Water Use Efficiency in Agriculture: The Role of Nuclear and Isotopic Techniques

A. Introduction

1. Agriculture is the predominant user (75-80%) of the available freshwater resource in many parts of the world. At present most of the water used to grow crops is derived from rainfed soil moisture, with non-irrigated agriculture accounting for some 60% of production in developing countries. Although irrigation provides only 10% of agricultural water use and covers just around 20% of the cropland, it can vastly increase crop yields, improve food security and contribute 40% of total food production since the productivity of irrigated land is three times higher than that of rainfed land. The Food and Agriculture Organization (FAO) predicts a net expansion of irrigated land of some 45 million hectares in 93 developing countries (for a total of 242 million hectares in 2030) and project that agricultural water withdrawals will increase by approximately 14% during 2000-2030 to meet food demand[1].

2. Competition among different sectors for scarce water resources and increasing public concern on water quality for human, animal and industrial consumption and recreational activities have focussed more attention on water management in agriculture. As water resources shrink and competition from other sectors grows, agriculture faces a dual challenge: to produce more food with less water and to prevent the deterioration of water quality through contamination with soil runoff, nutrients and agrochemicals.

3. Current response measures, including policies and regulations, consist of a combination of ways to ensure adequate and more equitable allocation of water for different sectors. Measures include improving water use efficiency, pricing policies and privatization. Similarly there is an emphasis on integrated water resources management, which takes into account all the potential stakeholders in the planning, development and management.

B. Improving Water Use Efficiency in the Agricultural Sector

4. Water use efficiency (WUE) is a broad concept that can be defined in many ways. For farmers and land managers, WUE is the yield of harvested crop product achieved from the water available to the crop through rainfall, irrigation and the contribution of soil water storage.

5. Improving WUE in agriculture will require an increase in crop water productivity (an increase in marketable crop yield per unit of water removed by plant) and a reduction in water losses from the plant rooting zone, a critical zone where adequate storage of moisture and nutrients are required for optimizing crop production. The amount of water required for food production depends on the agricultural commodities produced (see Fig. I-1). For example, the production of 1 kg of beef would

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[1] http://www.fao.org/newsroom/en/focus/2006/1000252/index.html

require 14 times more water than for 1 kg of wheat. Thus improving WUE in agriculture may also require some socio-economic adjustment to encourage more water efficient enterprises.

6. Improving WUE by 40% on rainfed and irrigated lands would be needed to counterbalance the need for additional withdrawals for irrigation over the next 25 years from additional demand for food. However, this is a big challenge for many countries.

7. Increasing WUE is a paramount objective, particularly in arid and semi-arid areas with erratic rainfall patterns. Under rainfed conditions, soil water can be lost from the soil surface through evaporation (termed **soil evaporation**) or through plant uptake and subsequently lost via openings on plant leaves (termed **plant transpiration**). It can also be lost through runoff and deep infiltration through the soil. Total amount of soil water losses associated with both soil evaporation and plant transpiration is referred to as **evapotranspiration**. When irrigation is considered, water losses also include the mismanagement of irrigation water from its source to the crop roots. Usually, more than 50% of irrigation water is "lost" for the crop at the farm level. However at the watershed level it might be less, due to possible recoveries from the subsoil and groundwater. These off-site losses of water can result from either inappropriate land management practices to capture a substantial part of the rainfall within an agricultural landscape and retain it in the plant rooting zone or excessive use of irrigation water. Such losses not only lead to water wastage but also to potential hazards of soil salinity and water pollution resulting from the transport of nitrate, phosphate, sediments and agro-chemicals to streams, lakes and rivers.

