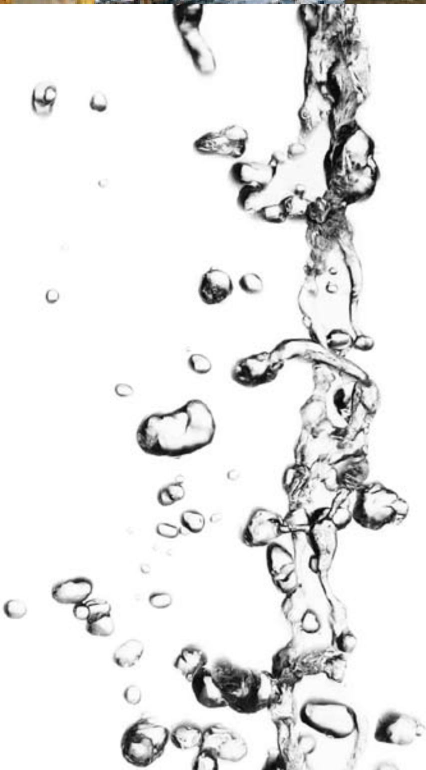
Water for food



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More food with less water

Water is essential for all food production in the world. It is therefore of the utmost importance that we learn to manage water resources better. A growing world population, rising world food prices, the impending climate changes and greatly increased investment in bioenergy crops on agricultural land threaten the realisation of the UN Millennial Goal of halving world poverty by 2015.

Rolf Annerberg, Director General, Swedish Research Council Formas

The situation is serious, but it is not impossible to deal with. In this publication, the fourth book of Research Council Formas produced for World Water Week, researchers describe the extent of the water problem and set out proposals for its solution.

One fundamental problem is the matter of priorities. If water resources continue to be used as now, with increasing urbanisation in the world, growing meat consumption and investments in bioenergy, these problems will soon be aggravated. However, if areas of land that have so far been reserved for meat production can be used for greater production of plant foods, there will also be space for energy crops. The threat from the increase in bioenergy production can also be turned into positive initiatives for the ecosystems, such as water filtration or mitigation of soil erosion.

Management of water resources can be made more efficient. In poorer parts of the world, food that has already been produced (and, indirectly, the water used in its production) is wasted through losses in the harvest, storage and transport, while in the richer parts of the world about one quarter of all food that has been bought is thrown away. By calculating the water footprints of agricultural products, their actual cost in terms of water use, in different parts of the food chain and in different geographical areas, can be estimated. The productivity of water used while crops are growing can be considerably improved by better planning of irrigation. Rainwater can also be utilisised more effectively – this can be achieved by small scale methods in local communities, such as those applied in many places in e.g. India.

Agricultural land is also exposed to a lot of stress. It is predicted that climate changes will result in heavy downpours in parts of the world. These will give rise to increased erosion of agricultural soils, and will need countermeasures at both farm level and in the catchment areas. Soils are also degraded and harvests spoiled by the leakage of nutrients which pollutes seas, rivers and lakes. Pollution of soils occurs through salinisation and concentration of minerals, caused by inadequate drainage or poor water planning with respect to the type of soil.

New methods of cultivation or genetically improved crops can prove to be of decisive importance in dealing with the drier climate that is expected in large parts of the world. Interesting examples of this can be seen in the new rice strains and cropping techniques which use little water, developed specially for conditions in Africa and Asia, or in the recently developed strains of maize which are now undergoing trials.

Water problems must be tackled on a broad front and with a mixture of small and large scale solutions. Many of these measures demand political resolutions based on international negotiations. In this way, the results of multifacetted research can provide guidance for the decisions regarding important prioritisations in the food supply and equity issues that the world is facing.

Rolf Annerberg
Director General
Swedish Research Council Formas

Further reading (www.formas.se)

- Water research – what's next? Formas (2004)
- Groundwater under threat, Formas (2005)
- Dams under Debate, Formas (2006)

Feeding the future world
– securing enough food for 10 billion people

Chief Technical Advisor Johan Kuylenstierna, UN Water, FAO, Professor Gia Destouni, Department of Physical Geography and Quarternary Geology, Stockholm University and Professor Jan Lundqvist, Stockholm International Water Institute.

Following a long period of global progress, the last decade has seen an increase in the number of undernourished people. Keeping pace with population growth remains a challenge in many regions, many of which also experience capacity problems to increase food production. If food prices continue to rise, hundreds of millions of hungry people might be added in just a few years which will also have severe impacts on development in general. To thwart this development, a combination of actions are necessary, ranging from productivity increase, changes in trade and market regimes, climate change adaptation and an increased focus on land and water management issues. The interconnectivity among issues add complexity and must be addressed. However, it is important to focus on options and actions and not only get stuck in discussing problems.

Food related headlines have been in focus lately. Suddenly, everyone is talking about a "global food crisis" and it is easy to forget that only a few years ago, food prices were at an all time low. The current situation is interesting, and challenging, from a number of perspectives;

- It shows the volatility and uncertainty of our (global) systems, how quickly things can change, when we in a few years (or even months) can move from a problem with food surplus and (historically) extremely low prices to a (perceived) shortage and bull-market increases in price. We still do not know if current food prices reflect just a spike or represent a structural adjustment following a sustained period of relatively low prices.

- It shows the complexity of current problems – how difficult it is to understand what the main drivers are and how they interact. Climate change, competition over land water, and changes in consumption patterns, bioenergy production, market influence (speculation), trade, etc, are just some factors currently discussed as the key drivers.

- It exposes vulnerability. With a population approaching 6.5 billion and still increasing by 90 million each year, the degree of freedom to act is becoming limited, and minor changes can trigger substantive effects. A disturbing example has recently been presented by the World Bank, arguing that dramatically increased food prices can push hundreds of millions of people back into poverty, and thus set back more than a decade of progress on poverty alleviation in just a few months. On the other hand, this could be an opportunity to secure that even poor farmers may see an increase in their income.

So, maybe, Malthus will prove to be right after all? We can probably only be certain about one thing. Whatever we project about the future, we will be wrong. Is the situation hopeless? Absolutely not!

Where we are coming from

Since 1800, global food production has generally kept pace with population growth, despite frequent references to an impending Malthusian disaster. Thomas Malthus published his famous "An Essay on the Principle of Population" in 1798, and ever since there has been an ongoing discussion on the close linkages between the challenges of population growth and the provision of food.

In 1800, the global population is estimated to have been around 900 million people. Malthus' concerns were not irrelevant at the time as it was really around the turn of that century that the dramatic population growth took off, not least in Europe. Between 1650 and 1800, the total global increase is estimated to have been about 300 million people (which was actually quite substantial compared to earlier history – total global population 2000 years ago is estimated to have been around 200 million), but in the next 150 years, population would grow by 1.5 billion, five times faster. Even this is nothing compared to the growth rate after that – to add the same number of people once again took only about 40 years.

So what about food production over the same period? If Malthus had been right, the world would have run out of the capacity to feed the population a long time ago and the population would not have grown so dramatically. Antony Trewavas provides an interesting example of the dramatic development in food production, which has so far helped us overcome Malthus' predictions, in an insight overview in Nature 2002; currently, one person needs about 2000 square metres on average for the growth of his/her annual food, while at the time of Malthus, he or she would need about 20 000 square metres.

There are certainly a number of reasons why food production has managed to keep pace with population increase. Science, technology and improved efficiency related to production, storage and transport have enabled a dramatic increase in food production. Subsidies, so often despised, have been instrumental in the development of irrigation and thus an important component of the green revolution. Without subsidies, and artificially low prices for the consumers, the 20th century expansion of agriculture would likely not have happened. This is not implying that subsidies related to water and energy are without negative effects. Trade has had a positive impact on food availability, at least in some regions. The twentieth century had witnessed a rapid development in the areas of plant breeding and genetics. Cereal yields have increased threefold over the last 50 years, thus coping with the more than doubling of the global population in the same period.

Science, technology and improved efficiency related to production, storage and transport have enabled a dramatic increase in food production.

However, things are continuously changing. An interesting question is, therefore, if the same technologies and methods that we have developed over the past two centuries will, with some refinements, be enough to cope with future challenges? Or will Malthus eventually prove to be right? Well, for anyone working with global development issues, it is a responsibility not to believe so.

At a turning point

To make any serious projections about the future, we need to understand the current situation. While many people are still struggling for day to day survival, humanity has also, at a greater scale than ever before, *moved from a situation of primarily securing resources to cover basic needs for survival to the challenges associated with sustaining more resource demanding* human desires. Consumption patterns are more and more important as drivers and will probably impact on the future more than population growth in itself.

From 1970–1997, the number of hungry people continued an earlier long-term trend and fell from 959 million to 791 million. This was mainly due to the dramatic progress in reducing the number of undernourished in China and India. However, the number of chronically hungry in developing countries started to increase at a rate of almost four million per year from the late 1990s and by 2001–2003, the total number of undernourished people worldwide had increased to 854 million. This despite political calls, to halve the number by 2015, made at the Global Food Summit in 1996 (later reiterated in the Millennium Development Goals). The total percentage of hungry people has continued to decrease, but improvements have lately not managed to keep pace with the total population growth.

If the current trend and rate of change were to continue, more than one billion people would again be undernourished by 2050.

Certainly, this development trend is not necessarily due to any progressing crisis in global food production. There may be a number of reasons behind it. Population growth continues to be highest in regions with, generally, the least capacity to increase their food production, insufficient infrastructure (for irrigation, storage, transport), poverty, lack of capacity, climate change etc, etc. At any rate, this is a trend that must be taken seriously. If the current trend and rate of change were to continue, more than one billion people would again be undernourished by 2050. With soaring food prices, some argue that hundreds of millions of undernourished people may be added in just a few years.

And competition is clearly increasing –for land, for water and over food products. Although it is still too early to say that, for example, increased bioenergy production has much to do with the current food crisis, it is an example of an emerging driver that needs to be considered in future projections. The same goes for climate change; climate variability has always been a reality in agriculture but things may be changing in ways never experienced before. And even market speculations may be behind some of the recent price increases, making the global food market look more and more like the stock market. What other issues will emerge as drivers?

Drivers of change

There will be many drivers of change that need to be considered, and dealt with, in the future. There is no room for complacency over past achievements. Many drivers are the same as in the past; others may be partly new and some we are probably not even aware of. The complexity of interlinked drivers will remain and likely increase. Population will continue to increase and we are undoubtedly altering many global systems at a rate not previously experienced. Climate change is the obvious example but not the only one. The Millennium Ecosystem Assessment, which was presented a few years ago, stated that humans have changed ecosystems more rapidly and extensively than ever before in the last 50 years in order to meet our growing demands for food, freshwater, timber, fibre and fuel.

Let us briefly discuss a few drivers.

Population growth will continue

It is difficult to predict the exact future increase in population. In recent decades, the projected rate of increase has actually decreased quite dramatically and it is now estimated that the global population will level out at 8–11 billion somewhere around 2050. This means that the global population will still increase by around 50 % in 50 years. There is still uncertainty – if today's fertility rate continues, the population will instead increase by around 80 % until 2050. This is at the global level. However, even more than in the past, the spatial differences may be dramatic. While population may continue to increase quite dramatically in some regions, it will actually decrease in others. The main challenge is that areas with the most rapid increase coincide with countries already facing severe development problems or scarcity of resources (in particular related to land and water). Thus, just because the total population growth may end toward the middle of this century, this will not necessarily imply that the risks of a "food crisis" will diminish. Simply stated, distribution (trade) and infrastructure may be even more important in the future.

Dynamics – urbanization

In 2007, humans for the first time became more urban than rural in real numbers, with more than 50 per cent of the world's population living in cities, including 900 million in urban slums.

Urbanization will also continue to drive development patterns. In 2007, humans for the first time became more urban than rural in real numbers, with more than 50 per cent of the world's population living in cities, including 900 million in urban slums. By 2050, some argue that the urban population will have doubled. Urbanisation adds complexity and challenges, but also offers new possibilities (of increased efficiency) if well managed. Trends show that an urban population in general generates more (resource intensive) consumption, for example increased meat consumption. While urbanization is more or less concluded in developed countries (with rural-urban ratios in general being around 1 to 9), it will continue to be high in many developing countries.

Changing consumption patterns

Changes in consumption patterns may have the most important impact on future food production requirements. There is a relationship between GDP and diet, and as global economy is expected to grow at a rate far exceeding population growth (a 10 to 26-fold increase over the next century), this is clearly a factor that needs to be carefully studied and where there remain large uncertainties (related to both the growth in GDP and the resulting changes in consumption patterns).

Approximately 0.5 m³ of water is needed to produce 1,000 kcal of plant-based food, while 4 m³ is required for the same energy content of animal-based food.

That this factor matters can be illustrated by one simple example. Approximately 0.5 m³ of water is needed to produce 1,000 kcal of plant-based food, while 4 m³ is required for the same energy content of animal-based food. Assuming a high level of food supply at 3,000 kcal/person/day (production is higher than consumption due to losses), what would be the effects of changes in consumption patterns? If we use an average ratio of 80 % plant based and 20 % meat based food production, water requirement per capita and year would be about 1,300 m³. Change this ratio by 10 percentage units, to 70 % plant based and 30 % meat based, and the water requirements jump to almost 1,700 m³ per capita. If we estimate the

world population to 9 billion people in 2050, the difference would be 3,600 km³ in total annual water requirement for food production. Is this a lot? Well, as a comparison, current total withdrawals for food production are about 7,000 m³. Our dietary choices surely make a difference.

Resource constraints

There are certainly resource constraints that will affect global food production – land, water, energy, fertilizers, just to mention a few. Constraints may be a result of physical limitation of the resource, lack of appropriate distribution systems and relevant infrastructure or capacity (management and economic) problems. Let us look in a little more detail at land and water as two examples.

Irrigation is the driver of water use in agriculture, but irrigated agriculture also accounts for about 40 per cent of the world's grain production.

At 70 per cent of the global water withdrawal, the globally thirstiest sector clearly is and will remain agriculture. Irrigation is the driver of water use in agriculture, but irrigated agriculture also accounts for about 40 per cent of the world's grain production. Water availability is also affected by demand in other sectors (competition), climate change (changes in spatial and temporal water distribution, changes in glacier runoff), and water quality degradation. A world-wide problem in regions with extensive irrigation is groundwater depletion, with falling groundwater tables and quality degradation, and water logging with associated salinization. The combined long-term effects can be dramatic and pose serious threats to future food production potential. Water is already a limiting factor in some regions. What are the expectations for the future? Current projections suggest that cereal demand may double by 2050. The impacts on water may be tremendous, increasing from a current use of about 7,000 km³ to somewhere between 10,000–13,500 km³. In less than 50 years. Sometimes, numbers speak for themselves.

So, how about land? Let us use a simple example. Just because the total population increases, total land area per capita will decrease. The population density in developed countries was, on average, 15 per km² in 1950, increasing to 22 per km² by 2000. It is estimated to remain the same by 2050. In developing countries, the average was 21 per km² in 1950, increasing to 59 per km² in 2000 and estimated to be 94 per km² in 2050. Such global averages are not relevant from a planning perspective but they provide an indication of the problem.

In the United States, it is estimated that one acre of land is lost due to urbanization and infrastructure development for every person added.

In addition, people have a tendency to live in areas most suitable for agriculture and many major cities are expanding over land previously employed for agriculture. Substantial amounts of productive land are therefore lost annually due to urbanization and infrastructure development. In the United States, it is estimated that one acre of land is lost due to urbanization and infrastructure development for every person added. This should be compared to the average 1.2 acres needed per person to sustain current American dietary standards. This should be added to other problems, such as land degradation due to poor management, climate change and ecosystem degradation. UNEP estimated in 2002 that about 2 billion ha of soil, an area bigger than the United States and Mexico combined, should be classified as degraded as a result of human activities. Maybe the effects start to show? Although the total irrigated area tripled between 1950 and 2003, from 94 million to 277 million hectares, the current trend is that irrigation growth is tapering off as water and land become scarcer and competition from other sectors increases. Forty years ago, irrigated areas were expanding at an annual rate of 2.1 per cent, but the last 5 years show growth of only 0.4 per cent.

Climate change

Climate variability and change adaptation (and mitigation) will be among the most important issues in the next decades. From 1992 to 2001, nearly 90 per cent of all natural disasters were of meteorological or hydrological origin. Maybe more important from a food production perspective will be the long-term spatial and temporal changes in (average) temperature and precipitation. However, our understanding of climate change impacts on water resources is limited, in part because the interactions are complicated and because changes are also governed by a range of non-climate factors, masking the climate signal. Modified landscapes and infrastructure development, as well as changes in hydrological systems (river modification), strongly influence the effects of climate variability and change. With increased flooding, for example, it is difficult for the planner to answer an essential question: how much of the increase is due to climate change and how much results from non-climatic factors?

The Intergovernmental panel on Climate Change (IPCC) predicts increased runoff (leading to more annual water availability) at high latitudes of North America and Eurasia and in the tropics, while Mediterranean climates will see decreased runoff. Changes in the seasonality of runoff due to shifts in the snow/rain ratio at high latitudes and in mountainous regions are expected with a high degree of certainty. The 2007 Human Development Report is blunter in its predictions, stating that large areas of the developed world face imminent water stress and that water availability for human settlements and agriculture will decrease.

A very difficult, and challenging issue, is the long-term change of glaciers. Most mountain glaciers are retreating, which for some time increases the annual net flow of water in rivers. This can have a positive effect on water availability in some agricultural regions (Asia, China, South America) in the short and medium term. However, at the same time, the glacier storage of water gradually decreases and when (or if) a glacier eventually disappears, the effects on the availability of water in downstream regions can be dramatic. The IPCC estimates that one-sixth of the global population rely part of the year on melt water from glaciers and permanent snow-packs.

Water management for agriculture is a local to regional issue. IPCC states that "There is a scale mismatch between the large-scale climatic models and the catchment scale, which needs further resolution." So should there be no action? Do we need to wait and see? Well, climate variability has always been a reality and if we strengthen capacity to deal with current variability, through improved water management and investments in infrastructure and adaptive physical planning, humanity will clearly be better prepared to deal with climate change by 2050.

