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Coping with water scarcity: What role for biotechnologies?

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Preface

22 March is World Water Day. Its international observance is an initiative that grew out of the 1992 United Nations Conference on Environment and Development in Rio de Janeiro. Coordinated by the Food and Agriculture Organization of the United Nations (FAO), on behalf of the 24 Agencies and Programme Members of UN-Water, the theme of World Water Day for 2007 was "Coping with water scarcity". The day provided an opportunity to reflect on the challenges posed by the unsustainable increase in water use and its degradation across the world and it also served as a spur to action to reverse current trends and work towards a more efficient and more equitable distribution of water for all.

Water scarcity affects all social and economic sectors and threatens the sustainability of the natural resources base. Addressing water scarcity requires an intersectoral and multidisciplinary approach to managing water resources in order to maximize economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems. Integration across sectors is needed. This integration needs to take into account development, supply, use and demand, and to place the emphasis on people, their livelihood and the ecosystems that sustain them. On the demand side, enhancing water productivity (the volume of production per unit of water) in all sectors is paramount to successful programmes of water scarcity alleviation. Furthermore, protecting and restoring the ecosystems that naturally capture, filter, store and release water, such as rivers, wetlands, forests and soils, is crucial to increasing the availability of good quality water.

About 150 events were organized throughout the world to mark World Water Day 2007 (www.unwater.org/wwd07/nfevents.html). These included a special World Water Day celebration ceremony held at FAO Headquarters in Rome, where the opening address was given by the FAO Director-General Jacques Diouf who called coping with water scarcity the "challenge of the 21st century" (www.fao.org/newsroom/en/news/2007/1000520/index.html). Among other FAO initiatives, a moderated e-mail conference was also held on "Coping with water scarcity in developing countries: What role for agricultural biotechnologies?", organized by the FAO Working Group on Biotechnology and the FAO Water Development and Management Unit. The conference took place over a four-week period that was timed to overlap with World Water Day. The background paper and summary report from that conference form the basis of this current publication.

Biotechnology is a broad collection of tools and these tools are currently being applied for a wide range of different purposes in agriculture (e.g. genetic improvement of plant varieties and animal populations or characterization and conservation of genetic resources). FAO considers that biotechnology provides powerful tools for the sustainable development of agriculture, fisheries and forestry, as well as the food industry and that when appropriately integrated with other technologies for the production of food, agricultural products and services, it can be of significant assistance in meeting the needs of an expanding and increasingly urbanized population (www.fao.org/biotech/stat.asp).

A number of key messages emerged from the conference and two of them may be underlined here. The first is that there was a general consensus among those that participated that biotechnology has a valuable role to play in addressing the challenge of water scarcity in developing countries, although opinions differed on the relevance of different biotechnology tools. Over the past years, opinions have indeed differed widely regarding one particular biotechnology, genetic modification, and the resulting genetically modified organisms (GMOs) that it produces. The controversy has been exacerbated by large-scale dissemination of misinformation, both for and against GMOs, through the media and elsewhere. In this polarized situation, FAO has strived to provide high-quality, unbiased, science-based, updated information about agricultural biotechnologies to its Member Nations and their institutions and will continue to do so in the future.

The second is that, despite their promise, many applications of biotechnology relevant to water scarcity have not yet met their full potential to deliver practical solutions to the end-users in developing countries. This second point is a reminder that biotechnology is not a silver bullet and that the pathway from a research development in the laboratory to an improved plant growing in the farmer's field can be quite long. To ensure that research initiatives to develop drought resistant crops are successful and that the resulting products actually reach the farmers, participants in the conference called for increased collaboration between researchers in different disciplines and for all relevant stakeholders to be involved in the design of solutions to the problems of water scarcity in agriculture. This is something we strongly support. In addition, there is also a need for greater political and financial support to overcome other obstacles such as the lack of sufficient research funding, human and institutional capacities and adequate infrastructure. The capacities of developing countries can be strengthened through greater collaboration between research institutions in different developing countries and also between industrialized and developing countries. In this, FAO and its partners stand ready to coordinate the collaborative efforts and to support these capacity-building activities.

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FAO Biotechnology Forum
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The FAO Biotechnology Forum is an e-mail based forum launched in the year 2000 with the goal of providing access to quality balanced information and to make a neutral platform available for all interested stakeholders to openly exchange views and experiences on agricultural biotechnology in developing countries. It covers applications in the crop, forestry, livestock, fisheries and agro-industry sectors.

Each conference takes one particular theme that is relevant to agricultural biotechnology in developing countries and opens it up for debate for a limited amount of time. From 2000 to 2005 it hosted 13 moderated e-mail conferences, and in these the e-mail messages came roughly 50:50 from participants living in developing and developed countries respectively (FAO, 2001, 2006a, 2006b). The Forum covers the broad range of tools included under the general term 'biotechnology'. Some of the technologies may be applied to all the food and agriculture sectors, such as the use of genomics, molecular DNA markers or genetic modification, while others are more sector-specific, such as vegetative reproduction (crops and forest trees) or embryo transfer and freezing (livestock).

For each conference, two key documents are produced. Firstly, before the conference takes place, a document is prepared to give a good background to the conference theme, in a balanced neutral way, and written in easily-understandable language so that people with little knowledge of the area may understand what the theme is about. The document also highlights any particular issues of special relevance to developing countries. Secondly, after the conference, a document is prepared to provide a summary of the main issues that were discussed during the conference, based on the messages posted by the participants.

This publication presents these two documents from conference 14 of the Forum, entitled "Coping with water scarcity in developing countries: What role for agricultural biotechnologies?", that took place from 5 March to 1 April 2007. As for other conferences of the Forum, it was moderated and the moderator was John Ruane. The conference was timed to coincide with World Water Day, which is celebrated each year on 22 March. In 2007 its theme was "Coping with water scarcity" and FAO was the coordinating agency within the UN system for the theme. The conference also complemented two meetings held recently in Rome and supported by FAO, i.e. "The 2nd international conference on integrated approaches to sustain and improve plant production under drought stress", that took place on 24-28 September 2005 (www.plantstress.com/ID2/default.htm), and the workshop that took place on 29-30 September 2005 on "Improving water use efficiency in Mediterranean agriculture: What limits the adoption of new technologies?" (www.distagenomics.unibo.it/wuemed/workshop.html).

Background to the issues 2

INTRODUCTION

The central role that water plays for this planet and its inhabitants has often been summed up by the expression 'water is life'. The water that falls from the sky represents, directly or indirectly, the basis for life on Earth. Water is a renewable but finite resource on our blue planet and one which is increasingly threatened. We are living in a time of great change and humankind's activities have put an ever-increasing strain on all of the world's resources including the most precious of all, water. Most of the freshwater supplies that are withdrawn for human use are employed in agriculture. The aim of this conference is to debate the role that biotechnology tools applied for agricultural purposes may play in helping us to cope with life on a water-scarce planet.

In this context, the primary focus will be on the use of biotechnology tools to increase the efficiency of water use in agriculture, while a secondary focus will be on two specific water-related applications of micro-organisms, in wastewater treatment and in inoculation of crops and forest trees with mycorrhizal fungi. To allow in-depth discussion of these areas and to avoid the debate becoming too broad, topics such as the use of biotechnology to increase yields (discussed e.g. in Conferences 1 and 5 of this Forum [FAO, 2001]) or to produce crops tolerant to soil salinity (resulting from irrigation), although related to water and agriculture, will not be discussed in this conference.

This document aims to provide information about the conference theme that participants will find useful for the debate. Firstly, a brief overview of the current status and future perspectives regarding water availability and use on Earth is provided, followed by discussion of some major strategies that can be employed to deal with water scarcity. More details on water use in agriculture are then given. Some of the potential ways in which biotechnology could contribute to this area are then considered. In the final part, some of the kinds of specific questions that should be addressed in the conference are listed.

A WATER-SCARCE PLANET

There is lots of water here on Earth; over 70% of the planet's surface is covered with water. However, almost all of it (97%) is found as saltwater in the oceans. The remaining 3%, nevertheless, still represents an enormous quantity of water, around 40 million cubic kilometres (km^3, where one km^3 is equivalent to a thousand billion litres of water). Most of this is held as freshwater in glaciers and icecaps (2% of all water) while 0.7% is groundwater (i.e. water found in the cracks or pores between rocks or grains of sand at varying depths below the ground surface). The remaining freshwater is found in lakes, soil, the atmosphere, in streams and rivers and within living organisms (e.g. Ritter, 2006).

Each year, an estimated 510 000 km^3 of water fall from the skies, mainly in the form of rain, but also in other forms such as snow and sleet. Roughly 400 000 km^3 fall on the seas and 110 000 km^3 fall on land, with very uneven temporal and spatial distribution patterns. The latter is obviously essential for agriculture and can be classified into two categories of freshwater. The first, green water, is the soil moisture generated by rainfall and available for root water uptake by plants. It is the main water resource for rainfed agriculture. The second, blue water, is the stored runoff of rainfall in lakes, streams, rivers, dams and aquifers (i.e. water-bearing layers of permeable rock, sand, or gravel that store and/or transmit water). It is the main water resource for irrigated agriculture. Of the 110 000 km^3 that fall on the land annually, almost 40% result in blue water (FAO and IFAD, 2006).

An estimated 7 130 km^3 of water are used each year for crop production globally, corresponding roughly to 3 000 litres used to feed a single person for one day (Molden et al., 2007a). Most of this water consumed by crop evapotranspiration comes from rain (about 80%) and about 20% is from irrigation Evapotranspiration, an important term in water science, is the combination of two processes: evaporation (the conversion of liquid water to water vapour) from the soil and transpiration (the process by which water absorbed by the plant, usually through the roots, is lost as vapour from the plant surface, occurring mainly at the leaves) by plants growing in the soil. Irrigation is practiced in places and times where rainwater is insufficient for adequately supplying water to crops. It provides a guaranteed supply of water and protects against droughts and dry spells. Out of the world's total land area of 13 billion hectares (ha), 12% is cultivated, and an estimated 27% is used for pasture. The 1.5 billion ha of cultivated land includes 277 million ha (18%) of irrigated land. In the period between 1960 and 2000, the amount of cultivated land increased by 13% while the human population was more than doubled, leading to a sharp reduction in the amount of land needed to produce food for one person. Between 1960 and 2000 the irrigation area almost doubled

(FAO and IFAD, 2006). These rapid increases in productivity were obtained through intensification of agricultural production, in which irrigation played an important role. Depending on various circumstances, irrigation helps to produce 2-3 times as much per hectare as non-irrigated agriculture (FAO and IFAD, 2006).