8. Many promising strategies for raising WUE are available. These include appropriate integrated land-water management practices such as (i) adequate soil fertility to remove nutrient constraints on crop production for every drop of water available through either rainfall or irrigation, (ii) efficient recycling of agricultural wastewater, (iii) soil-water conservation measures through crop residue incorporation, adequate land preparation for crop establishment and rainwater harvesting and (iv) conservation tillage to increase water infiltration, reduce runoff and improve soil moisture storage. In addition, novel irrigation technologies such as supplementary irrigation (some irrigation inputs to supplement inadequate rainfall), deficit irrigation (eliminating irrigation at times that have little impact on yield) and drip irrigation (targeting irrigation water to plant rooting zones) can also minimize soil evaporation thus making more water available for plant transpiration. In much of Sub-Saharan Africa, with sandy soils of low fertility, nutrient deficiencies override water shortages as the main factor limiting crop productivity. Crop growth is so poor that it can only absorb 10 to 15 % of total rainfall, the excess being lost through evaporation, deep percolation and run-off. The resulting WUE can be very low because the amount of water required to produce a person's food diet would be higher than the average value of 2000-5000 kg water/kg food (Fig. I-1). Under these conditions, increasing nutrient supply often leads to an increase in both crop production and WUE (I-1).

9. Fertigation, which combines irrigation and fertilization, maximizes the synergy between these two agricultural inputs increasing their efficiencies. Overall, improving irrigation WUE, as shown in the Agency's study comparing fertigation against conventional practices in eight of its Member States in West Asia [I-2] will help to minimise FAO's predicted increases in agricultural withdrawals of water.

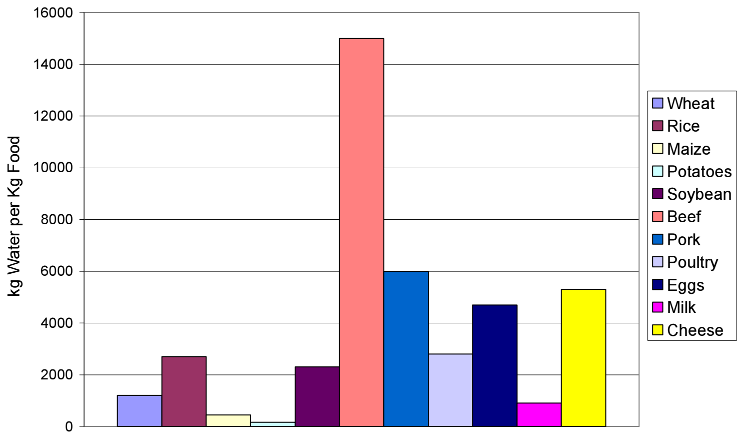

FIG. I-1. Water needed for food production (Liters of water per kilo of food).

10. Nuclear and isotopic techniques can play an important role in improving WUE in agriculture by:

- Improving water management through accurate soil moisture monitoring for optimum irrigation scheduling to minimize water losses.
- Optimizing crop water productivity with more crops per amount of water inputs from rainfall or irrigation.
- Assisting in the selection and evaluation of crop cultivars with tolerance to drought and higher crop water productivity.

11. The Agency, through both coordinated research projects (CRP) and projects in its technical cooperation programme (TCP), assists Member States in the use of nuclear and isotopic techniques to enhance WUE through the development of integrated management of soils, crops, water and fertilizer inputs. This review focuses on the role and application of the nuclear and isotopic technologies to address some key issues to improve WUE in agriculture. The applications of nuclear and isotopic technologies are illustrated with results obtained in the FAO/IAEA Programme through CRP and TCP activities.

C. The Soil Moisture Neutron Probe and Stable Isotopes in Improving Water Management

12. Improving water management in agriculture requires an improvement in soil moisture conservation measures and a reduction in wastage of irrigation water. Reduction in water wastage also brings about additional benefits in terms of reducing losses of applied nutrients, water erosion and pollution of surface and ground water. An accurate measurement of soil moisture content and water removal by soil evaporation and plant transpiration processes is therefore essential to establish the optimal soil water balance for crop sowing, fertilizer application and irrigation scheduling under different irrigation technologies, climatic conditions and farm management systems that aim to minimize soil evaporation and increase water accessibility for plant roots (Figs. I-2, I-3, I-4). The role of soil moisture neutron probe and stable isotopic techniques in contributing such information will be discussed in the following sections.