Bioenergy will strain land and water resources

A dramatic production increase of bioenergy could drastically alter future water and land use

It is always difficult to predict what future (emerging) issues may be. A few years ago, bioenergy was a parenthesis in discussions related to land, water and food. Owing to the necessity for climate change mitigation strategies, the whole discussion has changed over a few years. A dramatic production increase of bioenergy could drastically alter future water and land use – and thereby affect global food production scenarios. With some estimating that as much additional water is needed to meet our bioenergetical needs as to meet our food needs in the future, this issue will only grow in importance in the global water debate. There are already quite strict targets to consider – the US Energy Policy Act of 2005 promotes further use of biofuels, and by 2015 biofuels may account for about 23 % of

the country's maize output. Likewise, the European Union has set a target of a 5.75 % market share of biofuels in the petrol and diesel market by 2010. These targets were set prior to the current "food crisis".

What are the effects? Let us use one interesting example to illustrate future challenges, published by De La Torre and He last year. If all oil-based transportation fuels were replaced by fuels derived from biomass, about 30 million barrels of ethanol and 23 million barrels of biodiesel would be required per day. This would, in turn, require 300 million hectares of sugar cane (based on yields similar to those in Brazil) and 590 million hectares of corn (based on yields similar to those in the USA) to be planted in order to meet the ethanol needs alone. How much is that? Well, this is equal to about 15 times the current world planting of sugar cane and 5 times the current corn planting. For the biodiesel demand, 225 million hectares of palm, or 20 times the current area, would need to be planted. Imagine the land and water demands. Completely unrealistic, maybe, but examples such as these are important to keep in mind when we discuss future projections and possible actions. And there are still many uncertainties. a. There are, for example, quite different figures circulating about how much ethanol/biodiesel can be produced from various feed stocks. This is clearly a sector under rapid technological development and to predict where it will be a decade from now is almost impossible.

The future is not carved in stone

So, is the solution to continue to do what we have done in the past – just more and quicker? Population growth and dynamics, consumption patterns, climate change, competition over scarce resources and a range of known and unknown emerging issues will likely require both rethinking of old paradigms and new and innovative thinking. The situation is far from hopeless. We must remember that practically all the drivers that will influence the future can be affected by human decisions in both negative and positive directions; what they will eventually develop into depends on everything from decision making at all levels to the daily, individual choices that we make. Clearly, the responsibilities are very different between different countries and peoples. The World Bank estimated in 2001 that 2.7 billion people had a consumption level of less than 2 dollars/day. They surely have fewer choices and power to influence than others.

What, then, are the kinds of options that we have? Of course, science and technology development (including biotechnologies), infrastructure and other investments will continue to be important. Infrastructure is not only related to agriculture, it is also about transport and access to global markets, storage, packaging etc. We also need to continue improving the global trade regime, clearly a complicated issue considering that the current WTO trade negotiations (Doha round launched in 2001) have stalled due to differences about agricultural products (in particular on tariffs and subsidies). The 151 members have recently agreed that negotiations should be finalized in 2008. There are many uncertainties what the benefits will be*. We also need to look at both consumption and production aspects, such as demand management issues and efficiency improvement, and wastes in the entire production chain of food and productivity. Improved productivity is actually behind most of the increasing production of grain over the last 50 years.

A key aspect is also to better understand how different issues are interconnected, and change accordingly.

A key aspect is also to better understand how different issues are interconnected, and change accordingly. We continue to operate in far too fragmented ways and isolate ourselves in our safe, disciplinary boxes. Global food availability in 2050 will depend upon population and population dynamics, physical planning, climate change, resource utilization and competition, consumption patterns, economic growth, trade patterns, known and unknown emerging issues etc, etc. Clearly, each individual issue in itself is highly complex. Water and food issues have also complicated political dimensions that need to be considered.

However, we will not solve the problems by addressing them one by one. Addressing one issue has implications on others – look at climate change and bioenergy. These linkages will clearly require substantial changes in everything from how the multilateral system is currently structured and how it addresses the challenges (sector-oriented processes and political high-level meetings) to how governments at all levels are organized and what kind of research is promoted. How can we encourage further interdisciplinarity and communication? How can we promote a more balanced view on socio-economic development and environmental sustainability? How can we ensure equity and a global trade regime that is fair to all countries? How can we ensure that people understand that their choices matter, as a way to encourage positive changes? How can we ensure that the debate focuses on solutions and possibilities rather than only on dramatic doomsday scenarios and problems?

Good questions outrank easy answers. The following chapters in this book will provide more in-depth knowledge on some of these critical issues and propose various ways forward. The future is still in our hands. We can not afford Malthus becoming right.

* In a Reuter's article on May 20, 2008 it was stated that "One study in 2003 said a Doha deal could increase global income by $520 billion and lift an additional 144 million people out of poverty. But a World Bank study in 2005 put the gains by 2015 at only $96 billion, of which the developing countries' share was only $16 billion."

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Where has all the food gone?
– identifying and coping with food and water losses

Professor Jan Lundqvist, Stockholm International Water Institute.

Today, the possibility for all people in the world to lead a 'healthy and productive life' – the very definition of food security – has been reached twice over in terms of energy content of food produced. Yet, in many regions of the world, poverty still rules in the midst of plenty and levels of food insecurity are on the rise. In more wealthy regions, on the other hand, as much as a quarter of the food bought and brought home is thrown away. The sources of losses and spoilage in poor areas and the reasons for wastage in wealthier regions need to be dealt with.

The thirst of the atmosphere is timeless and so is the natural law of photosynthesis. With global warming this return flow of water back to atmosphere will be speeded up.

Unprecedented water drain for food security

Some ten years ago, Sandra Postel published an article in the WorldWatch Magazine: "Where have all the rivers gone?" A simple and valid comment to this pertinent question is that rivers have been drained of their water to enhance food production. Desiccation of rivers is largely due to an expansion of the irrigation system with the help of water from rivers, lakes and aquifers with the purpose to increase agricultural production, especially food. To a lesser degree, the dramatic reduction in river flow is related to a growing demand for water in urban centres, for households, industry, etc. and evaporation from reservoirs feeding hydropower plants. The water abstracted from rivers, lakes and aquifers has been spread over vast areas. A non-negotiable characteristic of food and other biological production in the open landscape is that huge volumes of water are required and that a large part of it will return to atmosphere as evaporation and transpiration and not drain back to the river or other recipients. The thirst of the atmosphere is timeless and so is the natural law of photosynthesis. With global warming this return flow of water back to atmosphere will be speeded up. In these regards, food and other agricultural production are significantly different from industrial production, which typically requires less and less water over time and where closed systems imply little consumptive water use.

The expansion of irrigated agriculture together with agronomic advances has meant a significant boost to food production and the agricultural sector. As discussed in other articles in this publication, the relative contribution from irrigated agriculture to overall food production is about half or perhaps two thirds as compared to the food that is produced under rain-fed conditions. In gross terms, world food production at the turn of this century is more than double as compared to the situation at the beginning of the 1960s when the Green revolution took off and when irrigation expanded. Importantly, the global per capita availability of food has improved, also in developing countries as a group.

In terms of energy content, the food produced at field level is roughly double the amount required for the entire world population to lead a 'healthy and productive life', which is the definition of food security. A healthy life is, of course, not only dependent on a certain intake of calories. Yet, about 850 million people, or 15 % of the world population, are undernourished. Recent dramatic trends in the food sector, e.g. price spikes and other serious disturbances and trends, have reminded us that food insecurity remains a lingering threat to human development and stable societies.

So, where has all the food gone? An equally relevant question refers to the future: Is the chosen strategy for food security compatible with an expected continuous growth in the demand for food? If and when even more rivers and other water sources will be gone, what do we do? Or, rather, how do we avoid ending up in such a miserable situation?

Food security has improved while producers are squeezed

The historically unprecedented boost in food production during recent decades has contributed to a reduction in the number of people who are undernourished, in relative numbers and, until recently, also in absolute numbers. Parallel with an augmented production and supply of food, the price of food has been gradually lowered, that is, until the recent price hikes. For the farmers, this has meant a continuous deterioration in the terms of trade vis-à-vis other products. For those who enjoy subsidies, the situation is different. For an increasing proportion of people in society who are not producing food themselves, a more steady and varied supply in combination with a relative decline in the price paid for food has naturally been welcome. For the poor consumer, this trend has been fundamental. It has literally meant that the balance between life and death has tipped in the favour of life. For the poor and marginal producer, this trend has been problematic, to put it mildly.

Undernourishment in the midst of plenty

A quick look at the situation before the improved food security situation may be useful to remind ourselves of how precarious the food situation used to be for large parts of mankind. Famines had haunted people and countries in many parts of the world throughout history. In his research related to food and water in southern India, Mats Lannerstad has compiled information about a dreadful sequence of 'famine, sickness and death' that recurred no less than 17 times over a period of about 100 years, from the beginning of the 19th century to the beginning of the 20th century. Usually, each devastating period extends over two or several years. A major cause behind this macabre series was the effects of an erratic and unpredictable north-eastern monsoon. No fewer than two-thirds of the seasons during this 100 year period were deemed unfavourable.

Today, with the same erratic rainfall and with a much higher population, there are no famines. Considerable increases in food production have been accomplished due to a combination of irrigation and agronomic improvements. Observers in India note that food is piling up in the stores of the Public Distribution System. This does not, however, mean that food security is achieved for all. Statistics presented in the third round of National Family Health Survey (NFHS-III) reveal that India is in a state of 'nutritional crisis'. The crisis refers to astonishingly high rates in the incidence of underweight and malnourishment, about 45 %, among children below the age of three. These figures, which are among the highest in the world, clearly underline that food insecurity can be extremely high for large segments of the population even though figures on food production and availability, in the same area, tell another story. Generally, poverty, social deprivation and conflict result in a lack of access to food and thus constitute a common factor behind food insecurity.

In spite of deplorable examples of food insecurity, it is important to note that the very thought of a famine is politically impossible today.

In spite of deplorable examples of food insecurity, it is important to note that the very thought of a famine is politically impossible today. Amartya Sen has shown that the media and the general awareness in society will keep politicians on their toes to ensure that famines do not develop. Angry crowds have recently demonstrated their grievances and desperate situation when food prices have skyrocketed in many countries, e.g. in Mexico, Burkina Faso, Mauritania, Senegal and Uzbekistan. Summits are organised to find remedies. In other countries, e.g. in China, governments are quite wary about the combination of inflationary effects and social unrest due to price increases of food and/or disturbances in supply. In their anxious attempts to act, solutions like export bans on food and price fixing may provide some short term relief but may also aggravate the problem.

Quite obviously, new circumstances have been factored into the water resources - food production & supply - food security equation. Now, there are tendencies of a reversal or at least a retardation of the positive trends indicated above. The head of the World Food Programme has warned that an additional 100 million people might be added to the already unacceptably high number of those who are food insecure and undernourished. Some of the main reasons are: Climate change reduces the potential yields substantially in areas where food insecurity is already a reality – which is not the same as a reduction in the actual yields but is serious enough; demand shifts within the food sector towards more water intensive diets and between food and non-food commodities, i.e. to energy and commercial crops.

Produce more or waste less?

In this situation and with the expectation of a considerable increase in the demand for food in years to come, primarily as a result of a steady and strong increase in GDP and disposable income in several countries in the world, effective approaches are urgently required. In principle, two options are conceivable. One approach is to provide incentives and support for an increased production. Another approach is to recognise that the losses of food 'from field to fork' are huge. As mentioned above, a critical issue is also the much skewed access to food that actually is available. Poverty will not disappear and a worrisome question is: what will be the fate of the poor in a more competitive and resource scarce situation?

Figures on the magnitude of losses are sketchy, but the information that is available does indicate that losses, conversions and wastage of food in the food chain are significant and amount to about half the food that is available at field level. It is important to distinguish between various categories of losses and to recognise that there is a significant difference between various countries and between various production and consumption categories. As discussed in a recent report produced by SIWI (2008), losses refer primarily to reduction in the amount of food, or degradation of quality, in the field (e.g. due to poor harvest technologies), during transport and storage. Wastage is commonly used in the literature and in media reports to describe the discarding of food in households and other units of consumption (e.g. the throwing away of food that is perfectly fit for eating). Spoilage is another concept used. Usually it refers to a reduction in the amount of food, or the quality of the food, during storage and distribution.

A number of circumstances are important in efforts to better understand and, hopefully, tackle the very high rates of losses and wastage of food. Available information shows that wastage is quite high in the rich part of the world, in the order of 25 to 30 %, whereas losses and spoilage are a bigger challenge in other parts of the world where harvesting, transport and storage technologies are outdated and lack capacity.

Obviously, there is a growing problem connected to the fact that the number of actors - and interests – increase with urbanisation and increasing affluence in society. Similarly, the gradual change in diets, away from cereals and other food items that are comparatively easy to store and transport, towards food items that are easily degradable, which can be harmful from a human health point of view, implies that the risk of losses and wastage increases. The latter category of food items is also more water intensive. Typically, meat and dairy products require strict treatment and should be consumed within a matter of days or a couple of weeks at most, whereas most cereals can be stored over extensive periods of time, with no or little risk of deterioration.

Both in terms of quantity and value of food, huge losses and wastage are recorded in connection with sophisticated food processing and distribution of food. A number of recent incidents in the US and other countries, where million of kilos of fresh and frozen meat have been recalled from retail, together with the generally high levels of daily wastage, show that there are significant challenges in sophisticated food chains with a number of intermediaries between the producer and the consumer. Apart from this kind of wastage, it is noteworthy that overeating is a much bigger problem, in terms of the number of people affected by overweight and obesity, as compared to undernourishment.

The tendency to blame farmers, and especially small farmers, for food losses and wastage is therefore misleading and ignores the problems related to the modern food chain dynamics.

The tendency to blame farmers, and especially small farmers, for food losses and wastage is therefore misleading and ignores the problems related to the modern food chain dynamics. As noted by Sunita Narain, the small farmer is often quite careful and expedient in taking care of the food that is available in the field or within the farm. Residues and part of the harvest are used for feed, biogass production and soil amelioration. There is thus a very important distinction to be made between the fraction of the food at field level that is lost due to poor harvest technologies, transport and storage and fractions that are not channelled to the market or to the food industry.

It should be added that production and productivity vary significantly between different parts of the world. A worrisome feature is that production is low in areas where additional food is most urgently required. In these areas, the question is not whether to produce more or waste less. In these areas, there is certainly a need to increase production, to meet demand and to improve the living conditions of the farmers. The basic issue is therefore not so much about producing more or wasting less. It is, however, plausible to suggest that if losses and wastage are reduced, the need to increase production becomes much less of an issue.

Losses and Losers

Losses and wastage of food between the farmers' field to our dinner table – in food storage, transport, food processing, retail and in our kitchens – are huge. This loss of food is equivalent to a loss of water. It is also a loss of income, development opportunities and it means an extra burden on the environment. Reducing food loss and wastage would lessen water needs in agriculture while freeing water for other uses, including the environmental flow requirements.

It is well to remember that globally, the amount of food produced on farmers' fields is much more than is necessary for a healthy, productive and active life for the world population. A hidden problem is that farmers have to supply food to take care of both our necessary consumption and our wasteful habits. This problem can be turned into an opportunity.

Clearly, distribution of food is a problem – many are hungry, while at the same time many overeat. The imbalance is illustrated by the fact that many of the small farmers are actually net food buyers. Support and institutional arrangements that make it possible for them to increase production are absolutely essential.

The continuation of prevailing policy implies that potential gains from a reduction in losses may be overlooked and that a number of losers are generated while it is hard to find anybody who would win from continuing a policy that allows losses at the current level.

Or, does anybody have a stake in losses and wastage?

Anybody with a stake in losses and wastage?

The situation and the stakes look different in different parts of the world and for different groups of people. With reference to the situation in the rich parts of the world, it seems to be irrational behaviour among consumers to throw away about a quarter of the food that we have paid for and carried home, especially if most of this food is perfectly fit to eat. Why should we do that? A common answer is that few consumers are aware of the magnitude of their wastage. And even if they are, they tend to think that disposal of food is good for the environment. A partial explanation is thus that few realize the size of wastage and its economic and environmental implications. In combination with gradually lower prices of food, shortage of time to prepare food etc. the wastage will be high. Maybe increasing food prices will change this practice?

Recent studies are scarce and often refer back to older works. Without awareness backed up by good estimates, policy design will be difficult.

Concerning losses in other parts of the world, policy has obviously been concentrated on production and supply issues during recent decades. In the 1970s and 1980s there were several studies conducted on global and regional post-harvest losses, for instance, under FAO guidance but the topic is now largely off the agenda. Few people deal with these issues. Recent studies are scarce and often refer back to older works. Without awareness backed up by good estimates, policy design will be difficult.

It is also important to recognise that the food chain has become much more complex with many more actors involved. Generally, the growth of the food processing industry and supermarkets has been quite noticeable. Representatives of these actors control a very significant part of the trade in food and together with consumer preferences they play an important role in what and how much food is grown and, generally, how the flow of food is developed from field to fork and in the value chain. Buying 'three for the price of two' is a slogan that is not primarily formulated from an altruistic idea or with the intent that all three pieces should be eaten and that nothing should be discarded.

Concluding remark: A new dichotomy in the world demands international action

Even in areas of extreme water scarcity, food security can be achieved, that is, if budgets allow imports of food.

In an era of climate change with considerable implications for water resources, with growing demand for agricultural commodities, a new dichotomy may develop further. One part of the world has a considerable surplus of food and another part is increasingly affected by a deficit of food, both in terms of production and consumption. The situation is quite serious, with leaders in all parts of the world being engaged. Soaring prices of food and increases in the supply of food can be handled among the first category while the same problems are devastating for the second group. The borderline between the two groups is only partly based on national frontiers. Even in areas of extreme water scarcity, food security can be achieved, that is, if budgets allow imports of food. As the example from India indicated, the opposite is unfortunately also true; food insecurity is found in the midst of plenty.

The new dichotomy is putting considerable pressures on national governments and international organisations. But who is in a better position to act in cases of overeating and discarding of food? It is not only politicians who overeat and discard food.

The potential to make better use of rainfall is an approach which deserves much more attention.

In this emerging situation, a two pronged approach is required. Efforts must be made to increase food production, especially in areas with severe food deficits and with prevailing low levels of production and productivity. Water management will play a major role in this regard. The potential to make better use of rainfall is an approach which deserves much more attention.

But it is hard to see that a production and supply approach, alone, will solve the challenges. Even if much more food can be produced, parallel with an increase in the production of other agricultural commodities, there are many and very good arguments for paying more attention to the demand and consumption side of food security.