Blue water is very important as, apart from its use for irrigation, it is the freshwater resource that sustains aquatic ecosystems in rivers and lakes; it can also be applied to drinking or domestic purposes, to industry or hydropower. Over the 20th century, the amount of blue water withdrawn for human use at the global level increased from over 500 km^3 in 1900 to just under 2 000 km^3 in 1960 to almost 4 000 km^3 today (Shiklomanov, 2000). Most of this water (currently estimated at 70%) is used for agriculture, mainly irrigation, although the part diverted for industrial (20%) and domestic (10%) purposes is growing rapidly (FAO, 2007a).

The figures given so far are all based on considerations at the global level. When the different parts of the world are examined individually, it is noted that there is tremendous variation regarding the water situation at the country level (and even at the within-country level). For example, some countries withdraw much more water per person than others, which is mainly linked to the countries' irrigated area per person. The amount of blue water withdrawn annually varies, for example, from over 1 500 m^3 per person in Turkmenistan, Uzbekistan, Kazakhstan, Azerbaijan, Kyrgyzstan, Tajikistan, Iraq and the United States down to less than 20 m^3 per person in many African countries such as Benin, Uganda and Rwanda (FAO, 2007a).

Many countries are withdrawing water at rates that are clearly not sustainable. Molden et al. (2007a) report that 1.2 billion people live in areas characterized by physical water scarcity, where available resources are insufficient to meet all demands, including minimum environmental flow requirements. Arid regions in the world are most often associated with physical water scarcity. Symptoms of physical water scarcity include severe environmental degradation including river desiccation and pollution, declining groundwater and problems of water allocation where some groups win at the expense of others. They also estimate that another 1.6 billion people live in areas that face 'economic water scarcity', i.e. where water resources available are abundant relative to water use but there is a lack of investments in water or lack of human capacity to keep up with the growing water demand (characteristic of much of sub-Saharan Africa). So, it is estimated that, in total, around 2.8 billion people, more than 40% of the world's population, live in river basins where one or the other form of water scarcity must be reckoned with.

Looking to the future, there are also a number of factors at play that are likely to exacerbate this situation. The first factor is the rise in the global population, currently at 6.5 billion people (2005) and predicted to reach 8.2 billion by 2030 and, in addition, the accompanying increase in urbanization of the world's population (UN, 2006). Whereas Molden et al. (2007a) estimate that 7 130 km^3 of water are currently used each year to feed the world's population, it is estimated that, without further improvements in water productivity or major shifts in production patterns, the amount of water consumed by evapotranspiration in agriculture will increase to between 12 000 and 13 500 km^3 to feed the increased population in the year 2050 (de Fraiture et al., 2007). In addition, whereas 49% of the world's population is estimated to reside in urban areas in 2005, this proportion is predicted to rise to 60% in 2030 (UN, 2006). There will therefore be far greater demands on the blue water withdrawn for human purposes for domestic use and for industry and the proportion remaining for agriculture is likely to decline. Also, as Jury and Vaux (2005) point out, the economic value of water in industrial and urban uses is typically far greater than in agriculture (or for environmental uses), so market forces will lead to a significant reallocation of water resources from the agricultural and environmental sectors to the urban sector.

The second factor is climate change, which is expected to have significant impacts on agriculture and food production patterns through three major pathways: global warming, change in rainfall patterns and the increase in carbon dioxide concentration in the atmosphere (FAO and IFAD, 2006). While hard to predict all of the consequences, FAO and IFAD (2006) suggest that, in a scenario of moderate climate change, those most vulnerable to these changes are the poor and landless in rural areas dependent on isolated rainfed agricultural systems in semi-arid and arid regions. The changes in the water cycle and rainfall patterns – more precipitation, more frequent intense rainfall events and more evaporation – will affect soil moisture and increase erosion. In drought-prone areas, the number and duration of dry spells is expected to increase.

SOME MAJOR STRATEGIES FOR COPING WITH WATER SCARCITY

The preceding Section has shown that scarcity of water is one of the major global problems facing humankind at the moment and that it is likely to be an ever increasing problem in the future. One clear message that emerges is that there will be increased competition for the water resources available for agriculture in the future, despite the fact that there will be an ever-increasing demand for water in agriculture to meet the needs of the increasing world population. A range of major strategies have been proposed to cope with global water scarcity and a small number of them will be considered here:

Desalination of saline waters

Desalination is an option to increase the availability of freshwater both in coastal areas with limited freshwater resources and in areas where brackish water (i.e. a mixture of salt and fresh water), such as saline groundwater and drainage water, are available. It can be carried out by distillation of saline water or using membrane technologies, such as electro-dialysis and reverse osmosis. Desalination processes require large amounts of energy and the energy required, as well as the high cost of desalinating brackish waters and seawater have been the major constraints to large-scale production of freshwater from saline waters. Environmental costs related to the safe disposal of residual brines are also an important issue (FAO, 2006c). It is, nevertheless, a well-established technology primarily for drinking-water supply in water scarce regions, such as the Near East. It is the main source of potable (drinking) water in the Persian Gulf countries and in many islands around the world and it is also being used in certain countries to irrigate high-value crops (FAO, 2006c). Desalinated water is becoming more competitive for urban uses because desalinating costs are declining and the costs of surface water and groundwater are increasing. In spite of this development, the costs of desalinated water are still too high for the full use of this resource in irrigated agriculture, with the exception of intensive horticulture for high-value cash crops, such as vegetables and flowers (mainly in greenhouses), grown in coastal areas (where safe waste disposal is easier than in inland areas). At the global level, the volume of desalinated water produced annually, estimated at 7.5 km^3, is currently quite low, representing about 0.2% of the water withdrawn for human use (FAO, 2006c).

Use of wastewater

As mentioned previously, although the majority of blue water withdrawn for human consumption is used for agriculture (70%), a substantial proportion is also used for industrial (20%) and domestic (10%) purposes and this proportion is growing. With increased use of this water by urban communities and industries, larger volumes of wastewater are also generated. Millions of small-scale farmers in urban and peri-urban areas of developing countries use this wastewater for irrigating crops or forest trees or for aquaculture, thus reducing the pressure on other freshwater resources. Surveys across 50 cities in Asia, Africa and Latin America show that wastewater irrigation is currently a common reality in three-fourths of the cities (IWMI, 2006). Additional benefits of applying wastewater to land are that it also removes a number of contaminants from that water, making irrigation a low-cost method for the sanitary disposal of municipal wastewater, and that it can significantly contribute to urban food security and nutrition (IWMI, 2003).

The wastewater may or may not be treated before use. When untreated, its use brings with it potential health risks to the farmer and to the consumer of any food produced using the irrigated water, as well as potential environmental risks. For example, the presence of heavy metals, such as arsenic, in irrigation water is a problem in several developing countries, including Bangladesh (FAO, 2006d). Guidelines on the safe use of wastewater in irrigated agriculture have been developed to adequately address health protection and risk reduction measures (WHO, 2006).

Most of the domestic wastewater generated in developing countries is discharged into the environment without treatment. Wastewater treatment and use is an issue primarily in urban areas with sewerage systems. Wastewater treatment is a great challenge for developing countries because of its high costs and the technical skills required for operation and maintenance. Experience shows that wastewater treatment and use is more likely to be funded in national budgets when integrated with national integrated water resources management plans and/or with environmental policies. Some countries, such as Mexico, Brazil, Chile and Costa Rica, are moving in this direction (UNCSD, 2005). Israel currently uses 84% of its treated sewage effluent in agricultural irrigation and in a few cities, such as Windhoek in Namibia, the water is treated to a very high standard so that it can even be used as drinking water (UNIDO, 2006). Despite the obstacles for developing countries, the long-term goal of integrated wastewater management will always be to move from the unregulated use of untreated wastewater to the regulated use of treated wastewater (IWMI, 2006). The use of biotechnology in wastewater treatment is discussed later.

Conventional wastewater treatment consists of a combination of physical, chemical, and biological processes and operations to remove solids, organic matter and, sometimes, nutrients from wastewater. Different sequential stages of wastewater treatment can be generally distinguished (see e.g. the FAO wastewater glossary (www.fao.org/landandwater/aglw/waterquality/treatproc.stm), FAO (1992) or WHO (2006) for more details):

i. Preliminary treatment, whose objective is the removal of coarse solids often found in raw wastewater.

ii. Primary treatment, whose objective is the removal of settleable organic (i.e. containing carbon) and inorganic (not containing carbon) solids by sedimentation, and the removal of materials that will float (scum) by skimming. The preliminary and primary treatments are usually physical processes.

iii. Secondary treatment, involving further treatment of the effluent from primary treatment to remove the residual organic material and suspended solids. This stage typically uses biological treatment processes where micro-organisms convert non-settleable solids to settleable solids. Several aerobic (involving the presence of oxygen) biological processes are used for secondary treatment, differing primarily in the manner in which oxygen is supplied to the micro-organisms (mainly bacteria) and in the rate at which the micro-organisms metabolize the organic matter. For example, in the activated sludge process, the contents of aeration tanks, containing wastewater and micro-organisms, are mixed vigorously by aeration devices that also supply oxygen; the micro-organisms feed on organic matter and aggregate into flocs (clumps) that remove organic material and that settle out in settling tanks (clarifiers). Part of the settled biological material (sludge) is then recycled from the settling tanks to the aeration tanks in order to speed up the process.

iv. Tertiary and/or advanced treatment is employed to remove specific wastewater constituents which cannot be removed by secondary treatment e.g. nitrogen, phosphorus or heavy metals. Heavy metals, such as lead, cadmium, arsenic and mercury, have negative impacts on human health and the environment and can find their way into the wastewater in a number of ways e.g. through industrial or domestic activities. High levels of nitrogen and phosphorus are undesirable because they can lead to the process of eutrophication where algal growth is stimulated resulting in reduced oxygen levels in the water and release of toxins that can harm aquatic organisms and even humans.

The level of water treatment varies between countries. For example, in the European Union, where the wastewater of about 85% of the population is collected and treated, a small number of countries have mainly primary treatment; most countries give at least secondary treatment to the water and four countries apply tertiary treatment for 80% or more of their population (Eurostat, 2006). Data for developing countries are much less complete, although the FAO wastewater database provides an overview of the types of treatment applied in individual FAO member states (www.fao.org/landandwater/aglw/waterquality/waterusedb.jsp).

