breeding of crop varieties and new land management techniques to conserve water or increase irrigation use efficiencies and more drastic changes in farming systems (including land abandonment). They are planned actions, and they should be focused on developing new infrastructure, policies, and institutions that support, facilitate, co-ordinate and maximize the benefits of new management and land-use arrangements.

In this chapter, we will be focused only on two strategies for saving water in agriculture: improvement of irrigation techniques and breeding and use of stress drought and heat stress resistant genotypes.

4. Water saving irrigation strategies

Under current and predicted climate conditions of drought and scarce water supply, the challenge for agricultural production is to increase water productivity (ratio between yield and amount of water used for irrigation) and to sustain or even increase crop yield. Therefore, considerable emphasis in the research is placed on crop physiology and crop management for dry conditions with the aim to increase crop water use efficiency (Chaves et al., 2002; Morison et al., 2008).

Another approach is to improve the irrigation management. Many results confirmed that the deficit irrigation strategy has the potential to save water for irrigation and optimize water productivity in agriculture. The term *deficit irrigation* describes an irrigation scheduling strategy that allows a plant's water status to decrease to the certain point of drought stress.

Currently, two deficit irrigation methods are in use: regulated deficit irrigation and partial root-zone drying (FAO, 2002). Both methods are based on the understanding of the physiological responses of plants to water supply and water deficit, especially the perception and transduction of root-to-shoot drought signals (Chaves et al., 2002; Morison et al., 2008; Stikic et al. 2010).

4.1 Regulated deficit irrigation (RDI)

Regulated deficit irrigation (RDI/DI) is a method that irrigates the entire root zone with an amount of water less than the potential evapotranspiration during whole or specific periods of the crop cycle (English & Raja, 1996). The principle of the RDI technique is that plant sensitivity to drought is not constant during the growing season and that intermittent water deficit during specific periods of ontogenesis may increase water savings and improve yield quality (Loveys et al., 2004).

The key to the RDI strategy is the timing of the water deficit and the degree of the deficit applied to the plants. To avoid the possible reducing effect of RDI on yield, the monitoring of soil water status is required in order to maintain a plant water regime within a certain degree of drought stress that could not limit yield.

Implementing RDI could also be difficult where there is a high water table or deep soil with a high water holding capacity. However, if RDI is managed carefully, the negative impact on yield could be avoided. Results for numerous field crops (maize, wheat, soybean, sunflower), tree crops and grapevine showed that optimal RDI managing might increase water productivity or yield quality, maintain or even increase farmers’ profits (reviewed by Fereres & Soriano, 2007).

4.2 Partial root-zone drying (PRD)

Regulated deficit irrigation is a method where water application is manipulated over time, while partial root–zone drying (PRD) is a method where water is manipulated over space. PRD is designed to maintain half of the root system in a dry or drying state, while the other half is irrigated. The treatment is then reversed, allowing the previously well-watered side of the root system to dry down while fully irrigating the previously dry side.

The principle behind PRD is that irrigating part of the root system keeps the leaves hydrated and in a favorable plant water status, while drying on the other part of the root system promote synthesis and transport of so-called chemical signals (particularly plant hormone abscisic acid) from roots to the shoot *via* the xylem to induce a physiological response (Dodd et al., 2006). The frequency of the switch is determined according to soil type, genotypes or other factors such as rainfall and temperature and in most of the published data the PRD cycle includes 10 to 15 days (Davies et al., 2000).

Effects of PRD on plant physiology are different from RDI because wet roots under PRD sustain shoot and fruit turgor that are important for plant growth. The drying roots in the PRD produce the sufficient amount of the chemical signals to maintain a physiological response to water stress. Triggering partial stomatal closure under PRD irrigation prevent excessive water loss and also the metabolic inhibition of CO_2 assimilation, that otherwise would occur in extensively development of drought stress (Chaves et al., 2002; Costa et al., 2007).