The supplementary approach is therefore to recognise that the very idea of food security, as formulated in the Rome Declaration of 1966 is to ensure that ".. the dietary needs and food preferences for an active and healthy life for all people at all times.." are met. That is, not too much food to eat and not too little. The question of what is "sufficient' must basically be interpreted from a nutritional and medical perspective. But what to do when preferences do not concur with water resources and environmental contexts? And what to do, and who should do what is required and sound, when preferences do not concur with sound diets for a 'healthy and productive life' and when the throwing away of food is socially and culturally acceptable?

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Bioenergy
– a new large user of scarce water?

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With climate change, a growing world population with changing dietary choices and an increased demand for biofuels, water is becoming a scarce resource in many parts of the world. There is, however, a large unrealised potential for efficiency increases along the food supply chain. This, together with a dietary change towards more vegetable food, might release vast formerly grazed areas to food and bioenergy production. Some energy crops are better suited than food crops for degraded land or wasteland, and plantations could also provide environmental services, like water filtration and erosion reduction in the agricultural landscape.

Introduction

Freshwater is already scarce in some regions of the world. A growing population and changing dietary trends mean a steeply rising water demand for food. Under the impact of climate change the population at risk of water stress could increase substantially. In this context, water demand for bio-energy production might place an additional burden on water availability worldwide and induce increased competition over water resources in an increasing number of countries. However, the link between increasing bioenergy and water use is not straightforward and increased bioenergy use does not always lead to increased water competition and a more difficult water situation.

This article discusses bioenergy as a prospective large user of water. Besides indicating the challenge by presenting possible future magnitudes of water use for bioenergy, the aim is to show how the integration of bioenergy with food production within expanding agricultural systems also presents opportunities in the development of more sustainable water and land use strategies.

Energy, food and fibre: some magnitudes

The global production of fossil resources is much larger than the biomass production in agriculture and forestry and most of the fossil resources are used for energy (Figure 1). Global industrial wood production corresponds to 15–20 EJ/year, or about 2.5 GJ/capita/year, which can be compared to the 390 EJ (60 GJ/capita) of fossil fuels that were commercially traded globally in 2005. The global production of the major crop types (cereals, oil crops, sugar crops, roots & tubers and pulses) corresponds to about 60 EJ (10 GJ/capita). Fibre production on cropland (e.g. cotton) corresponds to just a fraction of the total cropland output.

The observation on global level holds also for most countries. A few countries with large forest industries mobilize large wood flows and consequently residues and by-flows in the forest industry that can make up a considerable proportion of the energy supply. Biomass is also an important source of energy at present in developing countries, but this is at a very low level of per capita energy use and the biomass use – mainly combustion of wood and agricultural residues – has severe negative impacts*. The clear link between access to energy services and poverty alleviation and development is a strong motive to substantially improve and increase the supply of energy services in developing countries.

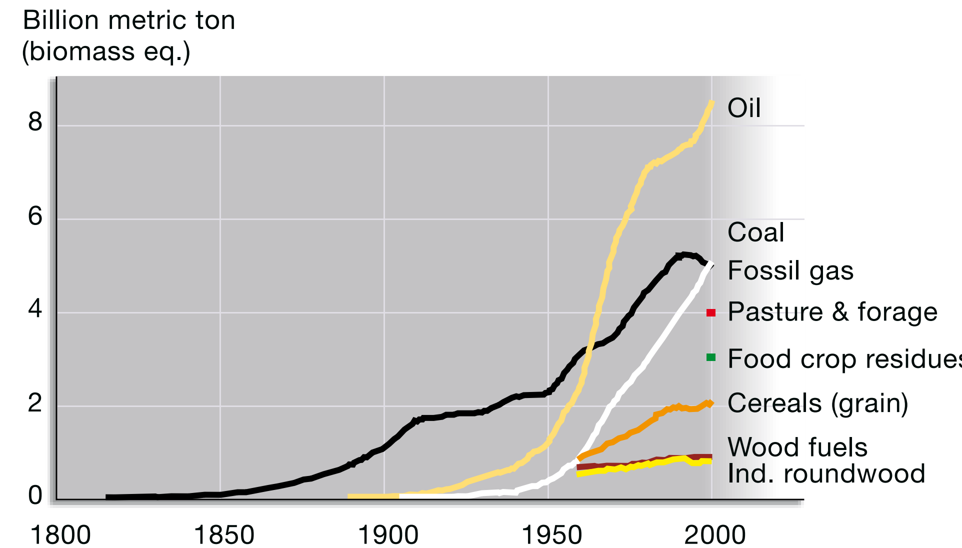


Figure 1. Global annual production of major biomass types in agriculture and forestry, and fossil resources. The fossil resources are given on a biomass equivalent basis (be) in order to facilitate a comparison with the different biomass types (conversion based on 1 ton oil equivalent = 42 GJ; 1 ton be=18 GJ). "Pasture & forage" refers to the part eaten by grazing animals. "Wood fuels" (FAO data) does not include all biomass uses for energy. For example, the FAO "Wood fuels" data for year 2000 corresponds to about 15 EJ, while the global biomass use for energy is estimated at about 35–55 EJ/ year.

Global energy consumption is expected to more than double during the 21st century. This means that the requirements of CO_2-neutral energy may have to grow to levels much higher than the present global total fossil fuel use, if we are to reach ambitious stabilization targets. Thus, a dramatic increase in the output from agriculture and forestry is required for making biomass an important primary energy source on the global level: bioenergy may even become a human use of photosynthesis that is comparable in scale to that for agriculture or forestry.

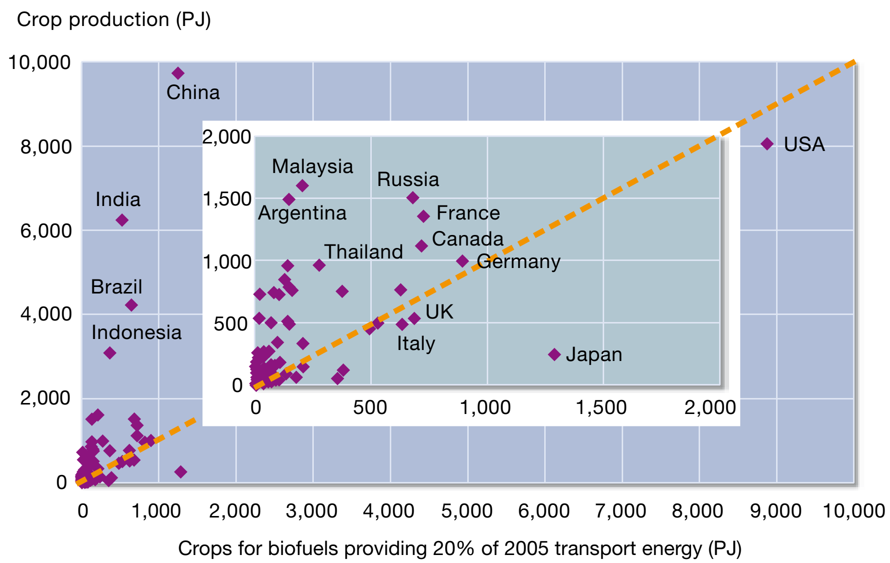
Figure 2 exemplifies a possible future situation for the case of biofuels for transport. If the demand for transport that emits less greenhouse gas mainly leads to increased cultivation of conventional agricultural food/feed crops – such as cereals, oil crops and sugar crops – for the production of so-called 1st generation biofuels for transport, the increasing global water use will resemble that driven by increasing food sector demand. However, the geographical pattern may be different since

* The combustion in confined spaces leads to indoor air pollution to which women and children are primarily exposed. This exposure has severe health consequences, including respiratory illnesses and premature death. Furthermore, in many instances the biomass use puts large pressure on local natural resources, leading to overexploitation with vegetation and soil degradation.

Figure 2 (below). An illustration of the crop harvest required for 1st generation biofuels to make a substantial contribution in the world. The y-axis shows the present domestic production of food and feed crops and the x-axis shows the amount of crops needed as feedstock for the production of 1st generation biofuels corresponding to 20% of domestic transport fuel-consumption in 2005. The red diagonal represents the situation where acountry would have to double the domestic crop production in order toreach the 20% biofuels share. It is assumed that the biomass is convertedinto biofuels at an average efficiency of 50% (energy basis). The inset smaller diagram is an enlargement of the lower left part of the largerdiagram.

the geographical distribution of the demand for biofuels for transport may be different from the increasing demand in the food sector.

Figure 2 illustrates the crop harvest increase required in the countries of the world if a future supply of 1st generation biofuels were to grow to a level corresponding to 20% of the motor fuel consumption in 2005. This can be compared, for instance, with (i) the minimum target of 10% for use of biofuels in transport in the EU to be reached by 2020; (ii) the biofuel goal for 2030 set by the Congress-established Biomass Research and Development Technical Advisory Committee – to displace petroleum corresponding to 30% of the present petroleum consumption in the USA; and (iii) the 10% targets in Japan (by 2008) and Thailand (by 2012).



Countries close to the diagonal line in Figure 2 would roughly have to double their crop harvest in order to support such a level of biofuel use, based on domestic feedstocks. Countries far above the line would require less relative increase in harvest, but this does not necessarily mean that they would be able to supply all the required feedstocks domestically: Figure 2 merely indicates the required effort in the agricultural sector to provide the feedstocks needed and should be complemented with information about the availability of not yet utilized land and water resources, considering also the expected increase in food demand in the coming decades. In addition, technology development might bring about biofuels for transport based on lignocellulosic sources (e.g., forest wood, agricultural harvest residues and lignocellulosic crops) and biomass may also be used for heat and power production, increasing demand further.

Use of residues can mitigate water pressures

To the extent that bioenergy is based on the utilization of residues and biomass processing by-flows within the food (and forestry) sectors, water use would not increase significantly due to increasing bioenergy. The water that is used to produce the food and conventional forest products is the same water as that which will also produce the residues and by-flows potentially available for bioenergy. The use of such flows improves water productivity – more utility (e.g. both food/forest products and bioenergy) per unit of water used. Some water is required for biomass processing to fuels and electricity but this is a rather small requirement compared to the evapotranspiration of the feedstock production.

Furthermore, there is scope for a substantial mitigation of the long-term land and water use in the food sector by increases in efficiency along the food supply chain. The total appropriation of terrestrial plant biomass production by the food system is roughly ten times larger than what is finally eaten by humans. Animal food systems account for roughly two-thirds of the total appropriation of plant biomass, whereas their contribution to the human diet is about 10–15%. The ruminant meat systems have the greatest influence on the food system's biomass appropriation, because of the size of ruminant meat demand and the lower feed conversion efficiency of those systems.

Animal food systems account for roughly two-thirds of the total appropriation of plant biomass, whereas their contribution to the human diet is about 10–15%.

Figure 3 shows the estimated production of by-products and residues in the present global food system and in scenarios for 2030. The three right-hand side alternative scenarios in Figure 3 were developed to investigate the influence of: (i) increased livestock productivity (IP), where the livestock productivity growth rates are higher than in the FAO study, but only slightly above the historical rates of the productivity increases since 1960; (ii) ruminant meat substitution (RS), where the IP scenario is modified by assuming a replacement of 20% of the beef, sheep and goat meat end-use with pig and poultry meat; and (iii) shifts to more vegetarian food and less food wastage (VE), where the RS scenario is further modified by assuming a somewhat increased efficiency in the end-use (i.e. less food wasted) and a shift in the structure of diets towards more vegetable and less animal food .

The alternative scenarios reveal that there is scope for a substantial mitigation of the long-term land and water use in the food sector by increases in efficiency along the food supply chain. There are also potentially major bioenergy feedstocks to be found in the large pool of appropriated biomass that does not end up as food: the utilization of harvest residues and biomass processing by-flows in the food and forestry sectors can clearly support a bioenergy industry of substantial scale and could mitigate the water demand related to a large scale bioenergy expansion.

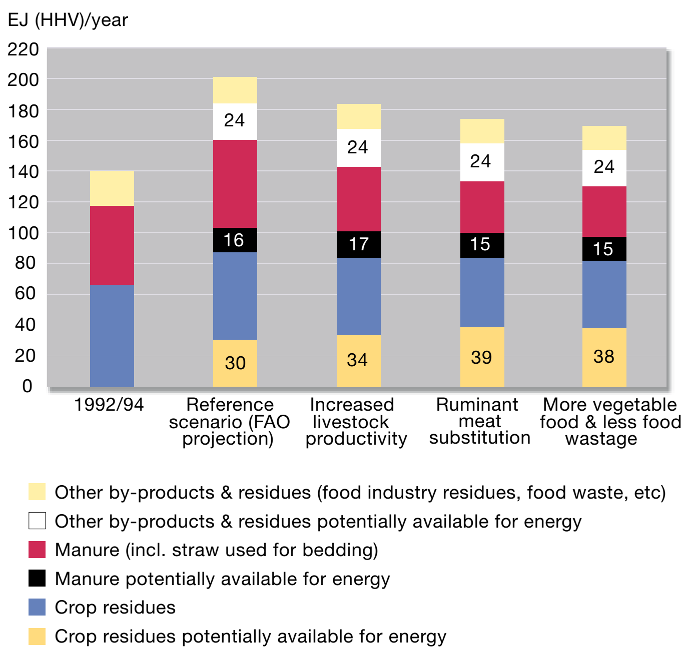


Figure 3: Estimated production of by-products and residues in the present global food system and in scenarios for 2030. The amounts possibly available for use as feedstock for bioenergy in the scenarios are indicated in the Figure (column fields with numbers). The Reference scenario depicts the projection by the Food and Agriculture Organization of the United Nations (FAO), presented in the publication "World agriculture: towards 2015/2030".

Thus, the volumes of agricultural residues that might become available for bioenergy in a few decades can be as large as the total present food sector harvest. In addition, the harvested and grazed amounts of biomass on croplands and pastures can be substantially reduced compared to a business as usual forecast such as the FAO projection in Figure 3. The reduced grazing requirement can be especially substantial, implying that large areas of pasture (on a global level, several hundred million hectares) could become available for other uses. If part of this land were targeted for bioenergy plantations, a considerable amount of biomass for energy could be produced without claiming land beyond what has already been appropriated.

However, pasture areas with sparse vegetation may experience increased evapotranspiration when bioenergy plantations are established and this may lead to lowered groundwater levels, aggravate river depletion and reduce downstream water availability. Clearly, the effects will vary depending on where in the world (and in the water basin) the bioenergy plantations are established; while some regions with abundant water availability are not likely to face water related difficulties, others may face an even more difficult water situation.

Bioenergy demand: both challenges and opportunities in relation to water

Bioenergy should not be regarded only as a threat to future water. Demand for bioenergy can lead to new opportunities to diversify livelihoods and develop land use strategies to adapt to climate change and water scarcity in agriculture.

Evaporation often dominates total evapotranspiration by annual crops during the early part of the growing season, and may comprise 30–60 per cent of seasonal evapotranspiration, sometimes even as much as 80 per cent. This is especially important in regions characterized by high evaporative demand, and under sparsely cropped farming systems. A major task is to change the relationship between the non-beneficial evaporation and beneficial transpiration. A progressive decline in non-productive evaporation in favour of plant transpiration is possible through a combination of rainwater harvesting techniques and improved soil and land management. If a larger fraction of the rainfall can be harnessed and consumed in plant production, a boost in productivity and total production can be accomplished without a corresponding increase in the pressure on freshwater in rivers, lakes and aquifers.

Given that several types of energy crops are perennial leys and woody crops grown in multi-year rotations, the increasing bioenergy demand may actually become a driver for land use shifts towards land use systems with substantially higher water productivity. Research has shown that agroforestry can increase water productivity by decreasing the proportion of unproductive rainfall, which would otherwise be lost as runoff or soil evaporation. For example, intercropping the Silky-oak, *Grevillea robusta*, with maize in semi-arid Kenya doubled overall rainfall utilization. In Kenya, the use of deciduous trees helps smallholders optimize water supplies while harnessing new economic products.

It is possible to cultivate biomass for energy purposes in areas where conventional food production is not feasible, for instance due to water constraints.

Yet again, as mentioned above, the integration of bioenergy crops within agricultural systems also presents challenges in the development of land use strategies: plantations of fast-growing trees can exacerbate water shortages and changes in water and land management and use will have an impact on downstream users and ecosystems. An important question is where the production of biomass for energy purposes can and will expand. A number of crops that are suitable for bioenergy production are drought tolerant and relatively water efficient, and by adopting such crops farmers may better cope with a change in precipitation patterns and increased rates of evapotranspiration due to higher temperatures. It is possible to cultivate biomass for energy purposes in areas where conventional food production is not feasible, for instance due to water constraints.

It has been suggested that by targeting degraded land, farmers could avoid/mitigate competition with food and also restore soil organic matter and nutrient content, stabilize erosion and improve moisture conditions. In this way an increasing biomass demand could become instrumental in the reclamation of land that has been degraded from earlier over-exploitation and improper management. Such a strategy is, for example, being attempted in parts of India, where about 13 million hectares of wasteland are being earmarked for cultivation of feedstocks that can grow in areas with a low rainfall, e.g. Jatropha and sweat sorghum. The establishment of suitable bioenergy crops on degraded lands may be an opportunity for shifting vapour flows on degraded lands to productive transpiration of the bioenergy crops. Such strategies could allow for the reclamation of degraded land and enhanced biomass production without compromising downstream blue water resources, hence mitigating both land and water competition.

The cultivation costs are lowest on the best soils and highest for the poorest soils when costs for land are excluded.

In addition to recalling the need for this analysis, it should be noted that some studies indicate that biomass production on marginal/degraded land may not be the self-evident outcome of increasing biomass demand. As bioenergy use increases and farmers adopt the bioenergy crops, they will consider the development in both food and bioenergy sectors when planning their operations. The economic realities at the farm level may then still lead to bioenergy crops competing with food crops, since it is the good soils that have the higher yields also for the bioenergy crops. The cultivation costs are lowest on the best soils and highest for the poorest soils when costs for land are excluded. Crop prices are reflected in land prices, and in a situation where prices for conventional crops are low, the higher yields on better soils outweigh the increased (land) cost of shifting cultivation from poorer to better soils. An increase in food crop prices will produce a movement for these bioenergy crops in the direction of poorer soils. If the prices for the bioenergy crops increase more than food crop prices, this will cause a movement of lignocellulosic crops to better soils.