Virtual water and food trade

Whereas the use of water for agriculture might require large proportions of already-scarce water in some countries (e.g. in the Middle East), it would not have the same potential negative impacts on the environment, industry and drinking water supplies in other water-rich countries (e.g. in Western and Eastern Europe or Latin America). It has therefore been argued that import of food from water-rich countries allows water-poor countries to save the water they would have used to grow the food themselves, thus being equivalent to the import of ‘virtual water’, and that their scarce water reserves can instead be used for more valuable domestic, environmental and industrial purposes. The amount of virtual water (defined as the amount of water used in the production and processing of a given product) saved depends not only on the amount of food imported but also on the kind of food imported (e.g. beef vs. maize) and the production system and management practices they would have used if they had produced it themselves. Depending on these factors, it can e.g. take around 1 000 litres of water to produce a kilo of cereals and 13 000 litres per kilo of meat (Renault, 2002). Countries with limited water resources might also change their production patterns to prioritize production of agricultural commodities requiring relatively little water and to import those requiring more water (FAO and IFAD, 2006). While the strategy of importing virtual water is appealing from a water perspective, it can also have substantial long-term political and economic implications for the importing countries.

Increasing agricultural yields

There is currently a major gap between potential and actual yields for most crop and livestock species. As most of the blue water withdrawn for human use is devoted to agriculture and as there will be increased demand for agricultural products in the future because of the rising world population, any agronomic improvements which will help to close this gap should help to reduce the demand for water for agricultural purposes. This could be done in a variety of ways e.g. by improving the efficiency of fertilizer use; preventing crop losses due to biotic stresses such as insects, diseases and weeds; or reducing post-harvest losses due to insects and to fungal and bacterial rots (e.g. FAO, 2005).

Improving the efficiency of water use in agriculture

Another approach to reducing the pressure on scarce water resources is to increase the efficiency of water use in agriculture so that the food and agricultural products are produced using less water. How can this be done? In order to answer this question, we will consider here the use of water in agriculture in more detail. The use of biotechnology to increase the efficiency of this water used, a major focus of this conference, will be considered after.

WATER USE IN AGRICULTURE: A CLOSER LOOK

To consider how its efficiency could be improved, it is important first to recognize that the use of water for agriculture involves a series of sequential steps, covering both physical and biological processes, which begins with the hypothetical water drop(s) and ends with the plant (or animal) biomass produced for human use. Any systematic attempt to improve the efficiency of water use has to consider therefore the whole pathway and not just its individual steps. This Section is based on Hsiao, Steduto and Fereres (2007). In their paper, they propose a comprehensive conceptual framework that can be used to examine the current levels of efficiency along any single pathway of agricultural water use; to assess the potential improvements that may be achieved in various parts of the pathway and their impact on the overall efficiency; and to aid in the optimal allocation of resources for the improvements. They illustrate the framework with three examples (irrigated crop production, dryland crop production and animal production on rangeland) and conclude that to improve the overall efficiency, it will be more effective to make modest improvements in several steps than to concentrate efforts on improving efficiency of just one or two steps.

For the first example, they show that the production of crop biomass using irrigation water can be analysed as a pathway with a series of eight consecutive steps. Each step has an output that is then used as the input for the next step. Most of these steps are also shared with the other two examples they consider. The eight steps are:

i. Moving water from a source (i.e. either a reservoir or a lake or a river) to the farm gate. The efficiency of this step, indicated as conveyance efficiency, can be calculated as the ratio of the quantity of water that arrives at the farm gate to the quantity of water taken out of the source. Efficiency could be increased by e.g. covering canals to prevent evaporation losses and/or repairing leakages along the pathways of canals and pipes.

ii. Moving water from the farm gate to the field. The efficiency of this step, also indicated as farm-distribution efficiency, can be calculated as the ratio of the quantity of water at the field edge to the quantity of water at the farm gate. It could be increased by e.g. lining on-farm water reservoirs with plastic sheeting to reduce water leakage.

iii. Moving water from the field edge to the root zone of the crop. Efficiency of this step (known as application efficiency in irrigation engineering) can be calculated as the ratio of the quantity of water retained at the root zone to the quantity of water at the field edge. Efficiency could be increased by improving management of the existing irrigation system or changing to a better irrigation system. For example, there is growing interest in deficit irrigation, an irrigation practice whereby water supply is reduced below maximum levels and mild stress is allowed with minimal effects on crop yield (FAO, 2002). As most or all of the water applied remains in the root zone, deficit irrigation should increase efficiency of this step.

iv. Removal of water in the root zone by evapotranspiration. Efficiency of this step (known as consumptive efficiency) can be calculated as the ratio of the quantity of water evapotranspired to the quantity of water retained at the root zone. The loss of efficiency in this step is due to water left in the soil at harvest time.

v. Use of the water removed by evapotranspiration for crop transpiration. The water that is evapotranspired can have been either taken up by the crop and transpired (which is generally regarded as a beneficial use of the water) or simply evaporated from the soil (not beneficial). Efficiency of this step can be calculated as the ratio of the quantity of water transpired to the quantity of water that is evapotranspired. Efficiency could be increased by e.g. promoting plant canopy growth to cover the soil (thus reducing water evaporation).

vi. Assimilation of carbon dioxide by photosynthesis. Transpiration of water from the crop occurs mainly at the leaves, through specialized openings (called stomata) that allow the passage of carbon dioxide into the leaf (and of oxygen out of the leaf) for photosynthesis. Efficiency of this step (known as transpiration efficiency) can be calculated as the ratio of the mass of carbon dioxide assimilated (i.e. taken up) by photosynthesis to the quantity of water taken up by the crop and transpired. Efficiency is influenced by factors such as the species being cultivated (as different species carry out photosynthesis in different ways) or the location of the crop (e.g. the temperature/humidity where it is cultivated).

vii. Conversion of the assimilated carbon dioxide to crop biomass (i.e. the leaves, stems, roots, grains etc.). Efficiency of this step (known as biomass efficiency) can be calculated as the ratio of the crop biomass produced to the mass of carbon dioxide assimilated by photosynthesis. It could be increased by e.g. growing the crop at lower temperatures (e.g. in a cooler location or part of the year) so that loss of the assimilated carbon dioxide by respiration could be reduced (respiration, the reverse process of photosynthesis, involves the reaction of carbohydrates with oxygen to produce energy, water and carbon dioxide).

viii. Partitioning the crop biomass. Only a part (e.g. the grains) of the plant biomass produced may be of value for food and agriculture purposes. Efficiency of this step (termed yield efficiency, equivalent to the well-known agronomic term harvest index) can be calculated as the ratio of the crop biomass that ends up in the harvested yield to the crop biomass produced. The efficiency will vary according to the species involved e.g. it is almost 1 for fodder crops and about 0.5 for grain crops. It has increased over the last century as a consequence of genetic improvement.

The pathway above began with blue water from a source and ended with harvested crop biomass for human use. Hsiao, Steduto and Fereres (2007) also use the same approach to consider rainfed crops and animal production on rangelands, two pathways involving non-irrigated water resources that begin with water inputs in the form of precipitation and end with production of crop and animal biomass respectively.

For rainfed crops, a total of seven consecutive steps can be described. The first step is the movement of water from the atmosphere into the soil. Its efficiency can be measured as the ratio of the amount of water that infiltrates the soil to the amount of water that falls as precipitation. Its efficiency can be increased by e.g. improving soil management practices (e.g. use of conservation tillage) or increasing plant canopy cover (so the momentum of rain is dissipated by the leaves before hitting the soil). The second step is the movement of water in the soil to the root zone of the crop. Its efficiency can be measured as the ratio of the amount of water retained at the root zone to the quantity of water that infiltrates the soil. The efficiency of the water use process thereafter is the same as for irrigated crop production, continuing from steps iv) to viii).

To consider the pathway of water usage for animal production on rangelands, a total of eight steps can be considered. The first six steps are the same as for rainfed cropping (i.e. beginning with the movement of water from the atmosphere into the soil and ending with the conversion of carbon dioxide assimilated by photosynthesis to plant biomass (step vii)). The next step is the consumption of the plant biomass by the animal through grazing. Efficiency of this step, calculated as the ratio of the plant biomass grazed to the plant biomass available, is influenced by factors such as the palatability of the plant material and the grazing density. The final step is the conversion of plant to animal biomass within the animals. Its efficiency can be roughly calculated as the ratio of live mass of the grazing animal to the plant biomass consumed and is influenced by factors such as the digestibility and nutritional content of the consumed plant biomass and the energy requirement of the animal for maintenance, grazing and other activities.

Similar pathways exist to describe water use in other kinds of livestock production systems and in aquaculture and forestry. For livestock production, the main use of water is for the feed and plants they consume as only a small fraction is devoted to their drinking water requirements. For aquaculture, the main uses of water are for production of feed they consume and for freshwater required in operation of aquaculture farms (Molden et al., 2007b). For forestry, most of the resources worldwide are found in natural, largely unmanaged forests and only about 5% of the forest cover is in forest plantations (defined as forest stands established by planting or/and seeding in the process of afforestation or reforestation). There is a growing use of wastewater for irrigation in forestry, in particular for hybrid poplars and eucalyptus which are effective in removal of nutrients and offer biomass from short-rotation forestry (Christersson and Verma, 2006).

WHAT ROLE CAN BIOTECHNOLOGIES PLAY?

The term biotechnology includes a broad suite of tools. They present varying degrees of technical sophistication, requiring differing levels of human capacity, infrastructure and capital inputs. They encompass techniques such as the relatively simple application of micro-organisms for pest control or as fertilizers in agriculture; the use of molecular DNA markers located close to genes affecting traits of interest (i.e. marker-assisted selection [MAS], where the traits might be genetically simple [e.g. many disease resistance traits in plants that are controlled by just one or a few genes] or complex [includes most economically important agronomic traits, which are typically influenced by many genes, so-called quantitative trait loci (QTLs), and environmental effects]); and the transfer of genes from one species into the genetic material of another species, producing transgenic or genetically modified organisms. All of these will be mentioned in this Section.

The main application of biotechnology that will be considered in this conference is in improving the efficiency of water use in agriculture and this will be discussed first. Then, two specific applications of micro-organisms in agriculture (as biofertilizers and for wastewater treatment) will be briefly discussed.