PRD may be applied by different techniques in the field depending on the cultivated crops or soil condition. PRD irrigation (alternate or fixed) could be done by subsurface or surface drip lines, furrow, micro-sprinkler or vertical soil profile methods (Kang & Zhang, 2004).

Figure 1 shows the scheme of the full irrigation (FI) and partial root-zone drying drip line installation in the potato field experiment. This experiment was a part of research activity in EU FP6 project SAFIR (www.safir4eu.org). For PRD irrigation, the subsurface drip system was applied, which consisted of two parallel bundled lines, each with 60 cm distance between emitters, but displaced to give 30 cm distance. In this way emitter from one line irrigated one side of the root, and emitters from the other line irrigated another side of the root system (Jensen et al., 2010; Jovanovic et al., 2008, 2010).

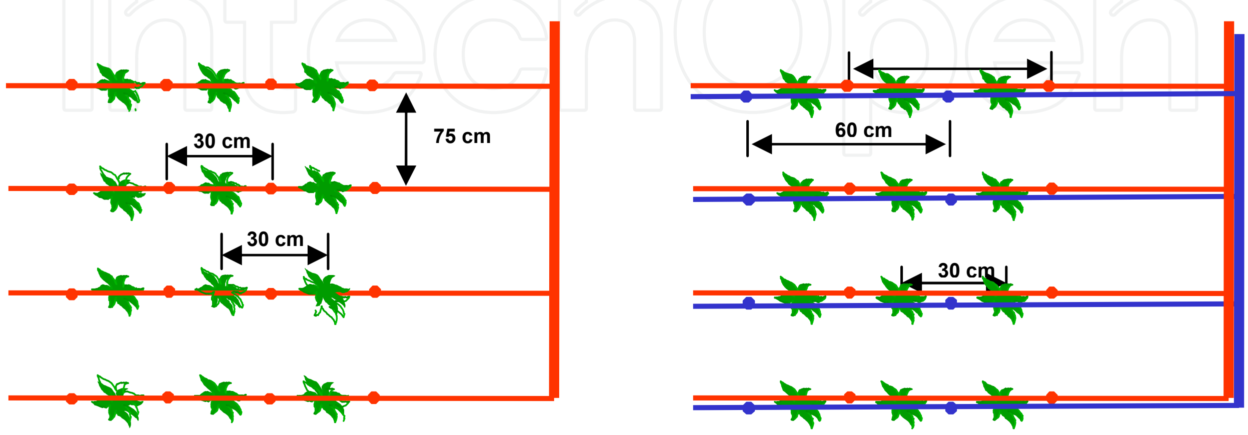

Fig. 1. Scheme of FI (left) and PRD drip lines (right) installation in potato experimental field.

Partial root drying method is applied in a wide range of different crops (Kirda et al., 2007; Sepaskhah & Ahmadi, 2010). Some of PRD experiments applied to the different agricultural plants are presented in Table 2. Comprehensive data sets from the most of these field and glasshouse studies have shown that under PRD irrigation, water may be reduced by approximately 30-50% without significant yield reduction and in some cases with an improved yield quality. An important mechanism of plant response to PRD, in addition to increase WUE or yield quality, may be the promotion of root growth and increase of root biomass. Enhanced root growth will increase the plants' ability to explore a greater soil volume potentially increasing soil water and nutrient acquisition.