Figure 4. The large photo illustrates a wasteland area in the state of Karnataka, India with its low vegetative cover and erosion prone surface. The photo to the right shows an attempt at water harvesting using gully check to increase the infiltration of rainwater in the district of Bidar, India.

Thus, biomass plantations may eventually be pushed to marginal/degraded land due to increasing land costs following increased competition for prime cropland, but this competition will likely also be reflected in increasing food commodity prices. Rules and regulations may dictate that certain bioenergy crops should be produced on certain soils not suitable for food/feed crops production (such as wastelands in India) or on lands where the cultivation of food/feed crops causes excessive environmental impacts (such as sloping erodible soils on the Loess Plateau in China). Regulations may also prevent farmers using more than a certain proportion of their land for energy crops production.

Biomass can be cultivated in so-called multifunctional plantations that – through well-chosen localization, design, management and system integration – offer extra environmental services that, in turn, create added value for the systems. Many such plantations provide water related services, such as vegetation filters for the treatment of nutrient-bearing water such as wastewater from households, collected run-off water from farmlands and leachate from landfills. Plantations can also be located in the landscape and managed for capturing the nutrients in passing run-off water. Sewage sludge from treatment plants can also be used as fertilizer in vegetation filters. Plantations can be located and managed for limiting water erosion, and will reduce the volume of sediment and nutrients transported into river systems. They may reduce shallow land slides and local 'flash floods'. Besides the on-site benefits of reduced soil losses, there are also off-site benefits such as reduced sediment load in reservoirs, rivers and irrigation channels.

Figure 5. A *Salix* field irrigated with pre-treated municipal sewage in Enköping, Sweden. The picture to the left shows measurement equipment used to chart the nitrogen flows in the field. An important question is how much of the nitrogen input is transformed into nitrogen oxide, a powerful greenhouse gas. The investigations until now indicate that the climatic impact of these discharges is small in relation to the climatic benefit of the produced biomass in replacing, for example, fossil fuels in municipal heating plants. Also important are the hygienic aspects of sewage-irrigated Salix production. Experiments show that the risk of spreading infection is low, but that unsuitable locations such as nearness to waterways should be avoided.

This article has briefly described both challenges and opportunities for food and bioenergy in relation to water, and has implicitly indicated research needs for supporting rational decisions and implementation of efficient policies. One example of a window of opportunity is that a number of crops that are suitable for bioenergy production are drought tolerant and relatively water efficient crops that are grown under multi-year rotations. These crops provide an option to improve water productivity in agriculture and help alleviate competition for water as well as pressure on other land-use systems. It also offers a possibility to diversify land use and livelihood strategies and protect fragile environments.

In this context, the development of technologies for producing second generation biofuels from lignocellulosic feedstocks is one crucial determinant of development opportunities. Firstly, they can use a range of agricultural and wood-related residues as their feedstock without any direct claims on land or water. Secondly, the land use efficiency of second generation biofuels based on lignocellulosic crops is commonly substantially higher than that of most first generation biofuels, leading to less land required per unit of energy produced. Thirdly, a wider spectrum of land types could be available for feedstock cultivation. Notably pastures and grasslands, not viable for first generation biofuels due to environmental and greenhouse gas implications (intensive soil management leads to soil carbon losses as CO_2), could become an additional resource for high-yielding lignocellulosic feedstocks under suitable management practices. Marginal areas could also be considered for lignocellulosic feedstock production.

The suggestion that large areas of pastures/grasslands and marginal/degraded lands may be available for lignocellulosic crop production must however be verified in relation to water availability and use. To assess the impact of land and water use and management, an integrated basin analysis is required; however, this is rarely done today. Science needs to increase our knowledge about how changes in water and land management will affect downstream users and ecosystems. In many cases such impacts can be positive. For example, local water harvesting and run-off collection upstream may reduce erosion and sedimentation loads in downstream rivers, while building resilience in the upstream farming communities. Conversely, the use of marginal areas with sparse vegetation for the establishment of high-yielding bioenergy plantations may lead to substantial reductions in runoff, which can be positive or negative depending on the specific context.

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The water footprint of food

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The international trade in agricultural commodities at the same time constitutes a trade with water in virtual form. Water in external areas has been used to produce the food and feed items that are imported. The water footprint of a good or a service is the total amount of water, external and internal, that is required to produce it. The concept can be used to calculate and compare the strain on water resources resulting from different options. It can also be extended to provide water budgets for whole nations or continents.

Water management is no longer an issue restricted to individual countries or river basins. Even a continental approach is not sufficient. The water footprint of Europe – the total volume of water used for producing all commodities consumed by European citizens – has been significantly externalised to other parts of the world. Europe is for example a large importer of sugar and cotton, two of the most thirsty crops. Coffee is imported from countries such as Colombia, soybean from Brazil, and rice from Thailand. European consumption strongly relies on water resources available outside Europe. How is Europe going to secure its future water supply? China and India are still largely water self-sufficient, but with rising food demand and growing water scarcity within these two major developing countries, one will have to expect a larger demand for food imports and thus external water demand. Water is increasingly becoming a global resource.

Although in many countries most of the food still originates from the country itself, substantial volumes of food and feed are internationally traded.

Although in many countries most of the food still originates from the country itself, substantial volumes of food and feed are internationally traded. As a result, all countries import and export water in virtual form, i.e. in the form of agricultural commodities. Within Europe, France is the only country with a net export of virtual water. All other European countries have net virtual water import, i.e. they use some water for making export products but more water is used elsewhere to produce the commodities that are imported. Europe as a whole is a net importer of virtual water. Europe's water security thus strongly depends on external water resources. Related to this, a substantial proportion of existing problems of water depletion and pollution in the world relates to export to Europe.

The water footprint shows the extent and locations of water use in relation to consumption by people.

The 'water footprint' has been developed as an analytical tool to address policy issues of water security and sustainable water use. The water footprint shows the extent and locations of water use in relation to consumption by people. The water footprint of a community is defined as the volume of water used for the production of the goods and services consumed by the members of the community. The water footprint of a nation is an indicator of the effects of national consumption on both internal and external water resources. The ratio of internal to external water footprint is relevant, because externalising the water footprint means increasing the dependency on foreign water resources. It also results in externalising the environmental impacts. European countries such as Italy, Germany, the UK and the Netherlands have external water footprints contributing 50–80 % to the total water footprint.

The global water demand for production of food, feed, fibre and energy crops is rapidly increasing. A key question for regions that already now depend on external water resources is whether they can keep up their position as net virtual water importers. Another key question is which role businesses in the food sector can play in delivering products in a water-sustainable way. This chapter introduces a recently developed analytical framework to study the relation between globalisation of trade and water management for both governments and businesses.

A key question for regions that already now depend on external water resources is whether they can keep up their position as net virtual water importers.

New concepts: virtual water trade and water footprints

The virtual-water concept was introduced by Tony Allan when he studied the possibility of importing virtual water (as opposed to real water) as a partial solution to problems of water scarcity in the Middle East. Allan elaborated the idea of using virtual-water import (coming along with food imports) as a tool to release the pressure on scarcely available domestic water resources. Virtual-water import thus becomes an alternative water source, alongside endogenous water sources.

The water footprint concept was introduced six years ago by Arjen Hoekstra. The concept is an analogue to the ecological footprint, but indicates water use instead of land use (see Box). The water footprint is an indicator of water use that looks at both the direct and indirect water use of a consumer or producer. The water footprint of an individual, community or business is defined as the total volume of freshwater that is used to produce the goods and services consumed by the individual or community or produced by the business. Water use is measured in terms of water volumes consumed (evaporated) and/or polluted per unit of time. The water footprint is a geographically explicit indicator that not only shows volumes of water use and pollution, but also the locations.

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Box: Three dimensions of the human footprint

The water-footprint concept is part of a larger family of concepts that have been developed in the environmental sciences over the past decade. A "footprint" in general has become known as a quantitative measure showing the appropriation of natural resources by human beings. The ecological footprint is a measure of the use of bio-productive space (hectares). The carbon footprint measures energy use in terms of the total volume of carbon dioxide emissions. The water footprint measures water use (in cubic metres per year).

In the mid-1990s, Wackernagel and Rees developed the concept of the 'ecological footprint'. They were worried about the amount of land required to supply the world population with what they consume, particularly if everybody in this world were to adopt a western lifestyle. People need land for living and moving, agricultural land (cropland and pasture) to produce the food required and forested land to supply things like wood and paper. Finally, there is forested land needed to transform the carbon dioxide emitted by human activities into organic matter. It has been argued that the total ecological footprint of all world inhabitants together can temporarily go beyond the available area, but only by exhausting the natural resource base, which is considered 'unsustainable'. Humanity has moved from using, in net terms, about half the planet's biocapacity in 1961 to over 1.2 times the biocapacity of the Earth in 2002. The global ecological deficit of 0.2 Earths is equal to the globe's ecological overshoot.

The carbon footprint is a measure of the impact that human activities have on the environment in terms of the amount of greenhouse gases produced, measured in units of carbon dioxide. It is an indicator for individuals and organizations to conceptualize their personal or organizational contribution to global warming. The carbon footprint can be seen as the total amount of carbon dioxide (CO_2) and other greenhouse gases emitted over the full life cycle of a product or service. A carbon footprint is usually expressed as a CO_2 equivalent (in kilograms or tonnes), in order to make the global warming effects of different greenhouse gases comparative and addable.

The total water footprint of an individual or community breaks down into three components: the blue, green and grey water footprint. The blue water footprint is the volume of freshwater that is evaporated from the global blue water resources (surface and ground water) to produce the goods and services consumed by the individual or community. The green water footprint is the volume of water evaporated from the global green water resources (rainwater stored in the soil). The grey water footprint is the volume of polluted water, which can be quantified as the volume of water that is required to dilute pollutants to such an extent that the quality of the ambient water remains above agreed water quality standards.

A water footprint can be calculated for any well-defined group of consumers (e.g. an individual, family, village, city, province, state or nation) or producers (e.g. a public organization, private enterprise or economic sector). One can also calculate the water footprint of a particular product. The water footprint of a product (a commodity, good or service) is the volume of freshwater used to produce the product, measured at the place where the product was actually produced. It refers to the sum of the water used in the various steps of the production chain. The 'water footprint' of a product is the same as what at other times is called its 'virtual water content'. Table 1 shows the water footprint for a number of common food items.

Consider the water footprint of beef. In an industrial beef production system, it takes on average three years before the animal is slaughtered to produce about 200 kg of boneless beef. The animal consumes nearly 1,300 kg of grains (wheat, oats, barley, corn, dry peas, soybean meal and other small grains), 7,200 kg of roughages (pasture, dry hay, silage and other roughages), 24 cubic metres of water for drinking and 7 cubic metres of water for servicing. This means that to produce one kilogram of boneless beef, we use about 6.5 kg of grain, 36 kg of roughages, and 155 litres of water (only for drinking and servicing). Producing the volume of feed requires about 15,300 litres of water on average. The water footprint of 1 kg of beef thus adds up to 15,500 litres of water. This still excludes the volume of polluted water that may result from leaching of fertilisers in the feed crop field or from surplus manure reaching the water system. The numbers provided are estimated global averages; the water footprint of beef will strongly vary depending on the production region, feed composition and origin of the feed ingredients.

Table 1. The water footprint of different food items.

Food item	Unit	Global average water footprint (litres)
Apple or pear	1 kg	700
Banana	1 kg	860
Beef	1 kg	15,500
Beer (from barley)	1 glass of 250 ml	75
Bread (from wheat)	1 kg	1,300
Cabbage	1 kg	200
Cheese	1 kg	5,000
Chicken	1 kg	3,900
Chocolate	1 kg	24,000
Coffee	1 cup of 125 ml	140
Cucumber or pumpkin	1 kg	240
Dates	1 kg	3,000
Groundnuts (in shell)	1 kg	3,100
Lettuce	1 kg	130
Maize	1 kg	900
Mango	1 kg	1,600
Milk	1 glass of 250 ml	250
Olives	1 kg	4,400
Orange	1 kg	460
Peach or nectarine	1 kg	1,200
Pork	1 kg	4,800
Potato	1 kg	250
Rice	1 kg	3,400
Sugar (from sugar cane)	1 kg	1,500
Tea	1 cup of 250 ml	30
Tomato	1 kg	180
Wine	1 glass of 125 ml	120

A new accounting framework

Traditional national water use accounts only refer to the water use within a country. In order to support a broader sort of analysis, the accounts need to be extended. This has resulted in an accounting framework as shown in Figure 1.

As can be seen in the figure, the water footprint of a nation has two components. The internal water footprint is defined as the water used within the country in so far as it is used to produce goods and services consumed by the national population. The external water footprint of a country is defined as the annual volume of water resources used in other countries to produce goods and services imported into and consumed in the country considered. It is equal to the virtual-water import into the country minus the volume of virtual-water exported to other countries as a result of re-export of imported products.

Figure 1. The new national water-accounting framework.

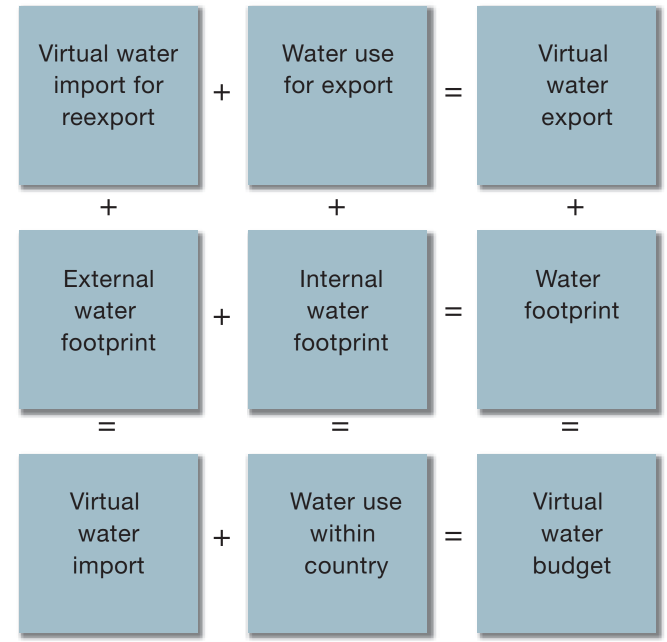
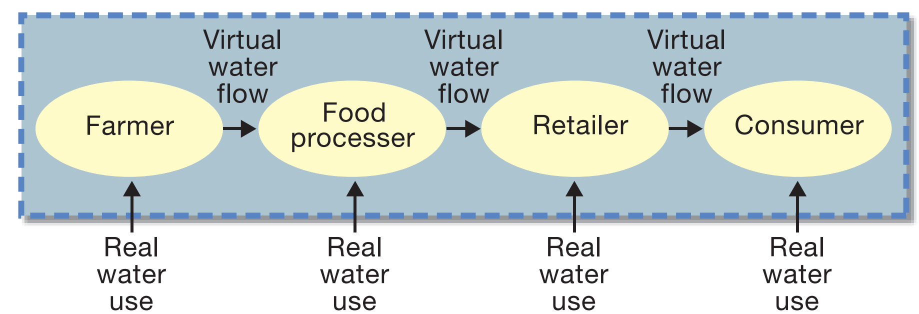


Figure 2. The virtual-water chain.



The virtual-water export consists of exported water of domestic origin and re-exported water of foreign origin. The virtual-water import will partly be consumed, thus constituting the external water footprint of the country, and partly re-exported. The sum of virtual water import and water use within a country is equal to the sum of the virtual water export and the country's water footprint. This sum is called the virtual-water budget of a country.

Not only national water use accounts need to be adjusted. Also business water accounts need to be extended in order to address issues of sustainability. Figure 2 shows the so-called 'virtual-water chain', which is the chain of production and consumption of water-intensive goods. A typical virtual-water chain consists of a farmer at the primary production end, a consumer at the consumption end and, depending on the commodity at stake, some intermediaries such as a food processor and a retailer.

The water footprint of a business is defined as the total volume of freshwater that is used, directly and indirectly, to produce the products and services of that business. The water footprint of a business consists of two parts: the operational water footprint and the supply-chain water footprint. The first refers to the amount of freshwater used within the business, i.e. the direct freshwater use for producing, manufacturing or supporting activities. The second refers to the amount of freshwater used to produce all the goods and services that form the input of the business, i.e. the indirect water use.

Reducing and offsetting the impacts of water footprints

The increasing focus on water footprints has led to the question of how humans can neutralise or offset their water footprint. The question is very general and interesting from the point of view of both individual consumers and larger communities, but also from the perspective of governments and companies.

The idea of the water-neutral concept is to stimulate individuals and corporations to make their activities 'water neutral' by investing in water saving technology, water conservation measures, wastewater treatment and water supply to the poor that do not have proper water supply. In other words, water-neutral means that the adverse environmental and social consequences of a water footprint are reduced and compensated for. The water-neutral concept was conceived by Pancho Ndebele at the 2002 Johannesburg World Summit for Sustainable Development. The idea at the time of the Summit was to quantify the water consumed during the conference by delegates and translate this into real money. Delegates, corporations and civil society groups were encouraged to make the summit water neutral by purchasing water-neutral certificates to offset their water consumption during the ten-day summit, with the offset investment being earmarked for improving water supply to the poor in South Africa and for water conservation initiatives. The water-neutral concept is currently being discussed within various communities, including academia, NGOs and businesses, as a potential tool to translate water footprints into modes of action.

Now that the water-neutral concept has been discussed in a bit wider audience it has become clear that the concept of water neutrality can be applied in a variety of contexts. Individual consumers or communities can try to become water neutral by reducing their water footprint and offsetting their residual water footprint. Rich travellers who visit a water-scarce country where many people do not even have basic water supply facilities can try to 'neutralise' their water use during their stay by investing in projects to enhance sustainable and equitable water use. Large events like the Johannesburg Conference or the Olympic Games, that generally have a significant additional impact on local water systems, can be organised in a water-neutral way by minimising water use and pollution by all possible means and by investing in local water projects aimed at improved management of the water system as a whole and for the benefits of society at large. Finally, businesses may like to become water neutral, be it from the perspective of minimising business risks (the risk of running out of water) or from the idea that it offers an attractive way of presenting the business to the consumer.