Improving the efficiency of water use in agriculture

As described previously, to improve the efficiency of water use in agriculture, all the sequential steps in the water use pathways need to be considered in an integrated approach as it is more effective to make modest improvements in several of these steps than major improvements in just one or two steps. For some of them (e.g. involving the movement of irrigation water from a source to the farm), improvements can be made by non-biological means only while others (e.g. assimilation of carbon dioxide by photosynthesis) are influenced by both biological (e.g. efficiency of photosynthesis in the plant) and non-biological (e.g. air temperature) factors. Several of the eight steps described previously are shared in different water use pathways in agriculture. Thus, steps iv) to vii), beginning with the availability of water retained at the root zone of the plant and ending with production of plant biomass, are common to the pathways for production of crop biomass (using either irrigation or rainfed water resources) and to animal production (through grazing and/or consumption of feed) as well as to aquaculture (when plant material is used in aquafeeds). For the steps influenced by biological processes, efforts can be made to increase their efficiency through application of conventional plant breeding and/or biotechnology tools.

Water scarcity and drought is a problem for many economically developed countries (e.g. Australia, United States) as well as many developing countries, so both public research organizations as well as private breeding companies in developed countries have invested considerable resources into investigating the genetic mechanisms controlling crop water use, albeit in a relatively limited number of crop species. While impossible to describe in detail here, a brief illustration of these advances can be provided by considering step vi) described previously i.e. involving transpiration efficiency, which describes the ratio of carbon dioxide fixation during photosynthesis relative to water loss through transpiration. Transpiration efficiency has been shown through extensive research to display significant genetic variation in plants (Masle, Gilmore and Farquhar, 2005). Using molecular markers, several potential QTLs for the trait have been detected over the last 15 years and the first one has been isolated recently, in the extensively-studied model plant species *Arabidopsis thaliana* (Masle, Gilmore and Farquhar, 2005). This erecta gene, previously known for its effects on flowering, influences transpiration efficiency in a number of ways (through e.g. an effect on the density of stomata on the leaves) and, using its DNA sequence, similar genes in species like rice, sorghum and wheat have been found. Masle, Gilmore and Farquhar (2005) conclude that finding the gene will "assist in designing strategies for improved transpiration efficiency under dry conditions on the one hand, and removal of stomatal limitations and increase of yield potential in well-watered conditions on the other". Several kinds of tools and approaches exist for the introgression of such genes and genomic regions into elite crop varieties that are sensitive to water scarcity (e.g. Varshney, Graner and Sorrells, 2005).

Transpiration efficiency is also influenced by the basic photosynthetic pathways used by plants i.e. whether they are C3 plants (where carbon dioxide is taken up by the plant to form molecules with 3 carbon atoms; includes most plant species e.g. rice), C4 plants (where carbon dioxide is taken up to form molecules with 4 carbon atoms; represents over 8,000 species of flowering plants e.g. corn, sugarcane, sorghum) or crassulacean acid metabolism (CAM) plants (where the C4 and C3 pathways are used at different parts of the day, e.g. cacti, pineapple). Transpiration efficiency is highest for CAM plants, which open their stomata at night when water evaporation rates are low, and are higher for C4 than C3 plants (Hsiao, Steduto and Fereres, 2007). Indeed, the International Rice Research Institute (IRRI) is interested in developing rice plants that are C4 rather than C3 (Normile, 2006).

Similarly, biotechnology can play a role in increasing the understanding and efficiency of other steps in the water use pathways. For example, for the 2nd step in the pathway described previously for rainfed crops, involving water that has infiltrated the soil moving to the root zone of the crop, the plant's roots system is clearly important and much work has been done to identify genes and biochemical pathways controlling the mechanisms of root growth (see e.g. http://rootgenomics.rnet.missouri.edu/prgc/index.html). Several studies have investigated QTLs for root traits (such as total root number, maximum root length) in rice and their associated effects on other drought-related traits. A small number of these studies have used MAS to introgress the desirable QTL alleles into different genetic backgrounds and these results indicate that the effect of the QTL alleles can be influenced by the genetic background (Tuberosa and Salvi, 2006).

Throughout this document, the focus so far has been on the improvement of water use efficiency, defined as output of harvestable biomass per input of water and little mention has been made so far of the many drought-related terms used in the scientific literature. Following Blum (2005), when one plant variety or species yields better than another one under a severe strain of drought, it is relatively more drought resistant. Plants can resist drought in two ways: by dehydration avoidance or dehydration tolerance. Dehydration avoidance is the plant's capacity to sustain high plant water status or cellular hydration under the effect of drought. The plant avoids being stressed through mechanisms such as enhanced capture of soil moisture (e.g. reaching deep soil moisture with a long root) or reduced water loss (e.g. having reduced plant size and/or leaf area). Reduced growth duration (with early flowering) is also an important mechanism as the plant generally uses less water and can also avoid the end of season (terminal) stress. Note, as the amount of rainfall generally varies throughout the year, the farmer can also sow in the season when water will be more plentiful for the growing crops, thus giving them the possibility of avoiding water stress. However, in some cases, there are obstacles to choosing the planting season to optimize water use, and conventional breeding and biotechnology can assist here. For example, in the Central and West Asia and North Africa region, chickpea is traditionally planted in spring and drought is a major problem. Research has shown that if planted in winter, it can produce higher yields because there is more rainfall and it can escape terminal drought as it matures about a month earlier. However, for winter planting the cultivars must possess resistance to Ascochyta blight (a fungal disease that is especially damaging when the crop is sown in winter) and tolerance to cold. Cultivars for winter planting can, however, be developed using conventional breeding, MAS or genetic modification (ICARDA, 2006).

Dehydration tolerance is the plant's capacity to sustain or conserve plant function in a dehydrated state. This strategy is relatively rare, with the notable exception of a group of flowering plants called 'resurrection plants', which can withstand severe water loss and stay in the dehydrated state until water becomes available, allowing them to rehydrate and resume full physiological activities (e.g. Bartels, 2005). In general, natural and artificial selection have given a preference to dehydration avoidance over dehydration tolerance as the major strategy for plants to cope with drought stress (Blum, 2005).

The relationship between the different water-related traits is sometimes not straightforward, which has important implications for deciding what the selection goal should be. For example, although water use efficiency is often equated with drought resistance, this is not always the case. Some studies have found that differences in drought resistance among populations may not be related to differences in water use efficiency. Furthermore, Blum (2005) concludes from a review of the scientific evidence that plants achieve high water use efficiency (which is a ratio) by reducing water use (e.g. by reduced plant size, leaf area or growth duration), the denominator, rather than by increasing plant production, the numerator, and that if low water use is the breeder's target, it is highly probable that selection for the trait can be achieved by directly selecting for characteristics such as small plant size, small leaf area or reduced growth duration rather than attempting to measure water use efficiency and select for this trait.

Whether low water use, or high water use efficiency, is the breeder's target can be influenced by socio-economic factors, such as whether the cost of water is low (e.g. due to government subsidies) or whether the farmers are motivated to conserve water to be used by other people (Hsiao, Steduto and Fereres, 2007). In addition, there are differences between irrigated agriculture, where the farmer is generally interested in saving water to lower input costs or increase production, and rainfed agriculture where the farmer is generally interested in maximizing use of the water that falls as precipitation in an effective and efficient way (e.g. through reducing evaporation and capturing deep soil water).

Finally, as further 'food for thought' for the debate during the e-mail conference, some of the conclusions from an important recent conference on sustaining and improving plant production under drought stress and water-limited agriculture are reproduced below (InterDrought-II, 2005):

- As a result of the spectacular development and attraction of molecular plant biology, emphasis in research and education in plant and agriculture sciences has shifted to an appreciable extent from plant breeding, agronomy and physiology towards biotechnology and molecular biology. This has resulted in a general reduction in the expert workforce and the research/teaching infrastructure of these disciplines. Education in agronomy, soil science, plant breeding, and plant physiology is hindered in terms of available teaching capacity and studentships.
- While basic research in plant biotechnology research towards the genetic improvement of crop productivity in water-limited conditions has expanded in recent years, the collaboration with plant breeding has been insufficient (with the exception perhaps of the private sector). This lack of collaboration hinders the delivery of biotechnology-based solutions to the end-user in the field, i.e. the farmer. There is an exponential growth of information in genomics with a proportionally minute rate of application of this information to effective problem-solving in farming under water-limited conditions.
- At the same time, conventional plant breeding has been making well-recorded achievements in releasing improved varieties that perform relatively well under water-limited conditions, almost everywhere around the world.
- Although substantial progress has been achieved during the past decade in our capacity to identify and clone genes and QTLs, the contribution of MAS towards improved crop production under water-limited conditions has not met the original expectations.
- Transgenic technology is coming of age in the sense that certain genes conferring drought resistance that were identified in model organisms are now being tested in the field in transgenic crop plants, with encouraging results. Successful case histories should be duly reported and further confirmed by multidisciplinary scientific teams operating under field conditions.

Two specific applications of micro-organisms

Micro-organisms (or microbes) are living organisms which are microscopic in size, and include bacteria, fungi and viruses. Here, two specific applications of micro-organisms of relevance to water use in agriculture are discussed; the first regarding inoculation of crops and forest trees with mycorrhizal fungi, which can improve plant productivity in water-limited conditions, and the second regarding use of micro-organisms to improve the treatment of wastewater that can then be used e.g. in agriculture.

Mycorrhizal fungi

Mycorrhizae are symbiotic associations that form between the roots of plant species and fungi (see e.g. Sylvia et al., 2005). The hyphae (thread-like structures that are part of the body of the fungi) spread through the soil, taking up nutrients such as phosphorus and absorbing water, and transporting them to the plant root, and in return the fungi receive sugars from the plant. Almost all plant species form mycorrhizae. A number of different types of associations exist, of which arbuscular mycorrhizae (AM, also called vesicular-arbuscular mycorrhizae) and ectomycorrhizae (EM) are the most widespread and economically important. In AM, the hyphae penetrate and grow within the plant root cells. The fungi that form AM are part of the Glomeromycota fungi, involving less than 200 described species, and most crops and forest trees form AM with these fungi which tend to have a broad host plant range. In EM, the hyphae of the fungi do not penetrate the plant root cells and the external surface of the roots is covered by a characteristic sheath of hyphae. Compared to AM, the fungi that form EM are more diverse, involving over 4,000 fungal species (including e.g. truffles), although the range of plant species that form EM is more limited, involving trees from just a few families, including the fir, oak and pine.