Crops	**Species**	**References**
Field crops	maize	Kang et al. (2000); Li et al. (2010)
	wheat	Sepaskhah & Hosseini (2008)
	sunflower	Metin Sezen et al. (2010)
	sugar beet	Sepaskhah & Kamgar-Haghighi (1997)
Vegetables	potato	Ahmadi et al. (2010a, 2010b); Jovanovic et al. (2010); Liu et al. (2006); Saeed et al. (2008); Shahnazari et al. (2007)
	tomato	Davies et al (2000); Kirda et al. (2004); Mingo et al. (2004); Zegbe et al. (2006); Zegbe-Dominguez et al. (2004)
	beans	Genocoglan et al. (2006); Wakrim et al. (2005)
Fruit tree and grape	grape	de Souza et al. (2003); dos Santos et al. (2003); de la Hera et al. (2007)
	apple	Leib et al. (2006); Zegbe & Serna-Péreza (2011)
	pear	Kang et al. (2002); O'Connell & Goodwin (2007)
	peach	Goldhammer et al. (2002)
	olive	Centritto et al. (2005); Wahbi et al. (2005)
	citrus	Hutton & Loweys (2011)
	almond	Egea et al. (2010)

Table 2. PRD experiments with different agricultural plants.

Table 3 presents some of our recent results in an experiment with tomato cultivar *Amati* grown under PRD and FI in commercial polytunnel conditions. These results, similarly to the others published showed that with the PRD method is possible to increase WUE and save water for irrigation, without statistically significant reduction of tomato yield. Furthermore, in our experiment the antioxidative activity was significantly increased in tomato fruits under PRD compared to the fruits of control plants. This improvement of PRD fruit quality could be also beneficial from the aspect of health-promoting value of tomato fruits.

PRD irrigation method has been also successfully trailed with potato (Table 2). Recently, we conducted potato PRD field trials with cultivar *Liseta* and with the aim to compare "static" PRD management approach with "dynamic" system, when amounts of water irrigated in PRD were changed according to the plant growth phases by increasing water saving during later robust growth stages (Jovanovic et al., 2010). In the 2007 season PRD plants received

70% of fully irrigated (FI), and in 2008 year 70% of PRD was replaced by 50% in the last 3 weeks of the irrigation period in order to further save water. Comparison of the effects of PRD and FI irrigation technologies did not show significant differences in yield in investigated seasons. However, water use efficiency of PRD plants compared to FI was significantly bigger in 2008 season when "dynamic" PRD was applied than in 2007 years when "static" approach of PRD irrigation was used (by 14%). Tuber quality data showed in both seasons a significant increase in antioxidant activity and in starch content in the tubers of PRD plants comparing to FI tubers. Table 4 present some of our data from potato PRD experiments (Jovanovic et al., 2008, 2010).

Water treatment	Yield (t ha^{-1})	WUE (kg FW m^{-3})	TSS (^{o}Brix)	TA (citric acid µmol g^{-1} FW)	AA (µmol TEAC 100g^{-1} FW)
FI	48.71	34.90^{A}	5.10	19.60	33.33^{A}
PRD	43.41	56.02^{B}	5.10	19.90	50.87^{B}

Table 3. Treatments means of yield, water use efficiency (WUE), fruit quality (total soluble solids - TSS, titrable acidity - TA and antioxidant activity - AA) in fully irrigated tomato (FI) and tomato under partial root-zone drying (PRD). Different letters show significant differences at 95% level for comparison between irrigation treatments.

Water treatment	Yield (t ha^{-1})	IWUE (kg ha^{-1} mm^{-1})	N (%)	Starch (% FW)	AA (µmol TE 100 g^{-1} FW)
FI $_{-2007}$	45.31^{AB}	241.00^{A}	2.18^{A}	13.72^{A}	19.92^{A}
PRD$_{-2007}$	41.78^{A}	334.27^{B}	2.45^{B}	15.02^{BC}	22.63^{B}
FI$_{-2008}$	53.19^{C}	236.40^{A}	2.25^{A}	13.45^{AB}	19.13^{A}
PRD$_{-2008}$	50.46^{BC}	380.14^{C}	2.68^{B}	15.76^{C}	22.81^{B}

Table 4. Treatments means of yield, irrigation water use efficiency (IWUE), tuber quality (%N, starch content and antioxidant activity - AA) of fully irrigated potato (FI) and potato under partial root-zone drying (PRD) during 2007 and 2008. Different letters show significant differences at 95% level for comparison between irrigation treatments and investigated seasons.