Water neutrality can be an instrument to raise awareness, stimulate measures that reduce water footprints and generate funds for the sustainable and fair use of freshwater resources. In a strict sense, however, the term 'water neutral' can be misleading. It is often possible to reduce a water footprint, but it is generally impossible to bring it down to zero. Water pollution can be largely prevented and much of the water used in various processes can be reused. However, some processes like growing crops and washing inherently need water. After having done everything that was technically possible and economically feasible, individuals, communities and businesses will always have a residual water footprint. In that sense, they can never become water neutral. The idea of 'water neutral' is different here from 'carbon neutral', because it is theoretically possible to generate energy without emitting carbon, but it is not possible to produce food without water. Water neutral is thus not about nullifying water use, but about water saving where possible and offsetting the negative environmental and social effects of water use.

Water neutrality can be an instrument to raise awareness, stimulate measures that reduce water footprints and generate funds for the sustainable and fair use of freshwater resources.

In order to become 'water neutral' there are at least two requirements:

1. all that is 'reasonably possible' should have been done to reduce the existing water footprint;

2. the residual water footprint is offset by making a 'reasonable investment' in establishing or supporting projects that aim at the sustainable and equitable use of water.

The investment can be made in the form of own effort, but it can also be in terms of providing funds to support projects run by others. The size of the investment (the offset or 'pay off' price) should probably be a function of the vulnerability of the region where the (residual) water footprint is located. A water footprint in a water-scarce area or period is worse and thus requires a larger offset effort than the same size water footprint in a water-abundant region or period. Besides, compensation is to be made in the same river basin as where the water footprint is located, which differs from the case of carbon offsetting, where the location of the offset does not make a difference from the viewpoint of its effect.

Discussion

For about a year there has been increasing interest in water footprint accounting, primarily from the international NGO and business community. Governments respond more slowly, but several governments at different levels have started to respond as well. Water footprint accounting is about extending the knowledge base in order to improve the base for decisions. Ideas about water neutrality are expected to receive more debate. The water-neutral concept includes a normative aspect in that consensus needs to be reached about what effort to reduce an existing water footprint can reasonably be expected and what effort (investment) is required to sufficiently offset the residual water footprint. The remaining key questions are:

1. How much reduction of a water footprint can reasonably be expected? Is this performance achieved by applying so-called Better Management Practices in agriculture, or Best Available Technologies in manufacturing? How does one deal with totally new products or activities?

2. What is an appropriate water-offset price? What type of efforts count as an offset?

3. Over what time span should mitigation activities be spread and how long should they last? If the footprint is measured at one period of time, when should the offset become effective?

4. What are the spatial constraints? When a water footprint has impacts in one place, should the offset activity take place in the same place or may it take place within a certain reasonable distance from there?

Finally, accounting systems need to be developed that prevent double offsetting. For example, a business can offset its supply-chain water footprint while the business in the supply chain offsets its own operational water footprint. How to share offsets? And where offsets are achieved in projects that are joint efforts, how much of any calculated water benefits can an individual entity claim?

Despite the possible pitfalls and yet unanswered questions, it seems that the water-neutral concept offers a useful tool to bring stakeholders in water management together in order to discuss water footprint reduction targets and mechanisms to offset the environmental and social impacts of residual water footprints. The concept will be most beneficial in actually contributing to wise management of the globe's water resources when clear definitions and guidelines will be developed. There will be a need for scientific rigour in accounting methods and for clear (negotiated) guidelines on the conditions that have to be met before one can talk about water neutrality.

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Water productivity and green water management in agro-ecosystems

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An important way of preserving water in farming is to increase the efficiency of water use through higher water productivity. This means lowering the ratio of evapotranspiration (i.e. green water use) in relation to yield size. There are a number of options open to the farmer, involving changes in water, soil or crop management. The chosen practice can be adapted to best suit the priorities or limitations of the farmer. On a watershed scale, water productivity considerations can assist in determining the best allocation of water use for planning purposes.

Introduction

To sustain global food production, an estimated 7,000 km^3 of water is consumed on current croplands annually, which can be compared with the total terrestrial consumptive water flow which is around 72,500 km^3 per year. However, to feed humanity in 2050, this amount is estimated to increase by an additional 2,000 – 6,000 km^3. Obviously, such large increases in water allocation will have negative effects on other ecosystems and water uses.

To increase agricultural outputs, three principal options emerge: to consume more water on current croplands, to expand agriculture into current non-agricultural areas, or to use the currently available water for crop and livestock production more efficiently. The latter means increasing water productivity (WP) (Box 1), i.e., consuming less water per produced unit of biomass (or livestock). Especially in low-yielding tropical rainfed agriculture, a large scope for improvements in water productivity has been identified. Future food production will probably involve a combination of these three options. However, improved water productivity in existing crop production systems will have the least negative impact on other water related services and uses in society and ecosystems.

This article describes opportunities for management to improve water productivity at the field scale, with particular relevance to current low-yielding sub tropical and tropical farming systems. We briefly discuss water productivity implications at the landscape scale and outline the impact on future water requirements of improvements in water productivity.

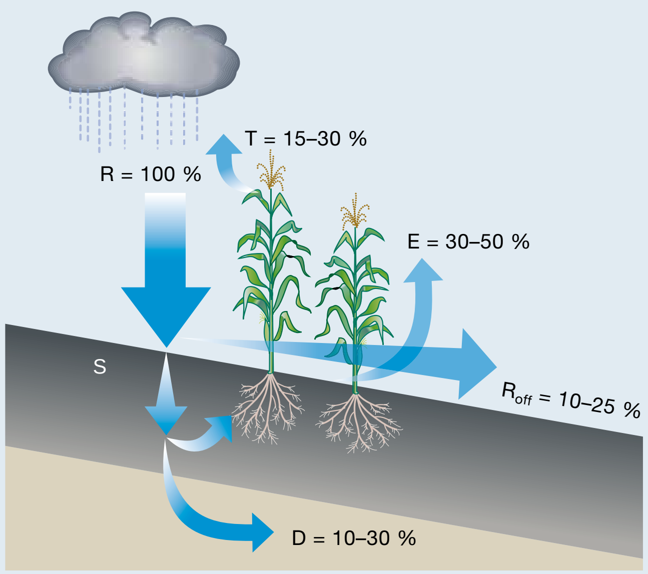
Box 1
The Water Productivity Concept and Green Water Management

Water productivity in the crop water management context refers to the amount of water needed (or used) to support the growth and development of biomass. In this article, we look at the field scale water productivity, and define water productivity as the amount of water consumed to produce a certain amount of (economic) yield:

$$WP = \frac{ET_a}{Y_g} \; [m^3 \, t^{-1}]$$

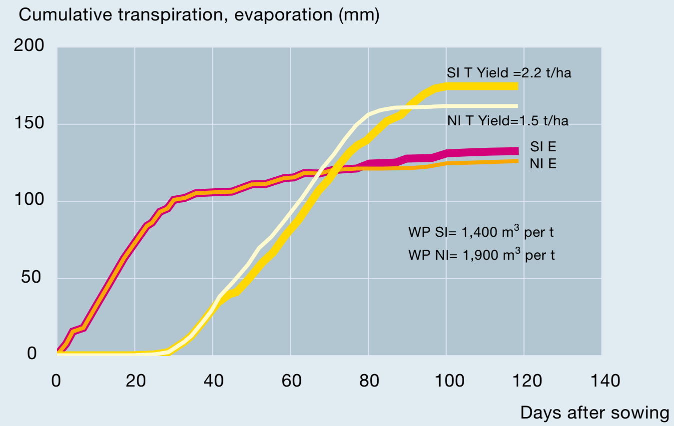
where ET_a is the actual evapotranspiration from sowing to harvest (in m^3 per ha land), and Y_g is the harvested grain yield in t ha^{-1} (unless otherwise stated). This means that a *low* number denotes *high* water productivity and vice versa.

Evapotranspiration (green water flows) consists of two components: productive transpiration, which is determined by species and crop stand conditions, and unproductive soil evaporation, which for example is affected by shadowing from plant canopies (see figure below) as well as soil surface characteristics.



Partitioning of rainfall on a typical farmer's field in the Savannah region. Unproductive losses of water (E), are large in relation to productive transpiration (T). Runoff (R_{off}) and drainage (D) are lost from the farmer's field, but can be used downstream

Very little water is actually stored in the biomass, but the continuous flow of water through the plant is partly a response to the to the stomata uptake of CO_2, i.e. an 'involuntary' gaseous exchange. Transpiration is directly proportional to total biomass during a growing season (see figure below). As the plant develops its canopy, the productive flow increases, and the unproductive flow decreases to near nil when the canopy leaf area exceeds 3 m^2 per m^2 soil. However, if the plant does not develop a dense canopy, the non-productive losses remain high throughout the season, and water productivity thus become low.



Seasonal development of a maize crop.
SI=supplemental irrigation; NI=no irrigation.
T = transpiration; E = soil evaporation.

A win-win relationship between yield and water productivity

Management that impacts on yield also impacts on water productivity. Especially at low yields, small yield gains have large positive impacts on water productivity (Fig. 1, note that high WP has low value in graph). This is due to two factors. First, denser canopy covers, which shade the soil and thus limit unproductive green flow soil evaporation. At yields greater than circa 4 tons/ha, the effect is negligible, since additional leaf area does not significantly alter the radiation that reaches the surface, affecting productive and unproductive green water flows. Secondly, each reduction in water stress, which may be bridged, i.e. the incremental addition of water, has a relatively higher final yield impact at lower transpiration (and yield) levels than at higher yield levels. In other words, the largest water productivity gains emerge in low –yielding crop systems, presenting a win-win situation for improvements - increasing yields and at the same time improving water productivity.

Field scale management impacts on water productivity

All types of crop, soil and water management impact on water productivity. Water management is perhaps the most obvious since it is a manipulation of the actual resource, but also changes in soil and crop management can have large impacts on water productivity. The main management strategies that impact on

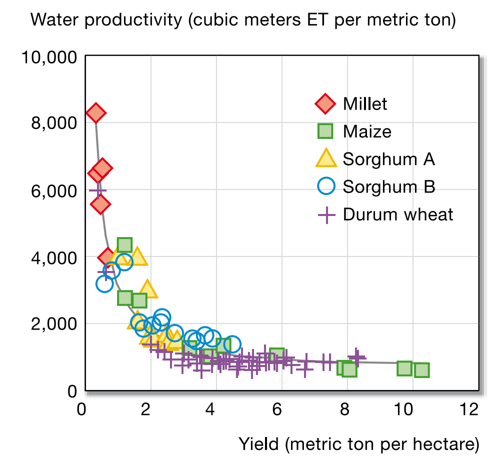


Figure 1. Dynamic relationship between water productivity and yield for cereal crops under various management and climatic conditions.

water productivity in a farmers' field are summarised in table 1. For the farmer, the purpose of using these options is primarily to improve yields, and thus changes in water productivity will become a 'positive externality' of these measures. The decision to use a certain management approach is affected by a number of factors such as yield maximisation, economic constraints, traditions, knowledge and availability of the specific technology. Moreover, the same management strategy might have very different impacts on water productivity depending on local conditions, such as soil type and climate.

Table 1. Management strategies that have an impact on water productivity, including a description of the main processes they affect.

Management	How	Why
Water management	Water collection method and storage	Evaporation, runoff generation
	Irrigation scheduling (e.g. deficit or full irrigation, timing of irrigation events)	Evaporation
	Irrigation method	Evaporation
Soil management	Tillage (incl. conservation agriculture)	Root length and density, evaporation
	Mulching (incl. organic manure)	Evaporation
	Weed management	Less unproductive transpiration
Crop management	Intercropping	Microclimate
	Crop choice	Water use efficiency, leaf area, drought resistance
	Fertiliser and manure	Leaf area
	Pest management	Leaf area
	Timing of operations (e.g dry planting)	Evaporation

Water management

Irrigation scheduling strongly impacts on water productivity. Both the timing and amounts of irrigation can be optimised for water productivity. For example, deficit irrigation (i.e. where only part of the whole plant water demand is given to the plant) results in lower yields, compared with full irrigation (Fig. 2). On the other hand, water productivity is higher. This means that when the plant is given water to cover its full plant water demand, less yield is produced per amount of water added. Thus, in this case there is apparently a conflict of interest between maximising yield and maximising water productivity. A simple but highly effective water saving can be to irrigate in the evenings around sunset when the potential evapotranspiration is low and winds die down, which gives the irrigation water the maximum possible time to infiltrate before sunrise, thus limiting soil evaporative water losses.

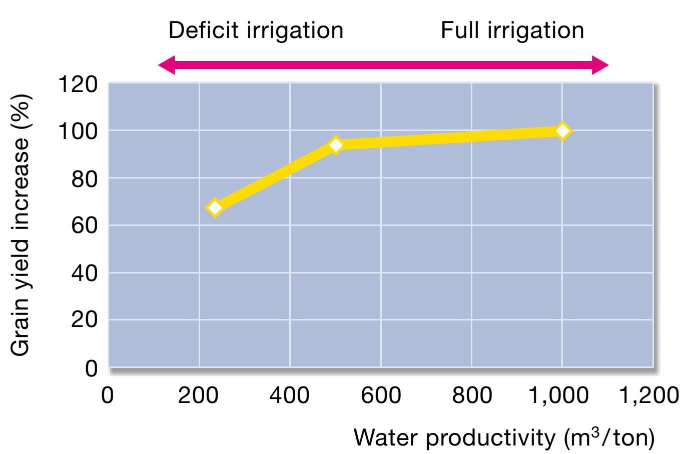


Figure 2. Water productivity as a function of irrigation water amount applied to the crop.

There are also large differences between irrigation methods in terms of water productivity. In more conventional systems, such as furrow and sheet irrigation, an average 50–60 % of the applied water is used as productive transpiration, while in sprinkler systems around 60–80 % of the applied irrigation water is used for transpiration. Drip irrigation systems have the highest irrigation efficiency; up to 90 % of the applied irrigation water can be used for plant transpiration (Fig. 3). Examples from India show that shifting from conventional surface irrigation to drip irrigation not only resulted in a yield increase by around 50 %, but also led to an improvement in water productivity that ranged from 40–250 %.

Figure 3. Drip irrigated tomato plant.

Soil management

Soil management, which preserves or enhances the available soil water storage capacity and nutrient availability but at the same time results in draining of excessive water, leads to improved water productivity. Such measures include preserving or enhancing a healthy soil system with low tendency for surface crusting and compaction damage, good pore space distribution enabling high crop water availability but also good drainage. An example to address multiple soil systems characteristics is the adoption of conservation agriculture, which aims to avoid soil compaction through reduced tillage, combined with increased input of organic matter and, if possible, extended coverage of soil surface through intercropping or mulch. These combined measures increase overall soil physical and biological features, which ultimately provides the crop with improved water access (to bridge dry spells), and nutrient uptake. Both these processes result in improved water productivity of the soil-crop system.

Figure 4. Plastic mulch prevents evaporation and the prevalence of weeds.

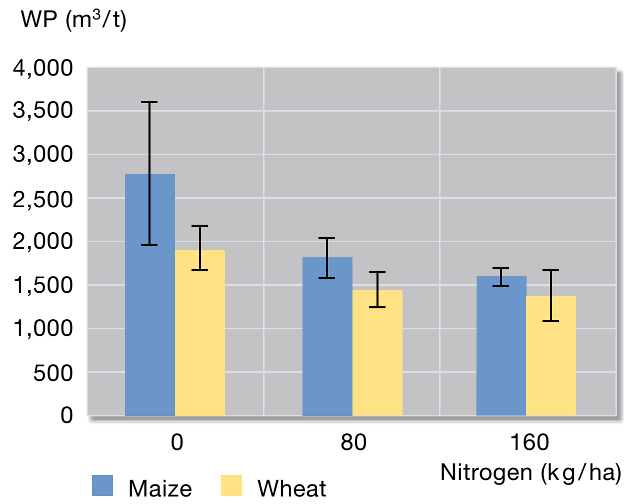
Mulching and manure covers the soil and prevents the unproductive green flows of soil evaporation. This has a direct positive impact on water productivity. Mulch and manure also increase biological activity and can reduce the prevalence of weeds (Fig. 4). Several studies have shown a large positive impact on yield and water productivity from mulch applications.

Crop management

Crop choice impacts on water productivity in several ways. Plants with larger canopies tend to shade larger parts of the soil, thereby limiting soil evaporation. For the same reason, pest management which enables the establishment of a large and healthy canopy, can result in higher water productivity. Moreover, crops and crop varieties differ in water use efficiency (amount of biomass produced per unit of transpiration) and drought resistance, which in turn impacts on water productivity.

Fertilisation has a positive impact on water productivity through increased leaf area, causing shading of the soil and thus preventing non-productive soil evaporation. Data from an experiment in Niger shows improved water productivity with increasing nitrogen fertiliser for a wheat and a maize crop (Fig. 5). At higher fertiliser levels, the effect on water productivity is less pronounced. This is due to the addition of water

Figure 5. Water productivity as a function of nitrogen fertiliser supply. Data from Pandey et al., 2000.



use as transpiration does not necessarily translate into additional amounts of grain yield or biomass. Once yield levels reach 3–4 t/ha for tropical grains, additional yield gains are not dependent on additional accessible water for transpiration, but more on crop management strategies including timeliness in operations as well as access to water and nutrients for crop uptake, and limited competition by weeds and pests.

Water productivity changes with climate

Climatic conditions, in particular air temperature, vapour pressure deficit and wind around the leaves which is where the plant transpiration is determined, are critical for the productive green flows of transpiration. But also the accessible soil water storage for plant uptake affects water productivity. Three key changes in climatic conditions will ultimately affect plant water productivity, as well as the potentials for landscape productivity.

Increased CO_2: it has long been suggested that an increase in CO_2 will make photosynthesis more efficient, i.e., less water use per produced unit of biomass (also called the CO_2 fertilizer effect) However recent research evidence from open-air chamber experiments indicates that the effect is marginal on key grain crops such as wheat, barley, rice (C3), and insignificant on typical tropical grains such as maize, millet, sorghum (C4). The small positive fertilizer effect of increased CO_2 proved higher on non-water stressed, well fertilized crops than on water stressed and low fertilized crops, i.e. the crop status that is often found in tropical and sub-tropical rainfed agro-eco systems.

Increased air temperature: The latest IPCC report is consistently showing increased air temperatures for most land areas in the world. It is notably higher for continental areas than for coastal zones. The implications of higher temperatures on water productivity are twofold. First, warmer air can generally hold more moisture, which affects the air vapour pressure deficit. The vapour pressure deficit has a strong effect on the stomata, thus affecting water productivity (fig. 6). Secondly, in tropical areas the increases in air temperature may exceed plant physiological optimal temperatures for photosynthesis. The result ultimately means lowering of water productivity as the plant suffers from heat stress.