FIG. 1-2. A simple technology targeting water to the plant rooting zone to minimize soil evaporation and enhance plant transpiration can improve WUE and increase incomes from cash crops (Courtesy FAO-17075-Peyton Johnson)

FIG. I-3. Furrow irrigation in Uzbekistan; a good water management practice can save a significant amount of the irrigation water.

FIG. I-4. Irrigation of a potato field in Cape Verde (Courtesy FAO-17075-M. Marzot). It is important to minimize soil evaporation (non-productive) and maximize plant transpiration (productive) components of evapotranspiration.

C.1. Applications of Soil Moisture Neutron Probes

13. The soil moisture neutron probe (SMNP) is portable equipment for measuring periodically soil water content at different depths through access tubes installed in the soil profile (Fig. I-5). Data generated from this monitoring are used to calculate the soil water balance and estimate the total amount of soil water removed by both soil evaporation and plant transpiration [I-3, I-4, I-5, I-6]. The Agency's activities through CRPs and technical cooperation projects have demonstrated that WUE by crops as measured by the SMNP can be increased by up to 50% by changing irrigation technologies [I-7, I-8] and/or management practices [I-9, I-10] to improve groundcover and thus reduce evaporation from the soil surface. For example, approximately 25-50% of irrigation water can be saved by using drip irrigation (Figs. I-6, I-7) over the traditional flood surface irrigation. Such savings also brought about other benefits including an increase in the efficiency of fertiliser applied to crops to the same extent (20-50%) and a reduction in nitrogen leaching losses beyond the plant rooting zone.

FIG. I-5. Scientists from the United Arab Emirates being trained by the IAEA in the use of the SMNP.

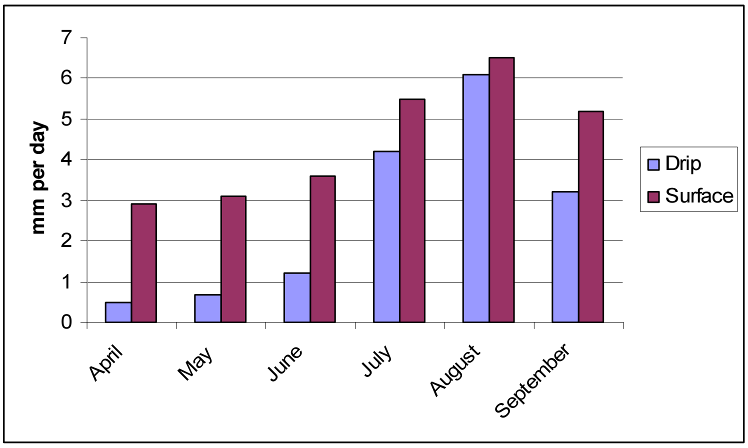

FIG. I-6. Cotton grown in Syria: the daily irrigation requirement (mm day^{-1}) is reported on a monthly basis for drip and surface irrigation. During the first three months of the cropping season, more than 60% of irrigation water can be saved using drip irrigation.

FIG. I-7. A low-cost drip irrigation system being practiced in Sierra Leone (SIL/8/002). Drip irrigation as a means of targeting irrigation water to the main plant rooting zone and avoiding water lost to the atmosphere through evaporation from the soil surface.

14. The SMNP, made available in the 1960s, has been a valuable tool for almost 50 years due to its rapid and reliable features that are needed for frequent and accurate measurement of soil water content. Although other soil monitoring methods have emerged, the SMNP is still relevant in areas where soil conditions such as salinity can affect the accuracy of other equipment [I-11, I-12]. The SMNP consists of two main parts: the probe in its shield and the electronic counting system. The probe contains a sealed radioactive source that emits fast neutrons, and a 'slow neutrons' tube-counter. During measurements, the probe is lowered to the desired soil depth inside an access tube. The fast

neutrons are scattered and slowed down in dependence of soil moisture since hydrogen, a component of soil water, is effective at slowing down fast neutrons. The slow neutrons density measured by the counter is directly proportional to the soil water content.