Furthermore, our potato results indicated that PRD treatment could improve the allocation of N from the shoot to tuber at final harvest and increase the N-use efficiency (Jovanovic et al., 2008, 2010). Similarly, Shahnazari et al. (2008) results also confirmed that PRD treatment may improve soil nitrogen availability during the late phases of potato growing season indicating a higher N mineralization. In general, our results indicate that "dynamic" PRD approach could be a more promising strategy for saving water for potato irrigation than the classical "static" approach.

4.3 Choice of RDI or PRD irrigation

Although RDI and PRD methods functioning differently, some of their main effects are similar. Both methods limit vegetative vigour and improve water use efficiency or water productivity (Kriedmann & Goodwin, 2003). Reduction of vegetative vigour is desirable characteristics for many crops in drought regions. Excessive vegetative vigor is a major problem for many fruit crops, since the use of assimilates in leaf growth restricts fruit set and development, and may cause shading and more fungal diseases (Morison et al., 2008). Reduction of vegetative growth may also induce a change of assimilate partitioning and source/sink relationships. The photosynthetically active tissue of mature leaves is an active source of assimilate for sink tissues, such as flowers, fruits, or roots. Among sink organs, fruits or tubers are defined as a high priority in the context of competition for assimilates between alternative sinks. Davies et al. (2000) results pointed out that reduction of carbohydrate strength (side shoots) in PRD-treated tomato plants resulted in a relative increase in the sink strength of tomato fruit such as carbohydrate previously partitioned towards the side shoots is redirected towards the fruit.

Both irrigation methods significantly increase WUE and may save 30 to 50% of water for irrigation depending on crops, soil or climatic conditions. Their effects also depend on the crop phenological stage and on the severity of stress that is imposed to the crops. For example, in Mediterranean or South-East European conditions, it is common to apply water deficit during the final phases of grape development to avoid water stress during the ripening stage, whereas in Australia the common practice is to apply less water early in the season with the aim to control berry size (McCarthy et al., 2002).

The potential reduction of yield is the main problem in the use of RDI, although this depends on the timing of application and degree of stress imposed by RDI. According to Kriedmann & Goodwin (2003) soil type is also an issue with regulated deficit irrigation. Sandy loams dry and re-wet more readily than clay soils, and are generally easier to manage. Although a clay soil has theoretically a greater range of plant-available moisture, root growth under RDI in this type of soil can be slower and water extraction by root smaller than in sandy loam soil. According to Fereres & Soriano (2007) to quantify the level of RDI it is first necessary to define the full crop ET requirements and then, adjustment of timing of irrigation with permanent control of management is necessary.

Many results showed that PRD may be a more beneficial technique than RDI, particularly in terms of lesser risk of yield reduction, especially during heat waves. Under both PRD and RDI treatments, stomatal conductance was reduced, but PRD plants due to wet side of the roots remained less stressed and pre-dawn water potential values are higher than in RDI plants (Kriedmann & Goodwin, 2003). Beneficial effects of PRD comparing to RDI are also in the increase in root growth and development (Mingo et al, 2004), quality of fruits and better control of vegetative growth and assimilate partitioning (Costa et al., 2007). Increased yield quality in many different crops could minimize the negative effects of PRD on the yield quantity in some experiments (Kang & Zhang, 2004).

For PRD irrigation scheduling less emphasis should be on evaporative indicators of the irrigation requirement and more emphasis on direct measurement of root-zone soil water content to drive both duration of irrigation, and timing of the switch from drying to re-wetting (Kriedmann & Goodwin, 2003). A key factor of PRD irrigation scheduling is re-watering of the dry side. During PRD irrigation, water must be switched regularly from one side of the root to the other to keep roots in dry soil alive and fully functional and sustain the supply of root signals. The time of switching required could present significant difficulty in operating PRD irrigation. This is one of the mean reasons that Sadras (2009) in his metaanalyses challenge the beneficial effects of PRD technique. He concluded that substantial improvement in water use efficiency can be achieved by closely monitored RDI, without the complexity and additional cost of PRD. Furthermore, PRD method is more costly than RDI because it requires installation of two drip lines.

