Improving Water Productivity in Agriculture: Editors' Overview

Jacob W. Kijne, Randolph Barker and David Molden
International Water Management Institute, Colombo, Sri Lanka

Introduction

One of the critical challenges of the early 21st century will be the resolution of the water crisis. This crisis is defined by scarcity of water, water-driven ecosystem degradation and malnutrition. In spite of massive water-development efforts for food security, the poor are affected the most, because they do not have the resources to obtain or maintain access to reliable and safe water. In the quest for improved access to water and food security, tremendous resources have been invested in developing water for agricultural uses. Yet we know that, with the growing demand for water for industry and municipalities, combined with environmental problems, there will be less water for agriculture in the future.

We hold that the solution to the water crisis is to be found in how water is developed and managed. Increasing the productivity of water means, in its broadest sense, getting more value or benefit from each drop of water used for crops, fish, forests and livestock while maintaining or improving ecosystems and the services they provide. Within agriculture, this means obtaining more production or value from every drop. We must increase the productivity of existing water resources and produce more food with less water. Increases in water productivity provide a means both to ease water scarcity and to leave more water for other human and ecosystem uses.

This book provides state-of-the-art knowledge on how to increase the productivity of water in agriculture. It provides concepts, methodologies, constraints and examples drawn from a wealth of experience from developing and developed countries. The book demonstrates that increasing water productivity will provide a focal point for practitioners and researchers from a variety of social science and physical science backgrounds.

Water-use Efficiency and Water Productivity

The first task in understanding how to increase water productivity is to understand what it means. As presented by Molden, Murray-Rust, Sakthivadivel and Makin in Chapter 1, the definition is scale-dependent. For a farmer, it means getting more crop per drop of irrigation water. But, for society as a whole, concerned with a basin or country's water resource, this means getting more value per unit of water resource used. Increasing water productivity is then the business of several actors working in harmony at plant, field, irrigation-system and river-basin levels.

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Crop water productivity means raising crop yields per unit of water consumed. Over the past three decades, this has been achieved largely through higher crop yields per hectare. But, with the declining crop-yield growth, attention has turned to the potential offered by improved management of water resources. Although there is considerable scope for increasing water productivity through this avenue, it is not as large as is commonly thought. As argued by Seckler, Molden and Sakthivadivel in Chapter 3, the amount of reuse (or recycling) of water is often underestimated. When reuse is taken into account, the options for further increases in water productivity are much smaller than were expected at first.

Seckler *et al*. side with those who find the traditional definition of irrigation efficiency misleading. They distinguish between what they refer to as the 'classical' and the 'neoclassical' concept of irrigation efficiency. Classical irrigation efficiency is defined as the crop water requirement (actual evapotranspiration minus effective precipitation) divided by the water withdrawn or diverted from a specific surface-water or groundwater source. 'Losses' in this approach include transpiration and evaporation (evapotranspiration), but also seepage, percolation and runoff, processes in which the water is not consumed. These latter so-called 'losses' may be captured or recycled for use elsewhere in the basin. Thus, classical measures of efficiency tend to underestimate the true efficiency and ignore the important role of surface irrigation systems in recharging groundwater and providing downstream sources of water for agriculture and other ecosystem services.

Seckler *et al.* agree with others that the word 'efficiency' has outlived its usefulness in the field of water-resource policy and management. Willardson *et al.* (1994) introduced the concept of consumed fractions. Others, e.g. Perry (1996), Burt *et al.* (1997) and Molden (1997) have referred to beneficial and non-beneficial depleted or consumed fractions. These are important distinctions that need to be kept firmly in mind throughout these discussions on limits and opportunities for improvements in crop water use.

Throughout this book the reader should be aware of the distinction between crop water productivity and water productivity at the basin level. Crop water productivity is defined in either physical or monetary terms as the ratio of the product (usually measured in kg) over the amount of water depleted (usually limited to crop evapotranspiration, measured in m^3). Occasionally – for example, in the context of supplemental irrigation – there is a felt need to express the productivity of the applied irrigation water. In that case, the denominator refers to irrigation water only, not to rainfall. Obviously, values of irrigation-water productivity cannot be compared with water productivity with depleted water in the denominator.