The extensive amount of research literature available on the subject (mostly on AM) indicates that mycorrhizae often have a substantive impact on water movement into, through and out of host plants, with consequent effects on plant tissue hydration and leaf physiology. They usually increase host growth rates during drought, by affecting nutrient acquisition and possibly hydration, and typically increase water use efficiency, with the effects influenced by the kind of fungi involved (Augé, 2001).

Mycorrhizal fungi can therefore be applied as a biofertilizer with the aim of increasing growth potential and reducing water and fertilizer use, and they are used in crop production, horticulture, habitat restoration, bioremediation and forestry. The mycorrhizal fungal inoculum can be applied in a number of ways e.g. by simply applying soils known to contain the desirable mycorrhizal fungi to areas lacking the fungi or using one of the many commercially available products available worldwide (Schwartz et al., 2006). Benefits, however, are not guaranteed and a number of factors have to be considered when assessing their potential application, such as competition with other soil micro-organisms as well as the dependence of the plant species on mycorrhizae, the nutrient status of the soil and the inoculum potential of the mycorrhizal fungi already present in the soil (Sylvia et al., 2005).

Micro-organisms in wastewater treatment

As described earlier, use of wastewater for crops, forestry and aquaculture is a reality in developing countries and treatment of the wastewater before use, although a major challenge, is important for human health and environmental considerations. In the secondary and tertiary stages of wastewater treatment, micro-organisms play an important role. According to Daims, Taylor and Wagner (2006), "biological wastewater treatment is among the most important biotechnological applications". A wide range of biotechnologies are applied here. A common one is selection of microbial cultures so they are highly efficient at carrying out a specialized task, such as degrading specific toxins in water. For example, Heesche-Wagner, Schwarz and Kaufmann (2001) selected genetically improved bacteria by inducing genetic variation using ultraviolet radiation and then selecting for superior mutants in an environment with ever increasing concentrations of organic toxins.

Daims, Taylor and Wagner (2006) describe how molecular techniques have greatly improved the knowledge available about key micro-organisms involved in wastewater treatment processes. These techniques include fluorescence in situ hybridization (FISH), where fluorescently labelled DNA sequences are added to bacterial cells, making it possible to identify, quantify and localize different bacterial species in complex microbial communities (e.g. in activated sludge) without having to actually cultivate the microbes. A further development of this technique, called FISH-MAR, which combines FISH with microautoradiography (MAR), also makes it possible to simultaneously analyse the physiology (e.g. what organic material they take up) and identity of uncultured micro-organisms. Daims, Taylor and Wagner (2006) describe the application of biotechnology to three specific aspects of wastewater treatment where e.g. one relates to the excessive growth of filamentous bacteria which can prevent settling of flocs during activated sludge processes, leading to potential operational difficulties as well as public health problems. Molecular techniques have been successfully applied to identify the filamentous micro-organisms involved and study how they function (what organic substrates they use etc.), in order to come up with solutions to the problem.

Sequencing of the genetic material (genome) is also underway or already completed for a number of specific micro-organisms involved in different aspects of wastewater treatment, such as ammonia oxidation, denitrification or nitrite oxidation (all involved in nitrogen removal) or floc/biofilm formation or bulking, both important in the activated sludge process (Daims, Taylor and Wagner, 2006). For example, the genome sequence of a key bacteria involved in the removal of phosphorus from wastewater was recently reported by Garcia Martín et al. (2006). Availability of these sequences will improve understanding of the diverse processes involved in wastewater treatment and how they can be improved.

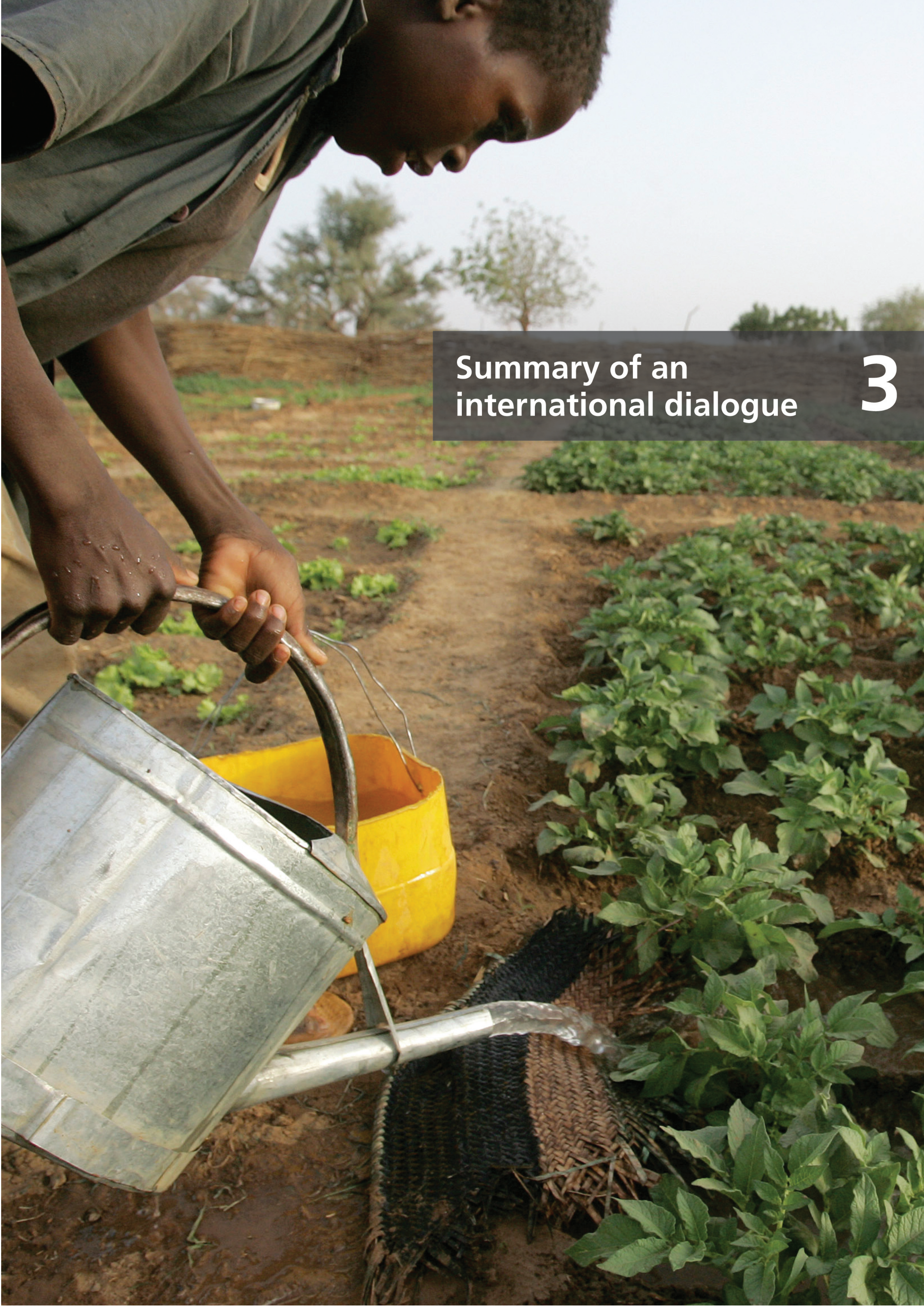
SOME ISSUES AND QUESTIONS RELEVANT TO THE DEBATE

As with each conference hosted by this FAO Biotechnology Forum, the focus is on application of agricultural biotechnology in developing countries. In this debate on the role of biotechnology for helping developing countries to cope with water scarcity, some of the specific questions that participants might wish to address in the e-mail conference are given below:

- In this document, a number of major strategies have been briefly described for coping with water scarcity. Compared to them, how important is improving the efficiency of water use in crops through biotechnology in developing countries?
- Which biotechnology tools have greatest potential for improving the efficiency of water use in crops in developing countries?
- How important are biotechnology tools compared to conventional breeding for improving the efficiency of water use in crops in developing countries?
- Research on water use in crops has focused on a few species of major economic importance while so-called orphan crops, of local or regional importance for nutrition and income in poor regions, have been neglected, despite their importance for food security. How can this situation be changed?
- Water use efficiency has different implications in irrigated and non-irrigated (dryland) agriculture. What can biotechnology offer developing countries in each of the two domains in terms of increasing productivity under water scarcity and improving the efficiency of use of the applied irrigation water?
- For the livestock sector, what role should biotechnology tools play in increasing the efficiency of water use in developing countries?
- For the forestry sector, what role should biotechnology tools play in increasing the efficiency of water use in developing countries?
- For aquaculture, what role should biotechnology tools play in increasing the efficiency of water use in developing countries?
- What role and relevance do biotechnologies currently have in wastewater treatment in developing countries? And in the future?
- Is the rapidly-accumulating molecular information on micro-organisms involved in wastewater treatment processes likely to result in the better design and operation of wastewater plants in developing countries?
- What role do biotechnologies have for the removal of heavy metals, such as arsenic, from irrigation water in developing countries?
- How important is application of mycorrhizal fungi as a biofertilizer in helping developing countries to cope with water scarcity?

Summary of an international dialogue

3



EXECUTIVE SUMMARY

The availability of water is a challenge for all countries, but especially for those with scarce water resources and where the livelihoods of its people depend heavily on agriculture. The term 'biotechnology' includes a broad suite of tools that present varying degrees of technical sophistication and require different levels of capital input. A number of them can be used to mitigate water scarcity in agriculture, including a variety of plant biotechnologies, e.g. marker-assisted selection (MAS), and microbial biotechnologies, e.g. use of mycorrhizal fungi as a biofertilizer. Many examples of applications of biotechnology in developing countries were cited during this FAO e-mail conference. There was a general consensus that biotechnology has a valuable role to play in addressing the challenge of water scarcity in developing countries, although opinions differed on the relevance of different biotechnology tools. Despite much promising research and significant possibilities, the conference also indicated that many applications of biotechnology in this area have not yet met their full potential to deliver practical solutions to the end-user in developing countries.

Among the different plant biotechnologies, MAS and genetic modification elicited most discussion. Although the general opinion of participants was that MAS had significant potential, some underlined the obstacles to its practical application in developing countries, such as the relatively high costs of breeding using molecular markers and the complexity of traits involved in drought resistance and water use efficiency in plants. For genetic modification, promising research results were reported but many participants expressed doubts about the role of genetically modified crops in helping developing countries to cope with water scarcity, referring to the kinds of obstacles also relevant to MAS (costs, complexity of the traits to be improved etc.) as well as to a number of additional concerns, such as intellectual property rights issues and potential environmental impacts.