Usually in the most applied PRD systems the switching is based on soil water depletion or stomatal reactions. Zhang & Davies (1990) suggested that the early wilting of older leaves may indicate the right time for irrigation. Recently, a novel model for prediction of the switching side was developed and is based on accumulation of xylem ABA in potato (Liu et al., 2008). The model was further improved and finally implemented into modified the agro-ecological model DAISY which simulate the mechanisms underlying the water saving effects of PRD irrigation (Plauborg et al., 2010).

It is difficult to recommend RDI or PRD for irrigation. Successful application and choice between RDI or PRD depends on different factors, including the irrigated crops, outputs of crop growing (increase WUE or yield quality, sustained yield etc.) and severity, timing and duration of the stress imposed to plants in specific agro-climatic conditions. Both methods require high management skills and the knowledge of crop response to drought stress (FAO, 2002). Recently, Jensen et al. (2010) suggested a new RDI and PRD irrigation guidelines for tomato and potato based on EU FP6 project SAFIR field experiments conducted under different climatic conditions (www.safir4eu.org). For these vegetables grown in the field conditions full irrigation is needed until the crops are well established, and then RDI and PRD should start. To avoid the yield decrease, water saving irrigation should start in potato after the end of tuber initiation, while in tomato after the first trusses were developed. After these periods 30% water saving can be applied, while finally during the last 2 weeks before harvest water saving could be increased to 50%.

In general, it could be expected that the successful implementation of deficit irrigation strategies can lead to greater economic gains for farmers, especially in the water scarcity areas, where there is not enough water for irrigation or in the areas where price of water is high.

5. Plant resistance to drought

Adaptation measures to mitigate the reduction of yield induced by drought besides the increase in crop water productivity includes the production and use of drought resistant genotypes. Additional opportunities for new cultivars also include changes in phenology or enhanced responses to elevated CO_2.

The prerequisite to produce resistant genotypes is a better understanding of the plant response and adaptation to drought stress, the improvement of phenotyping, the selection of key-genes involved in the resistance to drought and the evaluation of the impact of resistance on crop yield and quality. These are very difficult tasks because reactions of plants to drought is the complex phenomenon where the plant response depends on species or genotypes, the type, duration or intensity of drought and on phenological stage in which drought stress is experienced (Chaves et al., 2003).

According to the classic definition of Levitt (1980) plant resistance to drought stress can be divided to three main strategies namely escape, avoidance and tolerance. The plants "escapers" exhibit a rapid phenological development and thus are able to complete their life cycle before the water deficit occurs. This is associated with the plant's ability to store reserves in some organs and to mobilize them for yield production (Chaves et al., 2003). A short life cycle and maximal use of resources are particularly advantageous in environments with terminal drought stress or where physical or chemical barriers inhibit root growth (Blum, 1998).

Drought avoidance (DA) refers to the plant's ability to retain a relatively high level of hydration under water stress and involves two components: maximizing water uptake and minimizing water loss (Blum, 1998). Maximizing of water uptake can be achieved by increasing root growth, root thickness, root depth and mass (Price et al., 2002). Water loss can be minimized by closing stomata, through reduced absorption of radiation by leaf rolling, decreasing canopy area by reducing growth and shedding of older leaves. In selection and phenotyping of potato, these DA traits are often used as criteria Schafleitner (2009).