Basin water productivity takes into consideration beneficial depletion for multiple uses of water, including not only crop production but also uses by the non-agricultural sector, including the environment. Here, the problem lies in allocating the water among its multiple uses and users. Priority in use involves the value judgement of either the allocating agency or society at large and may be legally determined by water rights.

Productivity

The classical concept of irrigation efficiency as used by engineers omits economic values. To determine optimum-level irrigation efficiency, the economist would want to know the value of irrigation water and the cost of increased control or management that would permit a reduction in diversion. As water becomes scarce, increasing crop water productivity or reducing diversions would make sense if the water 'saved' could be put to higher-valued uses. But higher water productivity does not necessarily lead to greater economic efficiency. Moreover, water productivity or yield per unit of water, like yield per unit of land, is a partial productivity of just one factor, whereas the most encompassing measure of productivity used by economists is total factor productivity. The following definitions may help in understanding the differences between various productivity parameters.

Pure physical productivity is defined as the quantity of the product divided by the quantity of the input – for example, yield per hectare or yield per cubic metre of water either diverted or depleted. Combined physical and economic productivity is defined in terms of either the gross or the net present value of the crop divided by the amount of water diverted or depleted.

Economic productivity is the gross or net present value of the product divided by the value of the water diverted or depleted, which can be defined in terms of its opportunity cost in the highest alternative use.

Barker, Dawe and Inocencio address these issues in Chapter 2. The authors give examples of basins where unexpected off-site effects and externalities confound possible changes in water management intended to reduce water diversions. They do so by analysing the relationship between water productivity and economic efficiency and by investigating the possible role of water policies, such as water pricing, and institutions. Just as increased water savings do not necessarily result in increased water productivity, so also increased water productivity does not necessarily result in higher net returns at the farm or basin level. As the examples illustrate, it needs to be determined whether proposed water-management practices or technologies designed to increase water productivity and economic efficiency at the farm level translate into water-productivity and economic-efficiency gains at the system or basin level. Especially when basins become closed (basins are closed when all available water is depleted, i.e. rendered unavailable for further use),[1] setting the priority in the allocation of water among competing uses may reflect either political power at the basin level or a value judgement on the part of society. While the farmer may measure the benefits of increased water productivity in economic terms, valuing beneficial depletion in terms of reallocation of limited water supplies among competing uses and users at the basin level is an important but far more complex undertaking.

Scale Considerations

Water use and management in agriculture encompass many different scales: plants, fields, farms, delivery systems, basins, nations and continents. The focus of attention shifts according to the scale we are considering, from photosynthesis and transpiration, through water distribution and delivery, to allocation between various uses and between nations sharing the same basin.

In the classical irrigation efficiency concept, scale-dependent efficiency is commonly used: application efficiency (the ratio of the water delivered to the root zone over the water delivered to the field); conveyance efficiency (the ratio of the water delivered to the field over the supply of water delivered into the canal from the source); and project efficiency (the overall efficiency of the irrigation system).

The last term usually refers to the ratio of the total water consumption over the amount of water diverted to the system, regardless of how many times the water may have been reused within the system. It is recognized that production per unit of water is an important parameter for irrigation managers, but it is not comparable across scales or readily comparable across locations. However, it can be a useful indicator of performance over time. An increase in production per unit of water diverted at one scale does not necessarily lead to an increase in productivity of water diverted at a larger scale.

In Chapter 1, Molden, Murray-Rust, Sakthivadivel and Makin address these scale issues and discuss water accounting as a means of generalizing about water use across scales and of better understanding the terms in both the numerator and the denominator of the water-productivity ratio. They illustrate this with several water-accounting diagrams applicable to different scales and provide a helpful glossary of terms. Farmer-based strategies to increase water productivity at plant, field, farm, system and basin

[1] This is also the case when water flows to so-called sinks, i.e. into a sea, saline groundwater or another location where it is not readily or economically recoverable for reuse.

level are summarized in a table. Several of these are discussed in more detail in subsequent chapters.

Water Productivity in Rice Cultivation

Cultivation of rice in flooded fields (paddies) is very water-demanding. Declining water availability is seen as a threat to the sustainability of irrigated rice-based production systems. In Chapter 4, Tuong and Bouman explore ways of producing rice with less water. Finding such alternatives, they assert, is essential for food security and sustaining environmental health in Asia. Irrigation methods that require less water, such as saturated-soil culture and alternate wetting and drying can reduce unproductive outflows and raise water productivity at the field level without a reduction in crop yield per hectare.