To ensure that research initiatives to develop drought resistant crops are successful and that the resulting products actually reach the farmers, participants called for increased collaboration between researchers in different disciplines and for all relevant stakeholders to be involved in the design of solutions to the problems of water scarcity in agriculture. Research should not neglect dryland (non-irrigated) agriculture. The role of the Consultative Group on International Agricultural Research (CGIAR), a strategic partnership supporting the work of 15 international centres, in developing drought resistance crops was emphasized.

A positive outlook was foreseen for microbial biotechnologies in managing water scarcity. Participants described the potential of applying mycorrhizal fungi and certain bacteria as a biofertilizer to assist plants to cope with water stress, calling for greater research in this area. Several applications of biotechnology were reported as playing a useful role in treating wastewater, mainly on a small scale, involving the use of plants and microbes, so that it could be re-used for agricultural purposes. Participants also discussed the potential to design biotechnology-based wastewater treatment systems in such a way that they yield co-products (e.g. biogas) that could be used to generate income locally.

INTRODUCTION

The aim of this chapter is to provide a summary of the main arguments and issues discussed during the conference, based on the participants' messages. During the 4-week conference, a total of 78 messages were posted, each one numbered in order of posting. Specific references to messages posted, giving the participant's surname and message number, are provided here. All of the messages can be viewed at www.fao.org/biotech/logs/c14logs.htm. Note, in the Forum, participants are always assumed to be speaking on their own personal behalf and not on behalf of their employers, unless they state otherwise.

More than 400 people subscribed to the conference and the 78 messages were posted from 50 people living in 24 different countries; 75% of messages were from developing countries. Roughly 70% of messages came from people working in universities and in national or international research organizations, while the remainder came from people working as private consultants or in private companies, non-governmental organizations (NGOs), government ministries or UN organizations/projects.

Most participants directed their messages to the technical challenges associated with applying different biotechnology tools to address water scarcity in agriculture. Some discussed the application of biotechnology to develop drought tolerant crops, others with the aim to make more water available to crops through symbiotic associations with soil micro-organisms. A number of participants addressed the potential for biotechnology to treat wastewater for re-use in agriculture. Some participants addressed their remarks to the appropriateness of different biotechnology tools to confront the problem, in the context of other approaches or potential solutions. The challenge of delivering effective biotechnology-based solutions to the end-user in the field was discussed. Participants also addressed cross-sectoral issues, such as resource availability, constraints and international collaboration. Most of the discussion, however, centred on technical issues. There was considerable agreement among the participants that the suite of biotechnology tools currently available holds much promise to address the challenge of water scarcity in agriculture in developing countries, although opinions differed on the merits of individual biotechnologies.

Discussions in the conference are summarized here under three main subjects: applications of biotechnology to develop crops with improved drought resistance or water use efficiency; the use of mycorrhizal fungi and bacteria as a biofertilizer; and the use of biotechnology in wastewater treatment. The chapter concludes with information on participation as well as a list of names and countries of the people whose messages are referenced.

CROPS WITH INCREASED DROUGHT RESISTANCE OR WATER USE EFFICIENCY

Conference participants were acutely aware of the importance, as well as the challenges involved, in endeavouring to develop crops that are better able to cope with water scarcity in agriculture. For Murphy (71), the most serious threat to future food production will come from aridification, rather than temperature change, and the wise and selective application of our increased scientific knowledge of crop breeding and agronomy will “largely determine whether our agricultural systems can weather future episodes of widespread and prolonged aridity”.

A number of different biotechnologies can be used to produce crops that are better able to cope with water scarcity in agriculture. Most discussion was dedicated to MAS and genetic modification with a few messages also dedicated to other crop biotechnologies. [Note, more detailed information on MAS can be found in a comprehensive book recently dedicated to this technology (FAO, 2007b)]. The issue of how to deliver real solutions to farmers was also considered as well as the role of the CGIAR.

Marker-assisted selection

Prakash (72) highlighted that MAS had been successfully used in agriculture for many years and its key advantage was the shorter time taken to introduce desired traits. Boopathi (2) believed that MAS could increase the productivity of crops in fragile environments, but he also highlighted a number of challenges to its use, including those related to experimental design and statistical models used for quantitative trait locus (QTL) analysis, an issue also raised by Manneh (40). Gupta (14, 25) gave some assistance on this and drew attention to a number of computer programmes that can be used for QTL analysis. Kumar (18), however, cautioned that before using any software in this area, one should carefully examine the methodology employed.

Agbicodo (45) maintained that with MAS for yield under water stress, two main issues had to be considered. The first was to select a trait that could be measured with reasonable accuracy to first establish the linkage with specific molecular markers (where the trait could be grain yield and its components and/or a specific physiological or morphological trait). The second was to choose the kind of markers to be used for genotyping. Kumar (18, 23) reported on their work in India carried out on drought tolerance in pearl millet which had shown that terminal drought tolerance is the major factor for yield determination under drought-prone rainfed conditions of the semi-arid tropics. Lin (34) pointed to research showing, similarly, that the timing of drought had a significant impact on yield and commented that the division of drought according to time (pre-flowering, flowering and terminal drought), and its effects on yield components, highlights the complexity of breeding for drought resistance. He maintained that if, for a particular crop in a certain region, it is known that drought stress is most prevalent during a certain stage of crop development, then attention could be focused on QTL mapping for drought-related physiological traits at that stage of crop development.

Manneh (40) pointed out that significant genetic variation for drought tolerance at different developmental stages of rice had been reported by several researchers. He commented that although QTLs had been reported for some traits associated with drought tolerance (deep and thick roots, good osmotic adjustment etc.), not much success had been achieved in developing drought tolerant rice cultivars through MAS. He noted that many MAS research activities usually focus on introgressing a gene (or genes) for one trait at a time, even though the incidence of drought is highly unpredictable and the effects of drought stress on rice depend on the developmental stage at which the stress occurs, and so different gene complexes are involved. He therefore suggested that MAS for drought tolerance might require pyramiding appropriate alleles of different genes controlling traits that contribute to drought tolerance occurring at different developmental stages.

While comments about MAS were generally positive, Samanta (65) noted that high-tech molecular breeding is costly for developing countries and, instead, advocated that the existing genetic diversity for drought tolerance be evaluated by screening large numbers of genotypes under the specific environment where the variety would be cultivated. Gupta (78) agreed, suggesting that "expensive techniques of molecular biology should be used only when there is no substitute". Dulieu (55) doubted whether the large number of crop species used for human consumption in arid and semi-arid regions could be rapidly improved with the help of molecular mapping, considering that there is comparatively little financial support to achieve the goal by this means. He, supported by Boopathi (58), noted that plant breeding for drought resistance could also be carried out successfully without molecular markers and he proposed a rough strategy for crops where no molecular data existed that would allow the rapid selection of varieties able to survive and yield in water-limited conditions. In this context, Samanta (65) described the successful use of a local drought tolerant rice variety developed by traditional selection in West Bengal in India. Babu (48) argued that large-scale, field-based phenotyping under the target ecosystem for drought stress was critical for transferring drought tolerant lines to the farmer, and lamented the dearth of published literature in this area.

Rakotonjanahary (70) commented that while MAS tools have considerable potential to improve the efficiency of water use in crops, drought tolerance is a very complex trait and the application of MAS in developing countries has many bottlenecks, both technical and practical (costs, infrastructure required etc.). Ashton (67) argued that while advanced breeding techniques like MAS might offer some solutions, more readily affordable and available methods should be preferred.

Genetic modification

Prakash (72) reported that plant biotechnology had a good track-record in providing benefits to farmers in developing countries and that, even though most of the current genetically modified (GM) crops were developed by the private sector in industrialized countries, 90% of farmers using them were in developing countries. He also said that the private sector was actively developing technology to deliver drought tolerance in crops and, although not intended to result in crops grown under extreme desert conditions, their promising results led him to believe that this area should have some priority among technologies being developed to mitigate drought conditions in developing countries.

Participants discussed the technical feasibility of using genetic modification to create crops with enhanced drought tolerance. Venkateswarlu (42) reported on their ongoing research in India to produce GM crops with enhanced tolerance to abiotic stresses, where genes responsible for osmotic adjustment had been introduced successfully to sorghum and where similar work had been initiated on blackgram and greengram. Mundembe (44) was encouraged by the message of Venkateswarlu (42) and highlighted the ability of 'resurrection plants' (discussed in chapter 2) to tolerate near-total water loss in their vegetative tissues and revive to full physiological activity on re-hydration. He expressed the hope that it would be possible to develop crops with some of these traits. Lin (50) added that several groups worldwide were working on resurrection plants and drew attention to the work of one such group on *Xerophyta viscosa*, a native of Southern Africa, where several genes of interest had been isolated and transformation of maize plants was underway, inserting the ALDRXV4 gene, which in model plants conferred significant tolerance to severe osmotic and salt stresses.

In light of the discussion on MAS, which highlighted the complexity of the genetics of drought tolerance or water use efficiency, Kumar (23) raised a query about transgenic plants developed with a single gene, questioning how one such gene, like the erecta gene (also discussed in chapter 2), could exert control over the entire physiological process of water use efficiency or the pathway of genes involved. Murphy (73) also cited the promising research results on the erecta gene, isolated in the model plant *Arabidopsis*, but argued that although this approach merits further attention, many other genes might be involved in a practical field situation.

Murphy (73) commented that although much mention had been made of the potential of genetic modification to improve drought tolerance in crops in developing countries, limited knowledge of stress-associated metabolism in plants still constituted a significant handicap to this in practice. He also argued that it is often the combination of different stresses that negatively impacts crop performance, and because the co-presence of several stresses is the norm in the field, “the success of a molecular approach to stress remediation in crops will require a broader and more holistic approach than we have seen hitherto”. To support this, he drew a comparison with salt tolerance (an osmotic stress, closely related to drought stress) and noted that attempts to improve salt tolerance through genetic modification (or conventional breeding) had so far met with very limited success, largely due to the complexity of the trait. Similarly, El-Tayeb (57) argued that GM crops for drought tolerance and other environmental stresses are not likely to be available in the foreseeable future because of their complexity and “our extremely limited knowledge of biological systems and how genetic/metabolic functions operate”.