15. Modern neutron probes have advanced electronics such as micro-processors that utilize factory or user calibration curves to obtain directly soil water content data, which can be stored and then downloaded to a computer at the laboratory [I-12]. Since the SMNP contains a radioactive source, safety and radiation protection rules in the transportation, storage and field use need to be strictly observed, and the Agency has published several documents on these topics [I-11, I-13, I-14] (Fig. I-5).

C.2. Applications of Stable Isotopes in Water Management

16. Significant advances have been made in the development and application of isotopic techniques in water management in agriculture. The measurement of natural variations in the abundance of stable isotopes of oxygen, hydrogen, carbon and nitrogen in soil, water and plant components can help to identify the sources of water and nutrients used by plants and to quantify water and nutrient fluxes through and beyond the plant rooting zone as influenced by different irrigation and land management practices. These developments have been possible due to the increased sensitivity of continuous flow isotope-ratio mass spectrometers for analysing the isotopic composition in soil-plant-water components. For example, hydrogen and oxygen, as constituents of water can exist as light and heavy isotopes. These isotopes can be used to identify water losses through evaporation from soil surface since the light isotopes (hydrogen-1 and oxygen-16) evaporate more readily than the heavy isotopes (hydrogen-2 {^{2}H} and oxygen-18 {^{18}O}). The natural isotopic ratios of hydrogen ($^{2}H/^{1}H$) and oxygen ($^{18}O/^{16}O$), which are often expressed as delta units ($\delta^{2}H$ and $\delta^{18}O$) in soil water, water vapour within a plant canopy and plant leaves can provide estimates of soil evaporation and plant transpiration [I-15;I-16, I-17]. Such information will enable irrigation and land management practices to be developed to minimize soil evaporation (the non-productive loss of water) and channel this water for crop production. Some examples of recent applications of stable isotopes in estimating soil evaporation, plant transpiration and sources of water used by plants are reported below:

- Changes in the isotopic composition of hydrogen ($\delta^{2}H$) over a ten-day sampling period following surface irrigation of olive trees in Morocco indicated that soil evaporation as a proportion of total water removal (evapotranspiration) from both soil and crops ranged from 0% prior to irrigation to 31% after surface irrigation [I-15]. These results highlight that soil evaporation under the environmental condition studied was substantial, indicating that any management factors that minimize soil evaporation such as drip irrigation can be expected to significantly improve WUE.
- Partition of transpiration from overstory trees from that of understory grasses in the south west of the USA during the post-rainy period by measuring natural variations of both $\delta^{2}H$ and $\delta^{18}O$ indicated that the total water removal (evaporatranspiration) from the ecosystem was 3.5 mm/day of which 70% was from tree transpiration, 15% from the transpiration of grass layer, and 15% from soil evaporation [I-16]. The study highlights that overstory trees can minimize soil evaporation, thus improve the overall WUE of the studied ecosystem.
- Agency sponsored research in a CRP on *"Use of Nuclear Techniques for Developing Integrated Nutrient and Water Management Practices for Agroforestry Systems"* have demonstrated that natural variation in the abundance of ^{2}H and ^{18}O in the soil, plant and water can be used to quantify the contribution of hydraulically lifted water from the subsoil (4-5 m) by

deep rooting trees growing in association with grasses or crops in the dry savannah regions of Africa (e.g., Burkina Faso and Niger) [I-17]. Hydraulic lift is a process of water movement from subsoil to the topsoil through plant roots. This process could be one of the features contributing to the success of tree-crop association growing in parklands in the dry savannahs of the West African Sahel.

17. The currently developed FAO crop water productivity model *AquaCrop* [I-18] which aims to predict yield response to water for most major field and vegetable crops under a range of irrigation and land management practices requires a range of data on transpiration and evaporation. These two components of evapotranspiration can be separated by using stable isotopes as outlined above. The planned activities of the Agency in this area will provide valuable information to FAO's *Aquacrop* model, which will be a useful management tool to manage water in both rainfed and irrigated farming systems around the world.