Other approaches that may increase water productivity include the incorporation of the C_4 photosynthetic pathway into rice, the use of molecular biotechnology to enhance drought-stress tolerance and the development of 'aerobic rice', which refers to rice varieties that yield well under non-flooded conditions. (The potentials for plant breeding and molecular biology are discussed in more detail by Bennett in Chapter 7.) The authors contend that a shift towards aerobic rice will affect water conservation, soil organic-matter turnover, nutrient dynamics, carbon sequestration, weed ecology and greenhouse-gas emissions. Some of these changes lead to greater crop water productivity and are seen as positive; others, such as the release of nitrous oxide from the soil, are seen as having a negative impact.

Water Productivity Under Saline and Alkaline Conditions

The use of saline or alkaline water in crop production enlarges the available water resource but at the cost of lower yields and possible long-term effects on soil structure and soil productivity. Growing plants in saline soil or with saline or alkaline irrigation water presents another example of a trade-off for which the benefits and costs are likely to vary among locations.

Tyagi, in Chapter 5, discusses field-level measures that can be combined with the use of saline/alkaline irrigation water to enhance its productivity and mitigate its adverse effects. Such measures include the choice of the best cropping sequence, conjunctive use with good-quality canal water, water-table management, rainwater conservation in precisely levelled basins and chemical amelioration of alkaline water. The illustrations are taken mainly from the rice–wheat cropping system in the monsoonal climate with moderate rainfall (400–600 mm), as occurs in north-west India. Water transfer, water markets and the disposal of saline water with its basin-level implications are also discussed. Practical examples illustrate the importance of pre-sowing irrigation and the advantage of growing crops during the winter season when soil salinity is less and the evaporative demand is lower than during the pre-monsoonal summer season.

Knowledge of the leaching requirement, i.e. the amount of water that needs to pass through the root zone to maintain an acceptable salt level without unnecessary percolation losses, would help to determine whether increases in crop water productivity are feasible. Kijne, in Chapter 6, describes the difficulties both in determining the leaching requirement and, once known, in accurately applying the desired amount of water. Applying more water than needed causes the groundwater table to rise, which could lead to waterlogging. Evapotranspiration and leaching, which together constitute the beneficial depletion of the water resource under saline growing conditions, are linked through the yield–water–salinity production function. This relationship between yield and amount and quality of the applied water is not well known under field conditions, where crops are subjected to periodic and simultaneous water and salt stress and to non-uniform water application. Moreover, the feedback mechanism that lowers evapotranspiration when plants become more affected by soil salinity adds a further degree of complexity to the relationship between yield and salinity. Accordingly, knowing how much water to apply is important in terms of the sustainability of irrigated agriculture on saline soils.

Plant Breeding for Enhanced Water Productivity

Plant breeding over the last century has indirectly increased the productivity of water (in combination with other production factors) because yields have increased with no additional water consumption. Improved varieties have come from conventional breeding programmes where selection has been for yield per unit of land. Most of the increases have been due to improvements in the harvest index (the ratio of marketable product to total biomass or the so-called grain-to-straw ratio), which may now be approaching its theoretical limit in many of our major crops (Richards *et al.*, 1993). The development of an appropriate phenology by genetic modification, so that the durations of the vegetative and reproductive periods are matched as well as possible with the expected water supply or with the absence of crop hazards, is usually responsible for the most significant improvements in yield stability. Planting, flowering and maturation dates are important in matching the period of maximum crop growth with the time when saturation vapour-pressure deficit is low, and these characteristics may be genetically modified. One way of genetically increasing water productivity is to modify canopy development in order to reduce evaporation from the soil surface. Hence, much work has been done on the selection for large leaf area during the vegetative period to increase early vigour.