Several participants argued that alternatives to genetic modification should be used. Seshadri (54) was concerned about developing GM drought tolerant crops, arguing that they were just causing greater problems for the agricultural community, and proposed instead a list of 13 alternative technologies and strategies such as the use of biofertilizers, mulching and use of crop species that demand less water. Oehler (56) agreed, arguing that genetic modification was an extremely expensive means to deal with water scarcity, and she too advocated use of alternative solutions. Dulieu (63) also agreed with Seshadri (54), raising, among others, concerns about ownership of the genetic resources by the international corporations and about transgene flow. Ferry (64) also agreed, arguing that many better alternatives exist and that “genetic modification to introduce genes to improve drought resistance seems to me much more another hype for the biotechnology sector to get funds”. Varghese (66) supported Oehler (56), highlighting in particular concerns about the safety of GM crops. Ashton (67) agreed with Seshadri (54) and said genetic modification was a “questionable option” in this case, given his appraisal of its costs and benefits. Okoli (69), echoing Muralidharan (60), advocated use of proven traditional biotechnologies rather than putting “the major share of the strategies on modern biotechnology and expect miracles to happen”. Murphy (71, 73) argued that the present methods of genetic modification were still too primitive to contribute significantly, mainly because traits such as drought tolerance are highly complex and regulated by many genes, but maintained that non-GMO biotechnologies such as MAS could be useful. Echoing concerns also raised by Nasar (1) and El-Tayeb (57), Murphy (71) added that a drawback of most transgenic technologies is their ownership by the private sector, which can limit public-good applications. On the other hand, Prakash (72) noted that plant biotechnology is just one of many approaches to address water scarcity, and said that different approaches should be considered as complimentary, rather than as alternatives.

Other crop biotechnologies

Murphy (73) noted that another option to introduce drought tolerance was to use wide crossing and tissue culture methods, for example, to cross drought tolerant pearl millet with one of the other high-yielding cereal crop species, to create a new drought tolerant, high-yielding hybrid species. He pointed to the success of a similar strategy in creating the new rye/wheat hybrid species, triticale. Liu (28) also highlighted the success of the hybrid New Rice for Africa (NERICA), developed using embryo rescue and anther culture techniques, which “produces more than 50% more grain than current varieties when cultivated in traditional rainfed systems without fertiliser”. Dulieu (55) raised the issue of mutation breeding, noting that the available pool of genetic variability can be enlarged by mutagenesis, and low cost screening can be applied to identify plants with desirable traits. Rakotonjanahary (70) supported this and reported on their work on mutation breeding in Madagascar to generate drought resistant lines in rice, groundnut and bambara nut. Shanker (68) argued that genomics tools had already provided a wealth of data and better understanding of the changes in cellular metabolism that are induced by abiotic stresses, although fewer results had been forthcoming with respect to the functioning of the whole plant. Combined with tools such as bioinformatics, allele mining and proteomics, he saw that “it will be possible to rationally manipulate and optimize tolerance traits for improved crop productivity well into the twenty-first century”.

Delivering practical solutions to the farmers

To develop new successful varieties in this technically difficult area, participants said that researchers needed to collaborate across disciplines (e.g. Dulieu, 55; Murphy, 71; Prakash, 72). Krishna (35) suggested that in breeding crop varieties to grow in water-limited conditions, a major thrust should be directed to the development of varieties with high water-use efficiency, either through conventional breeding or with the aid of molecular techniques. She advised that in taking this approach, "a multi-disciplinary team consisting of molecular biologists, plant physiologists, geneticists, plant breeders and agronomists can deliver the product in a much more effective way than solely by the molecular biologists/breeders". Similarly, Nicolay (41) warned that a lack of cooperation between plant breeders and biotechnologists would lead to missed opportunities.

To develop new varieties, across-country collaboration and within-country capacity building may also be important. Primo (12) pointed that out in a small country such as hers, the Federated States of Micronesia, there might not be sufficient science and technology expertise to do the research in-country so partnerships and technology transfer would be crucial. Omari (22) and Rivasplata Maldonado (49) also underlined the importance of building the capacity of scientists in developing countries to take advantage of biotechnologies that can assist with water scarcity.

However, the successful development of drought tolerant varieties by good research initiatives is not the final goal in itself. After they have been developed, they should be used, but in practice there may be problems in reaching the farmers (Lin, 62). For example, Paul (17) wrote "India can boast of a highly technical and extensive agricultural research system with accomplished scientists and managers. But, somehow or other, the gains of research and development are not percolating down to the people in general". Ultimately, as pointed out by Shanker (68), the value of any genes or pathways for drought tolerance in crops can only be judged by their eventual performance in the field. The topic of how to ensure that results from the research laboratory lead to practical implementation in the field was also discussed in the conference.

Nicolay (41) emphasized that the bottom-line should be the delivery of sustainable and widely accepted services, products and approaches, and added that all relevant stakeholders should participate in the design of solutions. Referring to discussions in Conferences 8 and 12 of the Forum (FAO, 2006a), on the role of biotechnology in the agricultural research agenda and on public participation in decision-making regarding GMOs respectively, he suggested that if stakeholders such as farmers, consumers and local politicians were not involved in developing solutions to water scarcity in agriculture then they might not be implemented in practice. In a similar vein, Tchouaffé (47) commented that community leaders, local authorities and NGOs each had an important role to play in technology transfer and he stressed the importance of encompassing all stakeholders and establishing partnerships between public and private sectors to develop solutions that would be "efficient and economically viable, but also socially acceptable". In designing solutions, Nicolay (41) advocated using an holistic approach that, he argued, would help to close the gap between science, research and development on one side and "a rather confused society dealing with highly complex but existential issues" on the other. Sahoo (46), furthermore, asked "how can biotechnology be made popular among the farmers in developing countries where they are still guided by traditional customs and norms?" and cautioned that without addressing this issue, the success of an external agency introducing biotechnology-based solutions was doubtful.

Nicolay (61), returning to the question of how biotechnologies could best be implemented for practical solutions, emphasized that biotechnology could best play a role if it is accepted that it is only a part of the solution, and that institutions and the people involved constituted another part. Lin (62) highlighted the need to involve the private sector, arguing that public-private partnerships are a vital means to ensure that improved varieties will reach farmers who need them. Prakash (72) supported Nicolay (41, 61) and Lin (62), urging that once solutions have been identified, there is a need for stakeholders to form partnerships to evaluate them for different local contexts and to ensure that they are accessible, affordable and appropriately used.

Which kinds of farmers should be targeted by this research? Krishna (3) felt that dryland farmers were being unduly neglected. She argued that biotechnologies, such as MAS, were being used extensively in improving water use efficiency in irrigated or commercial crops, albeit without major success so far, but that greater attention should be given to dryland agriculture. The importance of focusing on dryland agriculture was also highlighted by Varghese (66) and Di Ciero (4), who mentioned in particular the small, poor farmers in the northeast of her country, Brazil. Several participants also highlighted the importance of a number of non-biotechnology approaches, such as mulching, to save water in dryland agriculture (e.g. Peter, 5; Tchouaffé, 6; Sangaré, 11; Paul, 17; Achakzai, 26; Liu, 28; Okoli, 69).

Role of the CGIAR

Abdel-Mawgood (37) highlighted the role that international research centres can play in providing help to developing countries to develop their own crops that are tolerant to abiotic stresses, urging that they should play a more substantial role in making breeding materials and genetic constructs readily available for researchers in developing countries. Lin (62) pointed out that the CGIAR has 22 mandated crops, where increased drought resistance is a breeding goal in all of them, and that for most of these crops, sources of enhanced drought tolerance had been identified, and several varieties had been released for evaluation by researchers and farmers. Some examples of this kind of research carried out at two of the CGIAR centres, the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) and the Africa Rice Center (WARDA), were provided by Kumar (18, 23) and Manneh (40) respectively. Lin (62) added, however, that a bottleneck exists in getting the released varieties to the farmers, because the CGIAR centres have no mandate to produce basic or certified seed for distribution, and state actors in many countries are unable to provide these services effectively. Murphy (71) advised that the scarce resources of organizations such as the CGIAR should be focused on the proven approaches of conventional breeding, supplemented by all available modern technologies, providing the latter are both appropriate and cost-effective for the crop or region in question.

USE OF MYCORRHIZAL FUNGI AND BACTERIA IN WATER-LIMITED CONDITIONS

Mycorrhizal fungi and bacteria can be applied as a biofertilizer with the aim of increasing growth and improving water uptake. Several participants raised this issue as one effective way that biotechnology might be applied to improve the efficiency of water use in agriculture (e.g. Krishna, 36; Venkateswarlu, 42; Nasar, 76), and there was a general call for greater research in this area. For example, Ashton (67) felt that the use of microbial inoculants in the soil was "perhaps one of the most exciting possibilities offered by microbiology towards reducing drought impacts on plants" but cautioned that this, like other solutions, cannot be analysed in isolation. Benefits, however, are not guaranteed, and participants reported that technical challenges to their use as a biofertilizer persist. Questions were also raised about access to the technology for farmers in developing countries.

Nasar (1) said that their results of farmer-participatory experiments over several years in India had shown that the use of microbial fertilizers in combination with organic compost reduced the amount of irrigation water required; lowered the amount of diseases and pests; improved crop productivity and quality; and improved the water-holding capacity of the soil. Lin (10) similarly highlighted various studies on the effectiveness of mycorrhizal fungi as a biofertilizer. Oehler (8) noted from her study of the literature that ectomycorrhizae are often involved in acquiring water and nutrients from microenvironments in the soil that are unaccessible to plant roots because of physical or chemical restrictions. She argued, however, that the inoculation of plants with desired strains was difficult and resource-intensive. Regarding the challenge of inoculation, Venkateswarlu (53) pointed out that the cropping systems could be organized in such a way that one of the crops in the sequence might be highly mycorrhizal dependent, so that naturally the mycorrhizal fungal population in the field would increase substantially without any inoculation.

Some participants raised the point that the efficiency of water uptake by plants aided by mycorrhizal fungi can be enhanced in the presence of other organisms and agents. For example, Krishna (36) noted that the application of mycorrhizal fungi can help increase the efficiency of water use, "especially when applied together with other beneficial micro-organisms such as Rhizobium, plant growth promoting rhizobacteria and phosphate solubilising bacteria or when combined with cheap sources of phosphorus such as rock phosphate".