D. The Use of Carbon Stable Isotopes to Select and Evaluate Drought-tolerant Plant Species

18. Carbon, the major building block of carbohydrate and proteins in plant tissues contains both light and heavy carbon stable isotopes (^{12}C and ^{13}C). The measurement of natural variations in the abundance of ^{13}C and ^{12}C in plant materials is increasingly being used to select and evaluate plant cultivars that can withstand drought. This technique obviates the need for measurements of the water budgets of a large number of plants during a large scale screening for WUE characteristics. Under drought, less carbon (in the form of carbon dioxide), particularly ^{13}C from the atmosphere is taken up by plants for growth because of plant stress, thus creating a major variation in the natural isotopic ratios of ^{13}C and ^{12}C in plant materials. A plant cultivar, which is resistant to water scarcity should display less depletion in ^{13}C compared with a susceptible cultivar. Such discrimination against ^{13}C (i.e., difference between ^{13}C and ^{12}C, expressed as delta $\delta^{13}C$) in plant tissues (leaves and grains) has been successfully used in the selection of drought-resistant barley, wheat, rice and peanut [I-19, I-20, I-21, I-22, I-23]. Scientists have shown that $\delta^{13}C$ in plant leaves and grain is negatively related to WUE. Besides acting as a surrogate for WUE, carbon isotope discrimination (often abbreviated as CID) measured in different plant parts at harvest can be used as an historical account on how water availability varied during the cropping season [I-24].

19. The Agency through a CRP "*Nutrient and water management practices for increasing crop production in rainfed arid/semi-arid areas*" has shown that the CID technique was successfully used as a diagnostic tool for predicting WUE and wheat grain yield.[2]. A current CRP on *"Selection for greater agronomic water-use efficiency in wheat and rice using carbon isotope discrimination"* also established that CID can be used as a selection criterion for wheat yield under a wide range of environmental conditions, in particular under post-flowering stress that represents the most common drought situation. The breeding lines will be further used to develop WUE crop cultivars matching specific environments prevailing in the participating countries.[3]

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[2] http://www-naweb.iaea.org/nafa/swmn/crp/d1_2006.html

[3] http://www-naweb.iaea.org/nafa/swmn/crp/d1_2008.html

E. Conclusions

20. The probable advent of increasing water scarcity in this century will see less increase in irrigated land available for food production than in the past. Novel irrigation technologies need to be tested under local environments and particular agricultural production systems of developing countries. While irrigation can benefit yields and enhance WUE in water-limited environments, the potential for full irrigation is decreasing, with increased competition from the domestic and industrial sectors. Thus the main challenge confronting both rainfed and irrigated agriculture is to improve WUE and sustainable water use for agriculture. This can be achieved through (i) an increase in crop water productivity (an increased in marketable crop yield per unit of water taken up by crop), (ii) a decrease in water outflows from the plant rooting zone other than that required by plants and (iii) an increase in soil water storage within the plant rooting zone through better soil and water management practices at farm and catchment scales.

21. Nuclear and isotopic techniques have been shown to be invaluable tools for improving WUE. The SMNP is recognised worldwide as an accurate instrument for measuring/monitoring soil water content. However, licensing, training of users and safety regulations pertaining to the radiation protection measures restricts their use in some situations.

22. Stable isotopes of water, ^{2}H and ^{18}O, at the natural abundance level; have been used for tracking and quantifying water flows within and beyond the plant rooting zone. These techniques show potential to partition evapotranspiration into soil evaporation and plant transpiration (the water component removed by plants for their growth). Information obtained can then be used: (i) to evaluate the efficacy of different irrigation and land management practices that minimize soil evaporation and optimize plant transpiration, (ii) to locate sources of water use by different plants so as to develop an integrated tree-crop system for sustainable food production particularly in dryland environments and (iii) to identify and develop management strategies that minimize the losses of water and associated fertilizers, pesticides, soils and animal manure from farm lands. The need to minimize such environmental impact from agricultural activities is increasingly important to enhance viable and sustainable agricultural systems.

23. The carbon isotope discrimination has potential as a tool for screening and evaluating large samples of cultivars with increased WUE under water-limited conditions.

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