Biotechnology is considered to have great potential for the development of drought- or salt-tolerant crops, but this potential has not been fully realized yet. In addressing these topics in Chapter 7, Bennett observes that the slow progress in breeding for drought tolerance is often attributed to the genetic complexity of the trait and its interaction with the environment. Complementary approaches taken to address this issue include improving the environmental simulations used for germplasm screening and analysis, defining how the impact of water deficit on growth and yield components changes during the growth stages and discovering the regulatory genes underlying the plant's responses to water deficit. One promising approach to discovering the genes responsible for drought effects on yield components is quantitative trait loci (QTL) analysis. Such studies tend to focus on indirect effects, such as the inhibition of panicle development by hormonal signals from stressed leaves and roots and the inhibition of carbon flow from leaves to the developing grain. For example, it may be possible to prevent early drought-induced shedding of leaves by the genetic regulation of cyclokinin production. However, it could also be argued that these processes might be more effectively altered through conventional breeding. Many promising properties for coping with drought stress have been introduced for years through conventional plant breeding. These include changing the length of the growing season and the timing of sensitive stages; selecting for small leaves and early stomatal closure to reduce transpiration; selecting for high root activity and deep rooting systems; and selecting for tolerance to salinity. In short, traditional breeding methods and modern methods based on biotechnology should be seen as complementary.

Water Productivity in Rain-fed Agriculture

Eighty per cent of the agricultural land worldwide is rain-fed, with – in developing countries – generally low yield levels and large on-farm water losses during occasional periods of heavy rainfall. This suggests there are significant opportunities for improvements in crop water productivity.

Serraj and his co-authors of the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) describe in Chapter 8 the complexities of drought management of rain-fed cereal and legume crops in the semi-arid tropics. These cereal and legume crops are characterized by their ability to withstand periods of water scarcity and still produce grain and biomass. Drought stress is a complex issue because of the unpredictability of its occurrence and duration during the growing season, the high evaporative demand on the crop and the low fertility of the soil in which these plants grow. In addition, the effect of drought stress is often compounded by other stress factors, such as infection by root and stalk rot-causing fungi, which can bring about severe lodging and premature death. Current insufficient understanding of the combined effect of all these factors on crop yield complicates the characterization of the physiological traits required for increased water productivity of the crops.

The authors discuss four genetic-enhancement approaches for the improvement of the adaptation of legume and cereal crops to drought-prone environments:

- development of short-duration genotypes that can escape terminal drought;
- conventional breeding of genotypes with superior yield potential in drought-prone areas;
- physiological breeding of drought-resistant genotypes;
- identification of QTL (described in the previous section) for drought tolerance and their use in marker-assisted breeding.

The focus in Chapter 9, written by Rockström, Barron and Fox, is on rain-fed agriculture on smallholder farms in sub-Saharan Africa. The authors present field evidence suggesting that mitigating the effects of intraseasonal dry spells is the key to achieving higher yield levels and higher crop water productivity. As a result of the unpredictability of dry spells, farmers tend to avert risks. For many smallholder farmers in the semi-arid tropics, it is not worth investing in external inputs, including, most importantly, fertilizers, as the risk of total crop failure remains a reality once every 5 years and the risk of severe yield reduction occurs once every 2 years. However, the authors show that, with significant investments in water harvesting, conservation tillage and supplemental irrigation during short dry spells, yields of staple food crops could be more than doubled in many areas of sub-Saharan Africa.

Rockström *et al.* suggest that the best option for increasing crop water productivity lies in combining such practices with management strategies that enhance infiltration of rain, increase the water-holding capacity of the soils and maximize plant water uptake through timeliness of farming operations and soil fertilization. Obviously, upgrading rain-fed production through supplemental irrigation would have site-specific implications for downstream water users. The authors recognize that the socio-economic viability of water-harvesting structures for supplemental irrigation needs to be carefully considered. Preliminary assessment of manually dug farm ponds and sub-surface tanks indicates that the benefit–cost ratio depends on the opportunity cost of labour, which is often low during the dry season in remote rural areas.

Future Cereal Production and Water Productivity

Crop water productivity varies with location, depending on such factors as cropping pattern, climatic conditions, irrigation technology, field water management and infrastructure, and on the labour, fertilizer and machinery inputs. For example, in 1995, water productivity of rice ranged from 0.15 to 0.60 kg m^{-3} and that of other cereals from 0.2 to 2.4 kg m^{-3}. Cai and Rosegrant report in Chapter 10 on an analysis of crop water productivity at the global and regional levels through an integrated water- and food-modelling framework developed at the International Food Policy Research Institute (IFPRI). The authors explored the impact of technology and management improvement on water productivity. Based on the best available information and assuming that water supplies for agriculture will become more and more restricted, they expect that from 1995 to 2025 crop water productivity will increase: the global average water productivity of rice from 0.39 to 0.52 kg m^{-3} and that of the other cereals from 0.67 to 1.01 kg m^{-3}. This increase is predicted to result from increases in crop yield and in water productivity at the basin level, with the major contribution coming from yield increases. One of the conclusions of this study is that investments in agricultural infrastructure and agricultural research may have higher payoffs than investments in new irrigation systems in order to accelerate this increase in water productivity and hence ensure food security in the next 25 years.