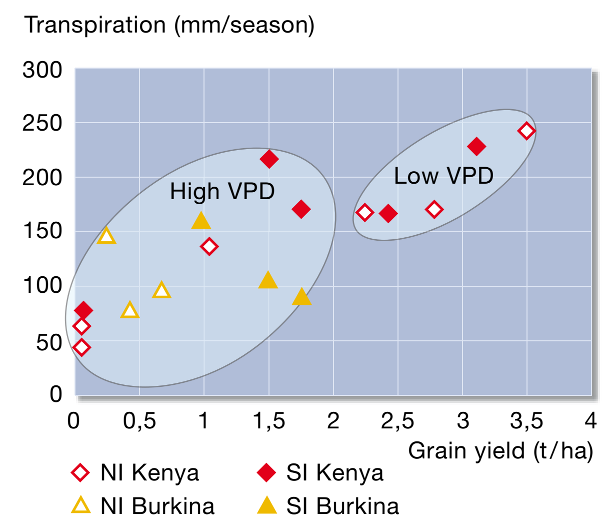


Figure 6. Measured and estimated seasonal transpiration (green productive water flow) from rainfed (NI) and supplemental irrigated and fertilized (SI) cereal. Data obtained at field locations in semi-arid Kenya and Burkina Faso. Seasonal mean VPD are indicated.
High VPD> 0.9 kPa day^{-1}, and low VPD < 0.9 kPa day^{-1}.

Irregular rainfall: The potential of increased rainfall variability, and the potential increase of dry spells and droughts for plants, will have a significant effect on water productivity at the plant to field scale. For most regions, the future climate change scenarios for the global sub-humid and semi-arid zones are predicting increased rainfall variability, and reduced rainfall. This may pose a greater challenge to improve water productivity in sub-humid and semiarid landscapes including agro-ecosystems.

Thus, the combined effects on water productivity of the three main changes in climate are contradicting and even counteracting each other. For tropical and sub-tropical areas, with current low yielding systems often subject to dry spells, water productivity improvements can only be achieved by active management of crop production systems and plant genetic material. This is where the soil and water inter-linkages will continue to dictate water productivity, together with possible suboptimal air temperatures, rather than the CO_2 fertiliser effect.

Water productivity in agro ecosystems at the watershed scale

Focussing on water productivity improvements on the farm scale provides opportunities for win-win management options, both saving water in the lands-cape and increasing yields.

As long as water uptake and transpiration is water limited during the growing season, water productivity can be improved through improved water availability. Focussing on water productivity improvements on the farm scale provides opportunities for win-win management options, both saving water in the landscape and increasing yields. In integrated water management in watersheds up to basin scale it is a different matter. A water loss on-farm may serve as a water gain down slope. An example is the terraced paddy rice systems of South-East Asia which 'leak' water to the benefit of down slope located paddy fields. A lined irrigation canal is not necessarily a water productivity gain at a landscape scale, as the leakage would eventually be re-circulated in another location of the landscape. The water productivity concept has a role to play to assist sustainable water resource planning at the landscape scale. Comparing different systems of water use is also gaining application with several case studies from different parts of the world.

In the Rufiji river basin, Tanzania, water is scarce and river flows were perceived as decreasing by different communities. Upstream, midstream and downstream farm systems were compared for economic water productivity: in which system did water generate the most value? Comparing rainfed cereals, rainfed vegetables, irrigated cereals and irrigated vegetables from the three different locations gave insight into the matter. However, since the downstream locations were dependent on livestock, the water appropriation and water productivity of these systems were also included in the analysis. The use of the water productivity concept made the different livelihood systems comparable, and it also helped in assessing the absolute amounts of water dependency for different livelihoods. By transparent comparisons, the stakeholders from different locations were aided in the negotiations of water allocation and also pricing.

In the Laoag river basin, Philippines, water productivity was explored with GIS tools and crop simulation models. By estimating the irrigation needs and fertiliser needs of different locations tailored for an individual rainy season, water managers could evaluate where the input of irrigation may be most efficiently used in the river basin.

The cost of water for irrigation can be used as a means to change allocation patterns. In examples from Syria with supplemental irrigation of cereals, it has been shown that the optimal water productivity from a water resource and allocation perspective is not necessarily the most cost effective amount of water for the farmer to apply. By adjusting water price for irrigation by water productivity, there is an opportunity to manage landscape water resource more efficiently in regard to output yield or biomass.

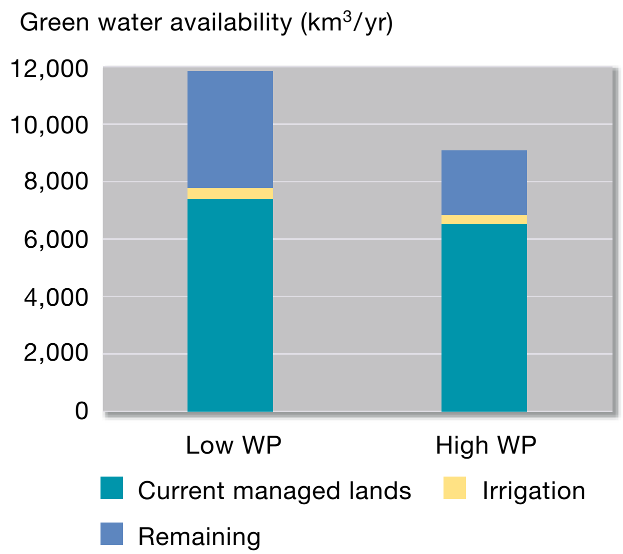
Thus, there is a growing scope to use the water productivity concept in water resource management at watershed to basin scales. It can help identify different land-use systems and re-direct allocation, possibly through costing mechanisms. So far, the benefits are most pronounced in situations when irrigation tends to become scarce, but there are a growing number of examples where water productivity also helps in comparing agricultural land-use with other land-use types for water allocation purposes.

How far can improvements in water productivity go to reduce future water requirements for food?

Future food production to feed the world is going to require large amounts of water. This large production increase will either have to take place on current croplands and pasture lands, or agriculture will have to expand horizontally, encroaching on other land-uses. The latter will result in a negative impact on the generation of ecosystem services from those areas. Another possibility is for water scarce regions to import food, resulting in what has been called virtual water trade. However, for a major proportion of currently low-income households, subsistence farming or locally produced food will continue to play the most important role in food consumption, and virtual water trade will therefore be of less importance.

An analysis of the impact of improved water productivity on future water requirements for global food requirements is presented in figure 7. A striking feature is the large gap between total water requirements and green water availability to meet local demands on current croplands and pasture (managed lands). Improving water productivity so that water requirement per capita is reduced from 1,300 m³/cap/yr to 1,000 m³/cap/yr, lowers this gap by 40 % This highlights the large opportunities for gains by improvements in water productivity. In particular, not allocating this water for food production limits the negative impacts on the generation of ecosystem services from increased food production in the future. The figure also suggests that even under very optimistic assumptions regarding improved green water management and irrigation expansion, a large amount of water has to come from virtual water trade or expansion of agriculture in order to meet future food demands*.

Figure 7. Green water availability and total dietary water requirements (total height of staples) for two different water productivities (WP). Low WP = low water productivity (1,300 m³/cap/yr); high WP = high water productivity (1,000 m³/cap/yr).



Concluding remarks

Gains in water productivity at the field scale from different management options have been quantified and are well documented. For temperate and highly industrialized crop systems there are a wide range of water productivity data available. But there is a large information gap, in particular in climatic zones and crop systems that hold the greatest potential for water productivity gains in the future. These are in particular croplands located in water scarce or water limited climatic areas, and currently low-yielding agro-ecosystems. This is partly due to the wide range of water productivity definitions used in different case studies, and partly to the lack of well-measured field sites in tropical environments with different levels of water, nutrient stresses as well as management treatments. For example, in a recent global review only 5 % of field measured water productivity cases could be identified for tropical and sub-tropical environments in Africa. Thus, for the climatic areas with the largest scope for improved water productivity in agro-ecosystems there is still a lack of substantial water productivity data for field trials. With a growing awareness of potential climate change impacts on agriculture, there are also information gaps, for example on how water productivity is affected by abiotic stresses such as ozone or other air pollution. It is estimated that adoption of new crop management strategies may take 3–5 years at the farm scale, and even more at community level. Breeding and genetic engineering for improved water productivity will at the earliest be available 10–15 years from initiation of research, and policy and management initiatives to address water productivity may be equally slow from initiation to effective action. Thus, to obtain the optimistic water productivity gains per capita diets, necessary and active step taken today may only be beneficial 10 years or longer from now.

* Note that the calculations only include water availability to meet demands. In wetter regions availability might be higher than demand, which allows for virtual water trade.

We conclude that improvements in water productivity as estimated in the field can potentially significantly reduce dietary water requirements in the future. Management has a large impact on water productivity; and with relatively well-known and easily implemented agronomic management there are large potentials to affect the green water flows and improve water productivity, in particular in low yielding sub tropical and tropical agro-eco systems. Future gains in water productivity in specific crop systems, taking the increased temperature, rainfall variability and additional abiotic stresses into account, needs further research. Careful breeding and genetic engineering may prove costly but necessary additional strategies for future higher producing crop varieties. At a watershed to basin scale, new tools in modelling, GIS and water productivity measurements can assist water management, inclusion of green water flows and allocation. However, there may a discrepancy between the water planner's interest (i.e. to achieve high water productivity) and the farmer's objectives (i.e. to maximise long-term production while keeping production costs at a minimum). The benefits of valued water together with water productivity assessments of landscape production entities may be one path for improved sustainable water use in times with multiple demands.

We conclude that improvements in water productivity as estimated in the field can potentially significantly reduce dietary water requirements in the future.

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The value of the raindrop

Director Sunita Narain, Centre for Science and Environment, New Delhi, India.

India is a country with vast differences in conditions for farming, with environments ranging from hot or cold deserts to snow laden or tropical mountains. Rainfall is often highly unpredictable or virtually absent for years. The inhabitants in several areas have proved that they can cope with these uncertainties through the use of locally invented water harvesting methods, but much of this traditional wisdom has been lost. More has to be done to empower local communities to manage their own water resources and rebuild a new relationship with water in society.

When I received the 2005 Stockholm Water Prize from the King of Sweden, at the function held at the city's beautiful town hall, I said that I was accepting this award as it recognises and respects the traditional wisdom of people living on the margins of survival. It is a prize which rewards the knowledge of the illiterate engineers and managers of water, who have been discounted in formal knowledge systems of the world. In other words, this prestigious water prize recognises that they knew how to manage water. They knew how to live and indeed share the scarce water resources. They knew how to build rich economies by using the simple principle of capturing rainwater when and where it falls.

This is the traditional water wisdom of India. In the late 1990s, CSE published its book *Dying Wisdom: The Rise, Fall and Potential of India's Traditional Water Harvesting Systems,* which documented the extraordinary wealth and ingenuity of its people living across different ecological systems to manage water. The systems ranged from ways of harvesting glacier water in the cold deserts to delivering water with precision over long distances through bamboo drip irrigation systems in the northeastern hills of India. The *kundi* of the hot desert of India incorporates the simplest of technologies for powerful impact. Rain is harvested on an artificially created piece of land, which is sloped towards a well to store precious water. The water maths is equally simple; As little as 100 mm of rainwater harvested on 1 ha of land will collect 1 million litres of water in this structure. On the other hand, in the other regions of the country, people harvested flood waters.

In other words, people had learnt to live, with the excesses of water, and with its scarcity. They all worked on the principle of rainwater harvesting in a country which gets rain for only 100 hours of the 8,760 hours in a year. They knew that all the rain of the year could come in just one cloudburst. The solution was to capture that rain and to use it to recharge groundwater reserves for the remainder of the year. The answer ultimately was to use the land for storing and channelising the rain — over the ground, or under. Catching water where it falls and when it falls.

The nature of the country's diverse ecology forced Indians to develop the art of water harvesting. Though the country has a high average annual rainfall – as much as 1,100 mm –this rainfall is not evenly spread across the year. In most parts of the country, there is precipitation for not more than 50 days.

On the days when the rainfalls occur, it does not fall over a period of 24 hours. In fact heavy showers are common. Most of the country receives rain for just 100 hours each year. Not surprisingly, any water gifted by the heavens or flowing past in a stream has been harvested in India since antiquity.

Not surprisingly, any water gifted by the heavens or flowing past in a stream has been harvested in India since antiquity.

India has an extraordinary diversity of agro-ecological systems, ranging from the hot desert of Rajasthan to the cold desert of trans-Himalayan Ladakh, from the sub-temperate Himalayan mountains to the high tropical mountains in the south; interspersed are various hill and mountain ranges, plateaus and the unique Indo-Gangetic plains which are more flood-prone than any other part of the world. Each region had its own specific way of harvesting water

It is also important to note that ancient Indian rulers rarely built water harvesting structures themselves. They instead created fiscal systems to encourage communities to build and manage water systems. This changed with the coming of the British rule into India. These Indian rulers preceding the British did not boast of irrigation bureaucracies or public works departments to create these structures. Though the role of the state varied from one region to another, what historical records show is that rulers rarely built irrigation structures themselves. The massive Pichola lake in the city of Udaipur, in Rajasthan, for instance, was built by nomadic gypsies. However, the rulers did play an important role in encouraging people to build water harvesting structures.

Water harvesting structures called kundis have been traditionally used by people in the desert state of Rajasthan to collect and store rainwater.

The famous Vijayanagar kings of south India (1336–1564 AD), for instance, placed great importance on developing irrigation facilities for agricultural improvement. But they used fiscal policies to encourage the development of people built and managed infrastructure. Land tax, which was collected in kind in the form of one-sixth of the produce, was an important source of revenue for Indian rulers. The rulers' fortunes depended on agriculture. The state, therefore, had a vested interest in encouraging private initiative to develop irrigation systems.

But there have been two major discontinuities in water management since the 19th century, in India. Firstly, the State has emerged as the major provider of water, replacing communities and households as the primary units for provision and management of water. Secondly, there has been growing reliance on the use of surface and groundwater, while the earlier reliance on rainwater and floodwater has declined, even though rainwater and floodwater are available in much greater abundance than river water or groundwater.

Rain captured from 1–2 % of India's land can provide India's population of 1 billion with as much as 100 litres of water per person per day.

Theoretically, the potential of water harvesting in meeting household needs is enormous. Rain captured from 1–2 % of India's land can provide India's population of 1 billion with as much as 100 litres of water per person per day. The calculations show that there is no village in India which cannot meet its drinking water needs through rainwater harvesting.

As there is a synergy between population density and rainfall levels, less land is required in more densely populated areas to capture the same amount of rainwater. And in such areas, there is usually more built-up area like rooftops which have improved runoff efficiency.

Rainwater harvesting not only provides a source of water to increase water supplies but also involves people in water management, making water everybody's business. Because it builds people's relationship with their water and maximises the use of local water resources, it also reduces the operational and distribution costs and most importantly enables people to internalise the full costs of their water requirements, thus encouraging conservation in water demand. Most importantly, water harvesting can not only meet people's basic water needs but is part of the strategy to improve the local food and livelihood security of the rural poor.

Water harvesting and integrated land-water management is not new to India or to many other parts of the developing world. The art and science of 'collecting water where it falls' is ancient but this 'dying wisdom' needs to be revived to meet modern freshwater needs and modernised with inputs from science and technology.

Water harvesting can be undertaken through a variety of ways:

It is clear that the management of water, and not scarcity of water, is the problem in many parts of the world.

a) Capturing runoff from rooftops
b) Capturing runoff from local catchments
c) Capturing seasonal floodwaters from local streams
d) Conserving water through watershed management

It is clear that the management of water, and not scarcity of water, is the problem in many parts of the world. Rainwater harvesting has shown the many ingenious ways in which people learnt to live with water scarcity. The solution practised diversely in different regions, lies in capturing rain in millions of storage systems – in tanks, ponds, stepwells and even rooftops – and to use it to recharge groundwater reserves for irrigation and drinking water needs.

The world faces a critical challenge to improve the productivity of rainfed and marginalised lands. In this challenge, water can turn a large part of the country's currently parched lands into productive lands, reduce poverty and increase incomes where it is needed the most. Localised water management is a cost-effective approach and more importantly that local water management – harvesting and storing water where it falls – can only be done through community participation.

In other words, this traditional technology has to be combined with social engineering. Water cannot become everybody's business until there are fundamental changes in the ways we do business with water. Policy will have to recognise that water management, which involves communities and households, has to become the biggest cooperative enterprise in the world. The prevalent mindset that water management is the exclusive responsibility of government must give way to a paradigm built on participative and local management of this critical life source. But it is equally clear that we need policies to optimise the water endowment of each region and we need practices to organise water management at each settlement, to harvest the most and to use it in the least wasteful way. Then this can only be done if local communities are involved in managing their water systems. The water agenda, therefore, needs building local interests and institutions so that its governance is put into the hands of people.

In the villages, which have harvested their raindrop, the inhabitants have water to drink. We have tracked these efforts over droughts – crippling droughts that have lasted 3 years or more. People have survived the crisis, because they had built their water reserves. They had learnt to value the raindrop.

Water from a series of check dams constructed by the villagers of sukhomajri in Haryana acted as a catalyst in the transformation of the village into a model of community participatory management.

Sukhomajri has the distinction of being the first village in India to be levied income tax on the income it earns from the ecological regeneration of its degraded watershed. It is located near the city of Chandigarh. In 1979, when the nation was facing a severe drought, the villagers built small tanks to capture the rainwater and agreed to protect their watershed in order to ensure that their tanks did not get silted up. The

The Arvari river in Alwar district of Rajasthan has been revived by the construction of hundreds of small check dams called johads along its catchment.

tanks have an area that has greatly increased grass and tree fodder availability. This, in turn, has increased milk production. Or take the case of Ralegan Siddhi, which is today held up as a model of development. It is a village situated in a drought-prone area of Maharashtra where the annual rainfall ranges from 450 mm to 650mm only and where the villagers were once not even assured one regular crop. Rainwater harvesting has brought the river Arvari in dry and drought-prone Rajasthan back to life. The river flows through a drought stricken region – villagers living on the margins of survival are desperately poor and find sustenance by migrating for work to cities. According to historical records of the region, the river Arvari used to provide groundwater recharge to wells in the area. But nobody can remember seeing it flow except during the short monsoon period.