Drought tolerance (DT) response is defined as the capacity of plants to maintain functional growth under low resources (water and minerals). Drought causes the reduction in water potential of the cell, as a result of solute concentration gradients and osmosis, and leads to the loss of cell turgor. Furthermore, the reduction of available water, induces also a reduction in nutrients, especially nitrogen. Some plants have the ability to tolerate dehydration or maintain turgor pressure through an osmotic adjustment *via* the active accumulation of solutes called osmoprotectants (amino acids, sugar alcohols, polyols and quaternary ammonium and tertiary sulfonium compounds), ABA content or by an increase of antioxidative and/or other defense mechanisms (Reddy et al., 2004).

All drought resistance strategies are not mutually exclusive and plants may combine a range of different response types for optimal reaction to drought. In most temperate climates, dehydration tolerance is the only relevant mechanism but in more severe conditions, such as in southern Australia and other Mediterranean climates, a combination of different mechanisms can be achieved (Berger et al., 2010).

According to Munns et al. (2010) strategies for water use that confers drought tolerance can be quite different for annual and perennial species, and for dry land versus irrigated agriculture. For annual crops such as wheat and barley in semi-arid environments, with mild winters and hot summers, one successful strategy is a fast rate of development, and a short time to flowering and grain maturity, allowing the available water to be used by the plant before it is lost from the soil as the temperature increases. Another is to choose a slow-developing cultivar and sow early. Perennial species can employ a conservative strategy, minimizing the use of water to avoid the risk of leaf dehydration, and resuming a fast growth rate when the rainy season returns. According to the same authors, the sensitive growth response to drought would be beneficial in rain-fed conditions, while the less sensitive response for crops growing in irrigated land. Selecting genotypes with diverse responses to a decrease in soil water potential would provide an option to growers in different environments (Munns et al., 2010).

5.1 Breeding for drought resistance

A major goal in plant breeding is the production of crops with increased tolerance to abiotic stress. While natural selection has favored mechanisms for adaptation to stress conditions, the breeding efforts have directed selection towards increasing the economic yield of cultivated species, hence, stress-adaptive mechanisms have been lost in the elite gene pool of our current crop plants. The special problem is that the genetic pressure imposed on crop plants throughout early domestication, and modern plant-breeding has severely eroded the allelic variation of genes originally found in the wild, making crop species increasingly susceptible to diseases, pests and environmental stresses (Tanksley & McCouch, 1997).

The complexity of drought tolerance mechanisms explains the slow progress in breeding for drought conditions. Breeding for drought tolerance is further complicated by the fact that several types of abiotic stress (as high temperature or high irradiance, water and nutrient deficiency) in the field conditions can influence plants simultaneously and activate different molecular mechanisms.

Retrospective studies have demonstrated that selection of plants characterized by high yield potential and high yield stability has frequently led to yield improvements under both favorable and stress conditions (Cattivelli et al., 2008). Rizza et al. (2004) tested in rain/fed and irrigated conditions 89 barley genotypes representing a sample of the germplasm grown in Europe. Eight of them showed the best yield in both irrigated and rain-fed conditions. Now, further progress will depend on the introduction of traits in high yielding genotypes that are able to improve stress tolerance to multiple stress factors without detrimental effects on yield potential.

According to Zamir (2001) development of exotic genetic libraries consisting of marker-defined genomic regions taken from wild species and introgressed to the background of elite crop varieties will provide a resource for the discovery and characterization of genes that underlie traits of agricultural value. Using this approach Gur & Zamir (2004) were able to demonstrate that introgressed tomato lines carrying three independent yield-promoting genomic regions produced significantly higher yield than then control lines grown under drought conditions.

Concerning drought resistance strategies, the improvement was done in the breeding for the drought escape mechanism and for earlier flowering due to the relative simple screening traits which were on the control of only few genes (Ludlow & Muchow, 1990). Earliness is an effective breeding strategy for enhancing yield stability in Mediterranean environments where wheat and barley are exposed to terminal drought stress. In this condition shortening crop duration, a typical escape strategy, can be useful in synchronizing the crop cycle with the most favorable environmental conditions (Cattivelly et al., 2008).