Case Studies

Chapters 11–19 contain a number of case studies that illustrate issues discussed in the first group of chapters.

The first case study (Chapter 11), presented by Oweis and Hachum, demonstrates that sustainable increases in crop water productivity can only be achieved through integrated farm-resources management. This approach combines water conservation, supplemental irrigation, better crop selection, improved agronomic practices and political and institutional interventions. The case study is based on experience with cereal and legume production in the West Asia and North Africa (WANA) region, with a specific example from Syria.

The second case study (Chapter 12) describes efficient management of rainwater to achieve higher crop water productivity and increased groundwater recharge. The example, written by Wani, Pathak, Sreedevi, Singh and Singh, is from the semi-arid tropics in northern India. The authors argue in favour of an integrated watershed management approach and identified community participation, capacity building at local level, multidisciplinary technical backstopping, and the use of scientific tools as important elements in efficient rainwater management.

The third case study (Chapter 13), by Ong and Swallow, illustrates the importance of water consumption by trees in irrigated areas and discusses how water productivity can be increased in forestry and agroforestry. The authors describe the differences in relative importance of the various components of the water balance of a tree cover and an agricultural crop. For a tree cover, direct evaporation from the soil is much less than for a crop but evaporative loss through canopy interception is higher. There are also significant differences between agroforestry systems and forests, as the former tend to have a relatively sparse tree density.

In the fourth case study (Chapter 14), Bowen reviews efforts to increase water productivity in potato cultivation. Potato is generally shallow-rooted and sensitive to even mild water deficits. Increasing water productivity in potato was done through a combination of improved germplasm and agronomic practices for potato production in warm tropical environments. The author concluded from the study that there exists a useful range of genetic variability that could be taken advantage of for the development of more drought-tolerant and water-productive genotypes for rain-fed and irrigated potato production.

The fifth case study (Chapter 15) is from the rice–wheat cropping system in south Asia, which covers about 13.5 million ha. Hobbs and Gupta describe how growth in area and yield per unit land has been responsible for continued growth in production for over 30 years. Future growth, however, must come from yield increases and higher crop water productivity. Improved resource-conservation technologies, such as zero tillage (now being widely adopted) and raised beds, are identified as the key to increasing water productivity. The authors also emphasize the importance of partnerships and participatory approaches in the research and adoption of new technologies by farmers.

In the sixth case study (Chapter 16), Hussain, Sakthivadivel and Amarasinghe illustrate the importance of irrigation-water management on crop water productivity in northern India and Pakistan, also with a focus on the wheat–rice production system. The case study refers to systems where the irrigation water is a combination of canal water and pumped groundwater. They found significant variability throughout the season, not only in canal water supply and groundwater use and quality, but also in non-land factors, such as seed variety, sowing dates and weedicide application. The case study indicates that substantial gains in aggregate yield can be obtained by a more equitable distribution of the canal water, which would boost yields in tail reaches without adversely affecting yields elsewhere.

Most of the major water basins in Thailand are closing, while an increasing amount of water is being diverted from agriculture. In the seventh case study (Chapter 17), Molle raises the question of whether water productivity can be increased by economic measures, such as water pricing and market mechanisms for the reallocation of water to other uses. The case study shows that, in the Chao Phraya basin in Thailand, farmers and irrigation administrators have made substantial adjustments to water scarcity in the dry season. Thus, the benefits of such economic measures are much smaller than expected and the transaction costs and political risks outweigh the possible gains.