Edema (43) was cautious, stating that a lot more work needed to be done to confirm the value of mycorrhizal fungi as a biofertilizer in helping developing countries to cope with water scarcity, indicating that some scientific studies had shown that, alone, they were not as efficient as believed. Gupta (14) acknowledged that a lot of research had been undertaken or was underway on the use of mycorrhizal fungi, but wondered whether there were examples of large-scale commercial use of this technology by farmers in the field. Morris (51) felt that the technology was being used more and more by larger commercial farmers with access to relatively short production distribution chains but noted the challenge of transferring the benefits to small farmers in rural areas in developing countries as many inoculant products have a relatively short shelf life or require stringent storage conditions that are often unavailable in these areas. He hoped that with advances in production and packaging it might be possible to increase the shelf life and tolerance of these products to sub-optimal storage conditions. As Venkateswarlu (53) summed it up: "ultimately, we need simple low cost approaches based on microbes, which farmers in developing countries can adopt."

Richardson (59) suggested that application of 'compost tea' (high in bacteria and fungi) had shown remarkable improvement on expansive grey clay soils, increasing friability, water intake, and productivity of many species of perennial grasses. He cautioned, however, that if the soil is degraded by erosion or poor management, several applications over several seasons may be necessary before the system becomes self-maintaining. Morris (51) reported that inoculation of crop roots with selected strains of *Trichoderma harzianum*, a fungus commercially produced as a biocontrol agent, can result in significantly larger root systems, many more root hairs and thereby more efficient nutrient and water uptake. Venkateswarlu (53) stated that although soil micro-organisms are generally known to be involved in nutrient transformation, their role in improving the fitness of plants in stress situations is now coming to light. Venkateswarlu (42) reported on their ongoing work on isolating rhizosphere micro-organisms that can improve soil aggregation when inoculated into the root zone, where they form a biofilm around the roots and significantly influence the water relations of the plant when subjected to water stress.

Gueye (16) discussed the role of rhizobia bacteria and argued that a lot of research supports the view that nodulation and nitrogen fixation activity in nodules were depressed in plants under drought conditions, but that no effect of water stress had been observed in plants inoculated with selected rhizobial strains. He added that nodulation and nitrogen fixation under water stress conditions depend not only on the plant species, but also on the selected rhizobial strains, and that suitable strains for use as inoculants are available in most microbiological resource centres devoted to rhizobial culture collections, in Brazil, Kenya and Senegal. He concluded that agricultural biotechnology should be focused on selection of specific rhizobial strains to maximize the process of biological nitrogen fixation to sustain agriculture in arid and semi-arid zones. Bhattacharyya (19) reported on the successful dual inoculation of pea plants with rhizobia and mycorrhizal fungi in desert soil in India.

BIOTECHNOLOGY IN WASTEWATER TREATMENT

Participants highlighted that an important way in which farmers cope with water scarcity in developing countries is the recycling of wastewater. The treatment of wastewater before use, although this in itself presents significant challenges, is crucial for human health and environmental considerations. This issue was raised early in the conference. Several applications of biotechnology were noted to have a useful role to play in wastewater treatment, including the use of plants and microbes.

Lin (9) drew attention to two ways in which biotechnology can contribute to improved water treatment - the development of biosensors for the detection of heavy metals, herbicides and other contaminants in water, and the development of biofilters to remove contaminants, such as heavy metals, from water. He reported that biofilters had been developed using the dry matter of the Azolla fern (a free-floating aquatic fern well-known for its capacity to absorb heavy metals) and that research was ongoing to use cyanobacteria (also known to be capable of absorbing heavy metals) in biofilters. Arora (20) agreed with Lin (9) and reported that her institute in India was working on using Azolla and algae for the removal of heavy metals, as well as nitrogen and phosphorus, to render wastewater safe for re-use in agriculture.

Okoli (27) supported such initiatives and reported on their research on indigenous plants in south east Nigeria to develop a simple method of bio-based treatment for wastewater, so that it would be suitable for livestock to drink. Both he and Van Milligen (24) mentioned use of the moringa tree for phytoremediation purposes and Bett (38) described the positive results from her project in Kenya using crushed seeds of the moringa tree to purify rainwater for household use. Rao (39), similarly, described the use of ground seeds of the tree *Strychnos potatorum* in rural Andhra Pradesh, India, to flocculate suspended matter, but noted that although these seeds, and seeds or wood paste of the moringa tree, can be used to clarify small amounts of water for domestic use, they are impractical for use on a larger scale. Similarly, Agarwal (52), while noting that small-scale farmers would like to treat wastewater and use it for their crops, was doubtful whether it would be possible for anything other than limited application, such as small kitchen gardens for growing vegetables.

Rivasplata Maldonado (49) noted that there were serious risks associated with use of wastewater without treatment. Omari (22) noted that the use of untreated water in Ghana to water vegetables was on the increase and argued that there was therefore an "urgent need to consider putting structures in place to treat wastewater used for irrigation purposes". She warned, however, that if not treated properly, use of wastewater could compromise water safety as the microbiological safety of treated wastewater was also a major concern. She called for more research on the biology of treated wastewater and the appropriate biotechnology tools that could eliminate harmful pathogens it might contain.

Nasar (1, 75), like Sharma (32), pointed out that arsenic contamination of the groundwater-irrigation water-soil-crop-animal-human continuum was a major concern. Nasar (75) noted that a number of weedy flowering and non-flowering plant species, crop varieties and cyanobacteria that absorb high levels of arsenic had been recorded and they were working to identify location-specific hyperaccumulators in West Bengal, India, for use in bioremediation of contaminated soils. He was, however, aware of the problems associated with this technology, such as the need for appropriate disposal after-use of the hyperaccumulating organisms, or the filtrates where arsenic filters have been used, to prevent toxic arsenic returning to the ecosystem. He was hopeful about the prospects of using genetic modification to develop organisms that could sequester heavy metals, but advised that at present the focus of developing countries ought to be on non-GMO options. Edema (43) said that biotechnology is playing, and will continue to play, a role in the efficient management of water resources in general and wastewater treatment in particular. Regarding removal of heavy metals from water, he noted that "there are many organisms that are able to degrade toxic materials and the application of biotechnology to improve their efficiencies holds a very promising future for water resources management and agricultural biotechnology".

Some participants highlighted the potential to design biotechnology-based wastewater treatment systems in such a way that they also yield co-products, such as oils, fertiliser and biogas, leading to the development of business opportunities. Van Milligen (24) pointed out that specifically crafted algae and other species can extract nutrients from polluted water, and not only clean it significantly, but also provide fuel, feed or fertiliser as a result. Rivasplata Maldonado (49) commented that anaerobic biotechnology can be applied in developing countries, since anaerobic wastewater treatments systems are relatively cheap and easy to handle. She remarked that upflow anaerobic sludge blanket reactors can help to reduce the organic load; are well adapted to tropical weather; do not require large amounts of energy; and generate biogas (that can be used e.g. for heating or cooking). The sludge produced can be used for re-inoculation or as fertiliser and the treated wastewater can be used to irrigate crops. She suggested that these co-products could be used to generate an income locally.

Omari (22) pointed to successes in the Netherlands in developing a bio-based water treatment system for vegetable processing facilities that had reportedly reduced water use by 50%, and in Germany, where an enzyme-based system for de-gumming of vegetable oil during purification after extraction had reportedly reduced water use by 92% and waste sludge by 88%. She urged developing countries to take advantage of these biotechnologies to address the challenge of water scarcity.

PARTICIPATION

The conference ran for four weeks, from 5 March to 1 April 2007. There were 431 subscribers to the conference, of whom 50 (i.e. 12%) submitted at least one message. There were 78 messages in total, of which 75% were posted by participants living in developing countries. Contribution to the conference came from all over the world, with 47% from Asia, 24% from Africa, 18% from Europe, 8% from North America and one message each coming from Latin America and the Caribbean and from Oceania. Contributions came from 24 countries, the greatest number from India, followed by France, the United States and Nigeria. The greatest proportion of messages came from people working in universities (42%), followed by those in research centres, including CGIAR centres (28%); in private companies or NGOs (8% each); and people working as private consultants (6%), for government ministries (4%) and UN organizations/projects (4%).

Name and country of participants with referenced messages (all can be read at www.fao.org/biotech/logs/c14logs.htm):

Abdel-Mawgood, Ahmed. Saudi Arabia
Achakzai, A.K.K. Pakistan
Agarwal, J.H. India
Agbicodo, Eugene. Nigeria
Arora, Anju. India
Ashton, Glenn. South Africa
Babu, R. Chandra. India
Bett, Bosibori. Kenya
Bhattacharyya, A.K. India
Boopathi, N. Manikanda. India
Di Ciero, Luciana. Brazil
Dulieu, Hubert. France
Edema, Mojisola. Nigeria
El-Tayeb, Ossama. Egypt
Ferry, Michel. Spain
Gueye, Mamadou. Senegal
Gupta, P.K. India
Krishna, Janaki. India
Kumar, P. Sathish. India
Lin, Edo. France
Liu, Junguo. Switzerland
Manneh, Baboucarr. Benin
Morris, Mike. South Africa
Mundembe, Richard. Zimbabwe
Muralidharan, E.M. India
Murphy, Denis. United Kingdom
Nasar, S.K.T. India
Nicolay, Gian. Ethiopia
Oehler, Friderike. Italy
Okoli, Charles. Nigeria
Omari, Rose. Ghana
Paul, D.K. India
Peter, K.V. India
Prakash, C.S. United States
Primo, Heidi. Micronesia
Rakotonjanahary, Xavier. Madagascar
Rao, Kameswara. India
Richardson, Dick. United States
Rivasplata Maldonado, Heidy. Canada
Sahoo, Sarbeswara. India
Samanta, S.K. India
Sangaré, M. Burkina Faso
Seshadri, S. India
Shanker, Arun. India
Sharma, H.S. India
Tchouaffé, Norbert. Cameroon
Van Milligen, Cornelius. United States
Varghese, Shiney. United States
Venkateswarlu, B. India

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Coping with water scarcity: What role for biotechnologies?

As one of its initiatives to mark World Water Day 2007, whose theme was "Coping with water scarcity", FAO organized a moderated e-mail conference entitled "Coping with water scarcity in developing countries: What role for agricultural biotechnologies?". Its main focus was on the use of biotechnologies to increase the efficiency of water use in agriculture, while a secondary focus was on two specific water-related applications of micro-organisms, in wastewater treatment and in inoculation of crops and forest trees with mycorrhizal fungi. This publication brings together the background paper and the summary report from the e-mail conference.

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