Drought tolerance is a quantitative trait, with complex phenotype and genetic control. Therefore, the molecular approaches in crop improvement must be linked with suitable phenotyping protocols at all stages, such as the screening of germplasm collections, mutant libraries, mapping populations, transgenic lines and breeding materials and the design of OMICS and quantitative trait loci (QTLs) experiments (Salekdeh et al., 2009). However, despite the increasing knowledge on the mechanisms involved in plant response to stress, the advancement of high-throughput OMICS technologies (refers to the comprehensive analyses of plants ending in the suffix-omics such as genomics, proteomics and metabolomics) to screen large numbers of genes induced by drought mechanisms to regulate plant traits and also the increasing development of marker assisted selection in many crop species, the improvement of breeding to drought has been relatively modest.

Cattivelli et al. (2008) suggested that further breeding progress requires the introduction of traits that reduce the gap between yield potential and actual yield in drought-prone environments. To achieve these three main approaches can now be exploited: (1) plant physiology has provided new insights and developed new tools to understand the complex network of drought-related traits, (2) molecular genetics has discovered many QTLs affecting yield under drought or the expression of drought tolerance-related traits, (3) molecular biology has provided genes useful either as candidate sequences to dissect QTLs or for a transgenic approach.

Although there is evidence for a lot of physiological traits associated with the tolerance to drought (Table 5), the success in trait-based approaches considering the drought avoidance and drought tolerance mechanisms is not big. Table 5 presents some of these traits in different plants.

Traits	**Plants**	**References**
Plant growth and phenological phases (early or late flowering, extended crop duration, anthesis-silking interval, grain number, leaf growth, stay-green)	wheat, maize, sorghum, barley	Borrell et al. (2000); Edmeades et al. (1999); Rajcan & Tollenaar (1999); Richards (2006); Siddique et al. (1990); Slafer et al. (2005); Tardieu & Tuberosa (2010)
Photosynthesis (gas exchange, activities of key-enzymes, chlorophyll fluorescence)	grapevine, durum wheat	Chaves et al. (2002); Yousfi et al. (2010)
Assimilate partitioning and stem carbohydrates utilization	wheat, rice	Blum (1988); Kumar et al. (2006); Slafer et al. (2005)
Root growth and hydraulic properties	wheat, barley, oat	Hoad et al. (2001); Richards (2006)
Water status, osmotic adjustment, stomatal opening and related traits (leaf and canopy temperature, different spectral indices)	wheat, barley, maize, soybean	Chen et al. (2005); Morgan (2000); Munns et al. (2010)
Water use efficiency (WUE), carbon isotope discrimination	wheat, sunflower	Lambrides et al. (2004); Rebetzke et al. (2002); Siddique et al. (1990)

Table 5. Physiological traits associated with tolerance to drought in different agricultural plants.

Most of the physiological traits that impact on response to environmental stress require detailed, sophisticated and usually expensive techniques to phenotype plants, and can be applied only to a very limited number of genotypes (Sinclair, 2011). Plant resistance is usually assessed on the short term experiments in controlled conditions and many of the investigated traits are more appropriate for plant survival rather than maintaining plant productivity. Therefore, there is a need do develop the new phenotyping methods and platforms that will allow to screen available genetic resources and to monitor in situ the plant response to drought in the field conditions. Very efficient and promising are new non–imaging technologies as thermal infrared, near infrared, RGB visible or fluorescence that enable the dissection of plant responses to drought into a series of component traits (Berger et al., 2010; Munns et al., 2010).

As traits maximizing productivity normally expressed in the absence of stress can still sustain a significant yield improvement under mild/moderate stress, yield is therefore, a suitable target for breeding. Salekdeh et al. (2009) in his review paper presented a conceptual framework for drought phenotyping based on expressing yield as the product of 3 components: water use (WU), water use efficiency (WUE) and harvest index (HI). They suggested that such a phenotyping is also relevant for molecular biologists and geneticist working on grain crops. Furthermore, they identified protocols that address each of these factors, described their key features and illustrated their integration with different molecular approaches.