The eighth case study (Chapter 18) addresses the need for data to monitor the productivity of land and water resources over vast areas. Bastiaanssen, Ahmad and Tahir illustrate how in this study measurements from the National Oceanic and Atmospheric Administration (NOAA) weather satellite were combined with ancillary data, such as canal water supplies and rainfall data, into a geographic information system (GIS). The satellite data were converted to crop yield, actual evapotranspiration and, indirectly, to net groundwater use. The analysis of data for the Indus basin is carried out at various scales. Large variations exist in crop water productivity, which the authors ascribe to variations in the relation between canal water supply and evapotranspiration. However, at a spatial scale of 6 million ha and higher, water productivity becomes constant, because at that scale in the closing Indus basin, all water supplied is depleted. The study reinforces the importance of groundwater recycling in the Indus basin.

In the ninth case study (Chapter 19), Zhang argues, on the basis of crop water-production functions, for the introduction of deficit irrigation in order to increase on-farm water productivity in semi-arid countries. The case study uses data from Syria, the North China Plain and Oregon, USA. Also in this case study, crop water productivity shows significant spatial and temporal variation. The risk of deficit irrigation, according to the author, can be minimized through appropriate irrigation scheduling to avoid water stress during the most sensitive growth stages. One of the conditions for success is that farmers control the timing and amount of the irrigation applications.

Conclusions

This book makes clear that increasing crop water productivity is a challenge at various levels. The first challenge is to continue to enhance the marketable yield of crops without increasing transpiration. The second challenge is at field, farm and system levels to reduce as much as possible all outflows that do not contribute to crop production. These three levels are interlinked and the available water for crop production must be used to its greatest advantage within the basin. This may involve allowing outflow to occur from some fields, knowing that this outflow is not lost for plant production but will be used better at some other location within the basin. The third challenge is to increase the economic productivity of all sources of water, especially rainwater but also waste-water of various qualities and saline (ground) water. Meeting the challenge will require developing methodologies and tools to be used for the collection and interpretation of relevant data and information. Scientific disciplines must work together in the analysis of interactions, synergies and trade-offs.

There are hopeful signs that these challenges will be met. At plant level, traits and genes for drought and salt tolerance have been identified in a number of crops, and lessons learned in some crops will be applied to others, making use of both conventional and molecular breeding techniques. For example, progress in respect of increasing production without a concomitant increase in evapotranspiration through changes in the harvest index and stay-green factor is expected to yield results for some crops within 5 years. At field level, further improvements in crop water productivity are expected from the introduction of supplemental irrigation in rain-fed agriculture and the expansion of drip, trickle and sprinkler irrigation. Further progress is also expected in the adoption and adaptation of water-productivity-enhancing practices when institutions and policies are amended to provide appropriate incentives for farmers. At basin level the importance of an integrated approach to land and water management is recognized, especially in respect of sustainable conjunctive management of groundwater and surface water.

But the task of achieving gains in water productivity is daunting. Technologies and management approaches appropriate for poor rural farmers need development. Incentives that would facilitate the adoption of water-productivity-enhancing field practices are not clearly understood and are lacking. The growing interdependence among water uses and increasing competition among users complicates the search for solutions that will improve the productivity of basin-wide water resources. Institutions and policies that can deal with these complexities and with political realities and yet create an environment for farmer productivity are needed. There is indeed scope for increased emphasis on research and application in all these areas.

We expect that the discussions of the challenges and the hopeful signs will help in understanding not only the limits but also the opportunities for increasing crop water productivity.

References

Burt, C.M., Clemmens, A.J., Strelkoff, T.S., Solomon, K.H., Bliesner, R.D., Hardym, L.A., Howell, T.A., Members ASCE and Eisenhauer, D.E. (1997) Irrigation performance measures: efficiency and uniformity. *Journal of Irrigation and Drainage Engineering* 123(6), 423–442.

Molden, D. (1997) *Accounting for Water Use and Productivity*. SWIM Report No. 1, International Irrigation Management Institute, Colombo, Sri Lanka.

Perry, C.J. (1996) *The IIMI Water Balance Framework: a Model for Project Level Analysis*. Research Report 5, International Irrigation Management Institute, Colombo, Sri Lanka.

Richards, R.A., López-Castañeda, C. and Gomez-Macpherson, G.A.G. (1993) Improving the efficiency of water use by plant breeding and molecular biology. *Irrigation Science* 14, 93–104.

Willardson, L.S., Allen, R.G. and Frederiksen, H.D. (1994) Universal fractions and the elimination of irrigation efficiencies. Paper presented at the 13th Technical Conference, USCID, Denver, Colorado, 19–22 October 1994. Duplicated.