The experience of villages like Sukhomajri, Ralegan Siddhi and villages in Alwar district and the several others scattered across the country shows that community based rainwater harvesting can, in fact, become the starting point to eradicate rural poverty itself. Increased and assured water availability means increased and stable agricultural production and improved animal care.

These are not tales of scattered micro-experiences across the country. This is an idea that politicians have accepted and worked on. Our president has done rainwater harvesting in this complex – improving his groundwater levels substantially. But in all the programmes, the key lesson was that the approach works where people have been involved, indeed have been in charge of building and managing their water systems. Recognising this, the Indian government has set up of a "people's mission for water conservation". The aim is to use the massive employment guarantee programme to invest in building natural assets – ponds, tanks, community wells, other traditional water harvesting structures – which will provide relief against drought. It is now imperative, for this programme to succeed, that communities across the country are engaged, in what can be known as the biggest cooperative exercise in the world. Rebuilding our water futures.

The way ahead

The fact then is that we can act on our political commitments. We can deliver on our promises. What impedes us? What are the obstacles?

Firstly, our technology choices and approaches must change. Currently drinking water programmes fail because they plan for the pipe and not the water source. Even as drinking water programmes reach 100,000 settlements each year through pipes and hand-pumps, they find another 100,000 on the list of the water scarce settlements. The problem is that we never plan for the sustainability of the water source or ensuring its quality. The answer is to adopt new approaches that build and improve on the traditions of the past.

It is also clear that water quality is going to be the key issue in the coming years. We know that the current paradigm of sewage management is unaffordable by most people. We know that we will have a huge challenge of water pollution in the years to come, which will further increase our costs of clean water and consequently our health costs. We have to find ways, even as we begin to generate more and more waste, to invent the most modern waste management system that reuses every drop of water discharged. Literally learn to turn sewage back into water. This will require investment in a new generation of water and waste technologies that do not destroy the earth. It will take money, expertise and collaboration.

Monsoon clouds hover over a check dam in the Jhabua district of Madhya Pradesh.

Secondly, we must understand that delivery mechanisms just do not exist to reach millions of poor, impoverished communities living at the margins of survival. It is for this reason that we need effective approaches to decentralise programmes and their implementation, so that people can be empowered to manage their resources.

Thirdly, we must realise that the investment we have made to date, and make today, is woefully inadequate to meet this challenge. The water-sanitation agenda is incomplete without an economic agenda, which allows the poor in poor countries to secure their economic space in an increasingly unequal world. Water security goes hand in hand with livelihood and economic security. We cannot build a water-secure world without this agenda.

It recognises that water is about building people's institutions and empowerment to take control over decisions. It is about deepening democracy and about the power of ideas to change the world.

This is important for our world. Clearly water will be the most important determinant of our future. Water will define whether we remain poor or become rich. It will define whether we are healthy or sick. But we also know that water scarcity is not about quantity. The northeastern region of Cherrapunji in India is known as the wettest place on earth, but it is drought affected. The desert city of Jaisalmer gets only 100 mm compared to Cherrapunji's 14,000 mm, but it has no recorded history of evacuation. In other words, water is about re-building society's relationship with water. There is never enough water. We will have to build cultures of prudence and wise use.

We know that unless we can reinvent the paradigm of growth and wealth-creation, we will not be able to secure our water future.

We have to remember this, even as we move to another phase of water-development. When we industrialise. When we use more. Waste more and pollute more. We know that unless we can reinvent the paradigm of growth and wealth-creation, we will not be able to secure our water future. It will take more learning and more listening to each other.

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Increasing rainfall and soil erosion

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According to reliable predictions annual rainfall will increase in several regions of the Northern hemisphere. Furthermore, heavy and extreme rainfall events are also forecast to occur more often, but with large geographical variability. The changing patterns are of great importance to farmland, since the erosive capacity of rain relates strongly to raindrop velocity. Even short but intense storms can lead to devastating erosion, especially of soils that have already been moistened by an increasing overall rainfall.

Flood waters carry sediment onto roads, Herefordshire, UK

Rill erosion on arable land in the UK

Changes in Annual Precipitation

Interpretation of long-term rainfall data sets, in conjunction with the increasingly accurate global and regional scale climate models, has lead to a general acceptance that climate change has resulted in significant shifts in rainfall characteristics. The observed trend in increasing annual rainfall is considered especially robust and 'very likely' to occur in most of northern Europe, Canada, north eastern USA, northern Asia and the Tibetan Plateau. In contrast, decreases in annual rainfall received in the northern hemisphere sub-tropics and tropics are considered 'likely' to occur in Europe and African regions bordering the Mediterranean, and in winter rainfall in south-western Australia.

Changes in Rainfall Characteristics

In addition to these findings, it is generally accepted that changes have also occurred in the intensity, amount, frequency and type of rainfall, with an increasing trend for 'heavy' and 'extreme' rainfall events. This is in large part due to increased water vapour in the atmosphere, arising from warming of the oceans, and the increased water vapour holding capacity of the warmer atmosphere. It is important to note that observed changes in precipitation are found to exhibit strong local and regional scale variability.

In 2002, researchers at the Hadley Centre for Climate Prediction and Research (HCCPR) in the UK considered 'extreme rainfall' in climate change modelling, using five 'extreme' event criteria:

- number of days with 'heavy' precipitation (greater than 10 mm per day);
- maximum 5-day precipitation total;
- daily intensity index (defined as the total annual precipitation divided by the number of wet days);
- proportion of total precipitation due to events exceeding the 95th percentile of the climatological distribution for wet day amounts; and
- number of dry days (as an indication of increased frequency of drought)

Significant increases were observed in the number of 'heavy' rainfall events during the second half of the 20th century. These findings were confirmed in 2006 by two independent international research teams, coordinated by HCCPR UK and the National Centre for Atmospheric Research (NCAR), based in Colorado, USA. The HCCPR led team utilized data derived from 600 precipitation stations within the northern hemisphere mid-latitudes with near complete data for 1901–2003. Precipitation showed a widespread and significant increase, but the changes were much less spatially consistent when compared with temperature change. The NCAR team assessed nine global climatic models that contributed to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC-AR4) under a range of emissions scenarios. This assessment confirmed the generally accepted trend of increased rainfall intensity as well as increased frequency of 'heavy precipitation' (greater than 10 mm d^{-1}) and 'extreme' (> 95th quartile) rainfall events.

Sediment generated from newly constructed, bare soil slopes, UK

Significant seasonal shifts in rainfall have also been reported by several groups, with an increased frequency and contribution of 'heavy' rainfall events to winter rainfall totals. For example, HCCPR reported that there has been a significant seasonal shift in rainfall patterns in the UK over the last 40 years, with a trend for wetter winters and drier summers. The increased winter precipitation has been attributed to four factors:

- increased amount of precipitation on wet days (daily rainfall greater than 0.4mm d^{-1});
- increased frequency of winter precipitation greater than 15 mm d^{-1};
- increased contribution of 'heavy' events (here defined as a single daily rainfall total greater than 15 mm d^{-1}) to winter totals; and
- increased frequency of 'heavy' events.

In contrast, summer rainfall totals have decreased, due to fewer wet days and the reduced frequency of wet days.

Changes are also expected both in the recurrence interval of precipitation extremes (frequency), as well as in the magnitude of extreme events. HCCPR report that over the last 40 years, the magnitude of extreme rainfall events has increased two-fold for some parts of the UK. Rainfall intensities previously experienced every 25 years are now occurring at 6 year intervals. A similar trend has been observed by research groups investigating changing rainfall patterns in the western United States, Caribbean, Italy and India. Climatic scenario modelling has predicted a distinct shift towards higher intensity and more extreme precipitation, and an increase in daily rainfall

Overland flow, carrying eroded sediment following heavy rainfall

intensity is forecast. This shift in precipitation towards 'extreme' events results in an increase in 'very heavy' precipitation events (defined as greater than 50 mm d^{-1}).

In northern Europe and in central Europe in winter, extremes of heavy precipitation are very likely to increase in both magnitude and frequency. In the Mediterranean and central Europe in summer, where reduced precipitation is predicted, extreme short-duration precipitation may increase. Wide spread increases in 'heavy' and/or 'extreme' rainfall have also been reported, even in areas where total annual precipitation is actually decreasing.

Rainfall and soil erosion processes

Any change in rainfall characteristics over time and/or space has the potential to influence the frequency and magnitude of hydrological processes such as soil erosion. This may be through direct effects (e.g. by changing the energy of the rainfall to cause erosion) or indirect effects (e.g. by creating favourable conditions for the growth of vegetation which can protect the ground surface from raindrop impact).

Soil erosion involves the detachment, entrainment and transport of slope forming materials. Soil is essentially a non-renewable resource, so loss of soil by erosion affects the provision of ecosystem services, namely:

- biomass production, including in agriculture and forestry;
- storage, filtration and transformation of nutrients, carbon, substances and water;
- creation of a biodiversity pool, including habitats, species and genes;
- provision of a physical and cultural environment for humans and human activities; and
- source of raw materials.

Without these services, human social and economic well-being is seriously threatened, as highlighted in the Millennium Ecosystem Assessment. As well as the on-site effects of erosion, eroded sediment can act as a pollutant in streams, rivers and lakes, especially if it carries contaminants such as heavy metals and agrochemicals. This process can cause declines in water quality, with adverse effects on aquatic ecosystems and increased water treatment costs. When eroded sediment is deposited in watercourses, it reduces channel capacities, so increasing flood risk during storm events. The costs of soil erosion in the US alone are estimated to range between US$30–44 billion annually. In Europe, soil erosion has been identified as a major threat to soil resources.

Overland flow, carrying eroded sediment following heavy rainfall

The ability of rainfall to cause soil erosion is termed "erosivity". This may relate to the erosion caused by the shearing action of individual raindrops on a bare soil surface within a given storm event. Erosion also occurs when rainfall-induced overland flow on the soil surface detaches and transports soil, leading to sheet, rill or gully erosion. Many researchers have attempted to isolate the rainfall properties that affect erosivity.

The intensity of rainfall (mm hr^{-1}) is strongly associated with erosivity. If, as predicted, climate change results in higher

Overland flow and sediment on road following heavy rainfall

rainfall intensities, this may result in higher rates of erosion, all other factors being equal. Rainfall intensity and erosivity are linked because intensity affects the drop size distribution of the rainfall event (commonly represented by the storm's median drop size – D_{50}). Median drop sizes increase with intensity, up to intensities of around 76mm hr^{-1}. At intensities greater than 76 mm hr^{-1}, larger drops tend to be unstable, as they oscillate, vibrate and spin when falling. They break up into smaller drops as they are disturbed by air turbulence and buffeting during free fall.

The increase in median drop size/mass with rainfall intensity results in higher drop terminal velocities (the fall velocity at which the drop no longer accelerates due to gravitational forces). A 1mm drop has a TV of 4.03 m sec^{-1}, whereas a 3 mm drop has a TV of 8.06 m sec^{-1}. In turn, this will affect the kinetic energy of the rainfall through the equation:

$$KE = 0.5\ m\ v^2$$

where m = mass of a raindrop; v = terminal velocity of that raindrop

The kinetic energy of each drop can be summed for all the drops in any given storm. Many researchers have found that the kinetic energy of a rainstorm is the one rainfall parameter most highly correlated to soil erosion. It is possible to estimate storm kinetic energy from rainfall intensity, for example:

$$KE = 11.87 + 8.73.\ \log_{10} I \qquad \textit{where I = Intensity (mm/hr)}$$

or

$$KE = 29.8 - (127.5 / I) \qquad \textit{where I = Intensity (mm/hr)}$$

In the UK one extreme summer storm generated more erosion than that recorded during six previous years of measurement.

Thus, any increase in the intensity of rainfall over time will be associated with an increase in erosivity and soil erosion rates, even if the amount of precipitation received decreases. Even infrequent, short duration, high intensity storms can be extremely erosive. For example, in the western Mediterranean over 50 % of the annual soil erosion is related to just three 'heavy' rainfall events. The predicted changes in rainfall in southern Spain of longer dry spells interspersed with short, violent storms will only exacerbate rates of erosion. In the UK one extreme summer storm generated more erosion than that recorded during six previous years of measurement.

The amount (volume) of precipitation during a storm event or over the year is only weakly correlated to erosivity. This is explained by the fact that kinetic energy is more sensitive to velocity rather than mass of rainfall, as explained above ($KE=0.5\ m\ v^2$). This implies that any increase in the amount (volume) of rainfall (due to more frequent and/or greater duration of storm events) will have little effect on soil erosion processes.

Preceding rainfall events will affect soil antecedent moisture content, with wetter soils being more prone to erosion by water.

However, there are indirect effects of rainfall amount (volume) on erosion processes. Preceding rainfall events will affect soil antecedent moisture content, with wetter soils being more prone to erosion by water. This is because the cohesive bonds between soil particles that resist raindrop and runoff shearing forces are weakened when wet. The opposite is true for detachment by wind erosion; drier soils are more friable and more susceptible to erosion. Another explanation for the poor correlation between rainfall amount (volume) and erosivity lies in the indirect effect of rainfall on vegetation cover – sites with high annual precipitation (especially if the rainfall is distributed uniformly throughout the year) often have good vegetative cover which protects the soil from any raindrop impact and erosive overland flow. Where the trend in annual precipitation is decreasing (see above), there may be a corresponding decrease in vegetative cover. Not only does this have implications for food, fodder and fuel production, it may also increase the susceptibility of the land to erosion, especially where this trend corresponds with an increase in the frequency of 'heavy' or 'extreme' events.

Conclusion

Changes in rainfall patterns have been observed and are predicted for the future. These trends include:

- increased frequency of intense 'heavy' rainfall events;
- shorter recurrence interval of precipitation extremes;
- seasonal shifts in rainfall towards wetter winters and drier summers; and
- increased short duration, high intensity events particularly in central Asia and the Mediterranean.

These trends have profound implications for the rate of operation of hydrological processes such as soil erosion. Effective on-farm and catchment scale soil and water management programmes must be devised to mitigate the irreversible damage caused by the erosion of non-renewable natural resources by increasing rainfall.

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Environmental impact of food production and consumption
– from phosphorus leakage and resource depletion to recycling

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Phosphorus is a key element in all agricultural production. Almost all phosphate rock mined in the world is used as fertilizer for food production, but the global reserves could be depleted in less than a hundred years. At the same time, a large proportion of the phosphorus employed is emitted and wasted as a water pollutant in the food production and consumption chain. A proper recirculation and saving of this precious resource would require better communication between consumers, farmers and various types of experts, where farmer's local knowledge is used to ensure sustainable use of fertilizer, as well as to avoid eutrophication.

Food production and consumption have a significant impact on the environment, in terms of both resource use and emissions that contribute to pollution of the atmosphere, lithosphere and the hydrosphere. The development of modern agricultural production has led to a state where we are depending on imported resources, including virtual water, oil and phosphorus, but where we also are exporting greenhouse gases to the atmosphere and nutrients to the aquatic environment.

In the light of global food security we will sketch the complex picture of food production and consumption and the flows of water and nutrients to and from these activities. We will also discuss approaches towards a sustainable future management of phosphorus, using both the resource and polluter perspective. The two perspectives are connected since, in some respects, the matter of water pollution is a reflection of resource depletion. In the case of phosphorus, we have a cycle of industrial and agricultural use of a limited – and about to be depleted – mineral resource which, when applied in food production, can contribute to eutrophication of inland waters and coastal zones. Environmental impact, food security and natural resource depletion are thus interconnected and must therefore be addressed from a system analysis perspective, with consideration given to global players as well as to local actors.

In addition to the fact that farming is the single largest anthropogenic source of phosphorus emissions to inland waters, the major part of the phosphorus emitted from rural households and wastewater treatment plants to inland and coastal waters is generated from the food we eat. Discussions of how to reduce phosphorus loads to inland waters and to the sea must thus be related to a political discussion of *what we eat, how and where it is produced, and how we treat and use human waste*. The average consumer is the driving factor in this process, since changes in food consumption have a direct influence on the environmental imprint.

Use of mineral phosphorus in modern agricultural food production

Modern agricultural food production is more or less dependent on continual inputs of non-renewable phosphate rock as fertilizer, and approximately 90 % of mined phosphate globally is used for food production. Scientific predictions of the depletion of the global reserves rank from the next 50 to perhaps 100 years. The recently rising prices of phosphate rock may partly be explained by the same reasons as global food prices – changing global food consumption patterns and to some extent also the increasing demand for biofuel. However, the rising price of mineral phosphorus fertilizers can, in turn, be expected to further accelerate the increase in the global food prices. The global use of phosphorus in mineral fertilizer is estimated to approximately 15 million tonnes per year. In Sweden, input of mineral phosphorus fertilizer for a regional production of an average diet has increased from none to approximately 2 kg per capita over the run of the 20th century, at the same time as the size of the population has almost doubled. Concerns about the possible geopolitical implications of the impending scarcity of this essential nutrient have been raised by a number of scholars in recent years. As in the case of the virtual flows of water through food production and consumption, we now need to focus on the virtual flow of phosphorus from the mine to the plate, with consideration given to the numerous emissions along the way as well as after the food has left the plate. This issue has a global dimension in terms of trade relations, political implications and currently rising food market prices and is hence strongly linked to changes in the global human diet.

In Sweden, input of mineral phosphorus fertilizer for a regional production of an average diet has increased from none to approximately 2 kg per capita over the run of the 20th century, at the same time as the size of the population has almost doubled.

Human food consumption

Human food consumption is an important driver in the circulation of phosphorus. What we eat and how it is produced determines the need for the input of phosphorus into agricultural food production. The consumer is the driving factor, since changes in food consumption have a direct influence on the environmental imprint. The influence of reduced consumption of meat or other animal products is of particular interest. This can be exemplified by a comparison of the diet of an average citizen of Linköping (a town in south-eastern Sweden) in the year 1870, who only consumed approximately half the amount of meat and dairy products (in milk equivalents) compared to the present average citizen. If today's citizens had kept the food consumption patterns of 1870 citizens, this would reduce the need of agricultural area per capita and consequently also the need for phosphorus fertilizers by 25 %. In addition, the phosphorus content in human waste would also be reduced by approximately 25 %. Consequently, reductions in emissions to water bodies from agriculture as well as from wastewater could be expected from a return to the 1870 food consumption pattern.