Quantitative trait locus (QTL) mapping provides a means to dissect complex traits, such as drought tolerance, into their components, each of which is controlled by QTLs. Molecular marker-supported genotypic information at the identified QTLs then enables quick and accurate accumulation of desirable alleles in plant breeding programmes. Plant tolerance to abiotic stress is mediated by complex traits that are sustained by multiple genetic factors with large QTLs-by-environment interactions. Due to these features, the practical application of marker-assisted selection for stress-related QTLs has proven difficult (Francia et al., 2005). The development of molecular marker technologies will help to identify a particular chromosomal location for genes regulating specific traits. The coincidence of loci for yield with the loci for the investigated trait will help in identifying if investigated trait is significant for drought resistance.

Genes connected to the drought could be those which encode an enzyme or other proteins. Many genes related to drought have been isolated and characterized in the last two decades in a variety of crop species. However, a lot of them was investigated in controlled conditions and not often proved in the field conditions. Therefore, it is difficult to exploit their expression and function for breeding processes. According to Cattivelli et al. (2008) the isolation of gene ERECTA that regulates transpiration efficiency in Arabidopsis and the transcriptional analysis of wheat genotypes with contrasting transpiration efficiency, is an example that demonstrated future approach for successful breeding. Significant progress in breeding for drought resistance will be achieved by integration of traditional breeding with physiology and genomics.

6. Conclusion

Agricultural production is highly dependent upon environmental variables, and it is expected that the climate change, especially drought, extreme temperature and water scarcity, will have significant effects on the food production and safety in many regions of the world. To address these challenges, the effort should be intensified to save water resources and to increase agricultural productivity per unit of water (“more crop per drop”). Better crop management and irrigation practice, deficit irrigation techniques and techniques for use of waste water for irrigation, will moderate the impact of climate change on water resources. However, the more efficient use of available water resources alone without growing of drought resistant crops could not have a significant long-term impact on reducing the impact of drought on agricultural production. Therefore, the more effort must be made in the future to produce crops able to deliver increased yields under drought conditions. In order to achieve this goal the focus should be in multidisciplinary approach, that integrates knowledge and research in the areas of crop physiology, genetic and molecular biology with the state-of-the-art breeding technologies.

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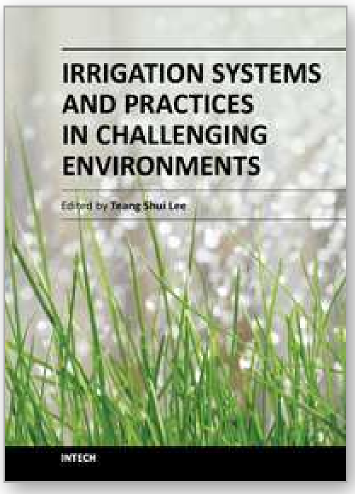

Irrigation Systems and Practices in Challenging Environments
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The book Irrigation Systems and Practices in Challenging Environments is divided into two interesting sections, with the first section titled Agricultural Water Productivity in Stressed Environments, which consists of nine chapters technically crafted by experts in their own right in their fields of expertise. Topics range from effects of irrigation on the physiology of plants, deficit irrigation practices and the genetic manipulation, to creating drought tolerant variety and a host of interesting topics to cater for the those interested in the plant water soil atmosphere relationships and agronomic practices relevant in many challenging environments, more so with the onslaught of global warming, climate change and the accompanying agro-meteorological impacts. The second section, with eight chapters, deals with systems of irrigation practices around the world, covering different climate zones apart from showing casing practices for sustainable irrigation practices and more efficient ways of conveying irrigation waters - the life blood of agriculture, undoubtedly the most important sector in the world.

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