This is in line with conclusions from what researchers in the BERAS (Baltic Ecological Recycling Agriculture and Society) project have estimated; that almost a third of the area in Sweden used for food production would become redundant if we replaced 75 % of our meat consumption by a doubling of our consumption of vegetables. If we also consider the area used for production of imported fodder, the total area in the world needed for feeding the Swedish population could be halved as a consequence of changed eating habits.

Another striking difference is that in 1870 almost all food production was local, whereas today the greatest proportion of the areas used for food production, including imported animal fodder, is located outside Sweden which illustrates that the global impact of resource depletion, as well as eutrophication, is not always easily traced when local food consumption is examined. This is an issue which could lead to moral dilemmas, since it could be argued that import of food might be a way to limit local eutrophication and thereby contribute to eutrophication in other regions, as well as limit the possibility of recirculating phosphorus in areas from where food is exported. The latter statement derives from the fact that the possibility of reusing phosphorus in human excreta in farming depends, among other factors, on the geographical distance between production areas and the location of the consumers. Reuse of human excreta has been stated to have the potential to supply at least one quarter of the chemical fertilizer currently applied in food production. With increasing urban populations, living at an increasing distance from agricultural production areas, awareness among consumers concerning the importance of what we eat and where it is produced can be of decisive importance for sustainable food supply as well as for the limitation of leaching from agricultural lands.

Handling of human waste

Virtual water is the total amount of water, embedded in food or other products, which is needed for their production. As in the case of virtual water, the amount of virtual phosphorus embedded in food is significantly larger than the phosphorus contained in the food, of which less than 1 % is absorbed by our bodies. The phosphorus that is contained in food (of which almost all is excreted in urine and faeces) amounts to more than half a kilogram per Swede per year, but the virtual phosphorus needed to produce this food is approximately 3.5 times larger than this.

Despite diet-related global variations, approximately three million tonnes of phosphorus are excreted as waste from human bodies annually. If this phosphorus had been reused for food production it could replace approximately one fifth of the total current input of phosphorus in mineral fertilizer that is applied to sustain the average global diet of today. Often, modern sewerage systems have developed in the opposite direction, contributing to losses to surface water and creation of toxic sludge that is unsuitable for agricultural production. The development of these systems has been based on sanitary requirements and the sustainable management of water, but the next generation of systems needs also to consider reuse of the 'urban phosphorus resources' that may be essential for securing the local food supply.

What obstacles need to be overcome to make this a realistic scenario?

The efficacy of phosphorus from human urine and mineral fertilizers is similar and technical solutions are available. Challenges that need to be met are linked to values and perceptions, cooperation between actors, institutional capacity, laws and regulations.

Eutrophication

Eutrophication of lakes is caused by overenrichment with nutrients, principally phosphorus (Fig. 1). Also for certain coastal waters, phosphorus can be a main factor for eutrophication. Eutrophication of the Baltic Sea calls for remedies to alleviate algal blooms and oxygen deprived "dead zones". The Baltic Sea contains eight times as much phosphorus now than in the early 1900s. An international expert group, called in by the Swedish NAPA in 2006, stated that more ambitious reductions in phosphorus inputs to the Baltic Sea have to be pursued. In particular, it was stated that both international and national efforts are needed in order to tackle diffuse inputs, especially from agriculture.

The Baltic Sea contains eight times as much phosphorus now than in the early 1900s.

In north-western and southern European countries, phosphorus contributions from point sources to water bodies have decreased during the latest decades due to improved wastewater treatment.

Although the increasing phosphorus content in soils has been favourable for crop yields, it has made soils more vulnerable to losses to water bodies.

In the same region, the phosphorus content of agricultural soils has gradually increased after the introduction of chemical fertilizers, although in most of the region it has levelled out during the latest decade. Although the increasing phosphorus content in soils has been favourable for crop yields, it has made soils more vulnerable to losses to water bodies. In contrast to nitrogen, however, phosphorus is to a high extent locked up in soils. Annual losses are therefore small compared to the annual input. In spite of that, a substantial amount of phosphorus is lost from agricultural land to surface waters, especially in locations where the transport of phosphorus from the soil to water bodies is favourable (in the form of e.g. surface flow or flow in large pores in the soil, connected to drainage systems).

Within the framework of the Helsinki Commission (HELCOM), the Ministers of the Environment from the Baltic Sea Countries and the High Representatives of the European Commission adopted the Baltic Sea Action Plan (BSAP) in November 2007. The greatest challenge in BSAP is to reduce the nutrient input to the Baltic. Sweden shall, in accordance with the provisional nutrient reduction requirement, reduce the anthropogenic input of phosphorus to the Baltic Proper by 63 %, corresponding to 291 tons per year.

In Sweden, agriculture accounts for approximately 45 % of the anthropogenic load of phosphorus to coastal waters. The contribution from rural households, not connected to wastewater treatment plants, was for the year 2000 estimated to 20 % of the anthropogenic load, whereas 16 % was estimated to emanate from wastewater treatment plants.

In Sweden, very strict requirements are imposed on urban wastewater treatment plants for the removal of phosphorus, with typically about 95 % reduction in emissions. Consequently, the main purpose of the strategies for wastewater treatment plants should be not to reduce emissions to surface waters, but, as earlier mentioned, to promote recirculation of nutrients. To deal with the eutrophication problem, there is a need to focus on other sources. One potential for reduction is to ensure that rural household wastewater is reused locally, and not discharged to surface waters after very limited treatment as is often the case at present.. However, even if recirculation of human waste had been implemented for all households that are not connected to municipal wastewater treatment plants, it would only contribute to a 20 % reduction in the stipulated BSAP goal for Sweden concerning the Baltic Proper, i.e. less than a third of the goal.

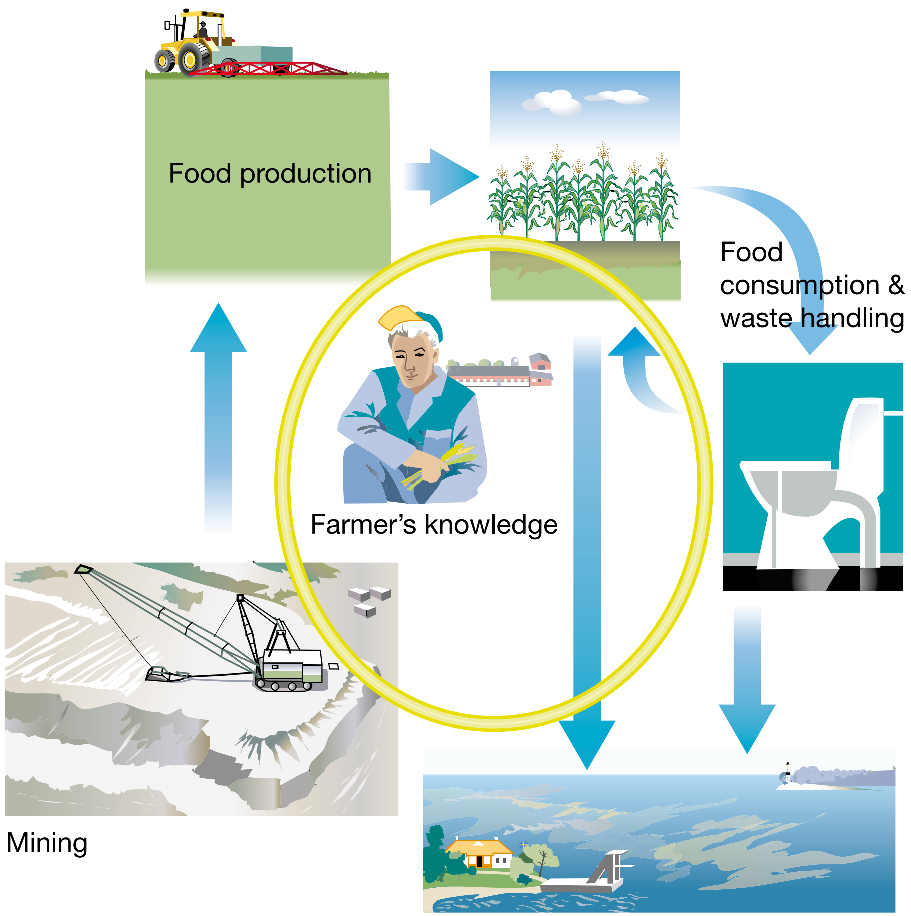
Consequently, in order to fulfil the Swedish phosphorus reduction goal of the BSAP, we need to focus on reduction of phosphorus leakage from agricultural food production. However, since phosphorus is tightly bound to soil particles, relationships between agricultural practices and losses to surface water are not always straightforward. The accumulation of phosphorus in the soil might increase the risk of losses, but the actual impact depends on factors such as soil type, precipitation characteristics etc. To achieve large and relatively fast reductions, it is necessary to combine more general measures, which aim to limit phosphorus surplus in agricultural soils, with more targeted measures in "hot spots". These are characterized by a combination of a high content of mobile phosphorus and pathways for fast transport of phosphorus to surface waters. Measures should thus be directed towards reducing the mobility as well as the transport of phosphorus to surface waters. The actions suggested in the first Swedish response to the BSAP, including buffer zones and wetlands, are estimated to reduce the load by 20 tons, i.e. only a small proportion (7 %) of the stipulated goal.

Measures should thus be directed towards reducing the mobility as well as the transport of phosphorus to surface waters.

However, discussions regarding the future reductions in nutrient emissions from agriculture to water bodies like the Baltic Sea must, be closely linked to ongoing societal development. In countries like Sweden, part of the expected reductions in phosphorus losses in the coming years will probably be attributed to reductions in the land area used for agriculture, with subsequent reduction in the use of mineral fertilizers. Countries like Poland, Estonia, Latvia and Lithuania, on the other hand, are expected to switch to intensive agricultural practices during the coming decade, in line with what already exists in most old EU member states. This could result in increased losses of nutrients to water bodies.

However, increased agricultural production does not necessarily have to imply increased losses. According to some researchers, the risk of losses of phosphorus could be almost eliminated by avoiding specialisation, either in crop farms that depend on mineral fertilizers or in animal farms that have a high input of purchased fodder and a surplus of plant nutrient in the form of inefficiently used manure. The alternative – a locally balanced crop and animal production, with emphasis on fodder and manure production has, however, been shown to increase food expenditure by on average 25 %. It could be argued that conventionally produced food has an environmental cost that will either have to be paid in the form of local or regional environmental problems, or exported to other parts of the world. Maybe not only virtual water or virtual phosphorus flows, but also virtual eutrophication, is an issue that has to be acknowledged in the globalized world of today.

Figure 1. The circulation of phosphorus in nature.



A sustainable agriculture needs to be based on cooperation between consumers, farmers, authorities and various types of experts.

Use of farmers' knowledge

As earlier discussed, food consumers have a significant impact on the circulation of phosphorus, and consequently indirectly also on the depletion of mineral phosphorus resources as well as on the leaching of phosphorus from agricultural production. A sustainable agriculture needs to be based on cooperation between consumers, farmers, authorities and various types of experts. As has been shown from participatory projects comparing farmers and other citizens, farmers are usually willing and able to contribute towards improving environmental conditions. Their ability to carry out environmental improvement must however be based on participation and trust between those involved, instead of being imposed by strict regulations and control from above. In a locally suggested remedial plan, developed by a cooperation between farmers, citizens, local authorities and experts in a drainage area in south-eastern Sweden, it was stated that decisions, to a larger extent than today, need to be based on local climatological conditions, landscape characteristics, as well as a consideration of citizens' s knowledge and desires for the environment of their catchment and surrounding coastal areas. Examples of prevailing regulations that were not based on local conditions included rules for subsidies being tied to county boundaries, rather than the boundaries of the catchment. Another example concerned the timing for spreading of manure, where the dates applied were strictly regulated by the calendar and not the climate. A more dynamic way of estimating when spreading should be locally allowed was suggested, including short-term as well as long-term weather forecasts, and consideration of variations in local soil and topographic conditions. These regulations should be agreed upon following a dialogue between local authorities and farmers, who stressed that they have the experience to decide when spreading of manure is feasible and when it is not. A third example concerned buffer zones. With present national regulations, it was estimated that the to introduction of buffer zones in most parts of the catchment would be difficult because many fields have narrow stretches. It was suggested that, based on a dialogue between local authorities and farmers, this could be compensated for by increasing the width of the buffer zones where this was possible.

Conclusions

The phosphorus resource needs to be considered in relation to its limited availability for future food production, for its potential reuse from human excreta and for the consequent decrease in pollution from rural waste sources.

The main flows of phosphorus to the hydrosphere originate from agriculture and from human excreta – and thus mainly from food production and food consumption. While phosphorus is considered to be a major polluter of surface waters such as the Baltic Sea, it is also an increasingly important resource in a global food security context. In order to deal with this complex issue, various approaches are needed. The phosphorus resource needs to be considered in relation to its limited availability for future food production, for its potential reuse from human excreta and for the consequent decrease in pollution from rural waste sources. Phosphorus pollution needs to be tackled in co-operation with a number of actors, especially farmers who possess particular local knowledge of the conditions for a sustainable use of fertilizers in order to achieve a decrease in the eutrophication of surface waters.

The future challenge we are now facing is to reconnect phosphorus flows and emissions for the entire cycle of food production, consumption and emissions.

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Soil degradation caused by human water management

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Irrigated soils account for almost half of the agricultural production in the world. However, poor management of the water supplement has led to soil degradation, especially in developing countries. Alkalinisation and salinisation have resulted in lower yields and reduced quality of the produce. A smaller, but growing, proportion of soils are affected by acidification from sulphuric acid, formed by oxidation of sulphide minerals. The measures that are needed to mitigate soils subjected to alkalinisation, salinisation or acidification include a better control of water drainage and applications of supplementing substances such as gypsum (alkalinisation) or combinations of lime, organic material and mineral fertilizers (acidification).

Introduction

Both alkalinity and salinity cause reduced production and also affect the quality of the produce.

Irrigated agriculture occupying 260 M ha produces 40 % of the world's food supply while it occupies only 18 % of the total cultivated area. The high productivity achieved by a regulated water supply is however threatened by soil degradation caused by poor water management. Alkalinisation, salinisation and acidification are generally caused by poor adaptation of water management to local conditions. It is considered that about 30 % or 77 M ha of the irrigated land is affected by salinity or alkalinity as a consequence of human activities. This soil degradation is concentrated to developing countries at lower latitudes. Both alkalinity and salinity cause reduced production and also affect the quality of the produce. Another water related problem is caused by drainage of sulphidic soils where sulphuric acid is produced. This is a smaller problem area-wise, but it is increasing in all climatic regions from high latitudes to tropical areas. About 17 M ha worldwide are affected by this type of acidification.

Alkalinisation and salinisation

Alkalinisation is characterised by an elevated pH in sodium-dominated soil and soil solution. The sodium surplus leads to a loss of soil structure as the sodium ion (Na^+) cannot tie soil particles together with its single positive charge. Furthermore, at high pH many plant nutrients, like phosphorus and trace elements, become less available. Alkalinisation is brought about through excess water evaporation from a soil irrigated or wetted by alkaline water characterised by an excess of bicarbonate (HCO_3^-) ions over calcium (Ca^{2+}) ions. This water tends to favour precipitation of calcium carbonate ($CaCO_3$). Due to the resulting surplus of easily soluble HCO_3^- and Na^+ ions, pH is allowed to increase and sometimes reaches levels of 9–10.

Alkalinisation is often caused by irrigation where there is insufficient drainage.

Alkalinisation is often caused by irrigation where there is insufficient drainage. This is especially the case when there is a capillary contact between the ground water and the soil surface. Then the alkalinisation process may be very fast. The reason for poor drainage is often both physical and economical. In flat landscapes the digging of drainage canals requires the handling of very large volumes of soil, which is expensive. Because of this, drainage is often not done properly during the initiation of an irrigation scheme. When problems arise there is often no funding available for drainage.

Secondary effects of alkalinisation are seen in terms of decreased availability of trace elements such as iron, zinc and copper. This causes a decrease in crop yield and also affects food quality. Wheat is especially sensitive to soil zinc deficiency, which may decrease the yield by as much as 50 %. Zinc is also of the utmost importance for the immune system in humans, not least for children after weaning when they are no longer nourished by breast milk. About 20 % of the child mortality in poor countries is considered to depend on zinc deficiency. Another secondary effect of alkaline soils is that the groundwater may acquire excess fluoride concentrations. The fluoride (F^-) concentration is generally controlled by the solubility of calcium fluoride (CaF_2) and when dissolved calcium concentrations become low the fluoride concentrations may increase to toxic levels. About 65 M people in India are exposed to excess fluoride concentrations which may cause dental and skeletal fluorosis. It has been observed in India that excess fluoride tends to appear in irrigated areas with poor water management. 8–9 M ha out of a total irrigated area of 70 M ha are alkaline or saline in India. Even arsenic may become more soluble under alkaline conditions, a phenomenon observed in northern Argentine.

Salinisation may occur in areas close to the sea or in closed basins with poor drainage.

Salinisation may occur in areas close to the sea or in closed basins with poor drainage. The salinity may eventually be so high that the low osmotic potential prevents plant growth. A capillary upward movement tends to concentrate the salinity in the upper soil sections, even causing a depositing of salt crusts on the surface. While salinisation is usually caused by poor drainage, it has also been caused by forest clearing in Western Australia. The removal of the transpiring trees has allowed the groundwater to raise and come into capillary contact with the soil surface in the lower parts of the slopes. Thus the land clearing has become counterproductive. The Indus basin in Pakistan is another area with considerable salinity problems. About 6.3 M ha are salt-affected, especially in areas between the river branches where the irrigation water tends to accumulate and cause these areas to become more or less water logged .

Acidification

Acidification is mostly due to oxidation of sulphide minerals which through drainage are exposed to oxygen.

Acidification is mostly due to oxidation of sulphide minerals which through drainage are exposed to oxygen. The acidification mobilises metals, most notably aluminium (Al^{3+}), which may be toxic to plants growing in the affected soil.

The drainage of metal-containing acidic water, with heavy metals like zinc, nickel, copper etc may also cause the death of downstream aquatic fauna.

So called acid sulphate soils are common in South East Asia where this type of soil covers 2.1 M ha in Vietnam, 4.1 M ha in Indonesia and 1.5 M ha in Thailand. However, they also occur on 0.38 M ha in Finland and 0.14 M ha in Sweden. In the Nordic countries, acidification is due to the still ongoing rise of the land after the latest glaciation as well as drainage activities for gaining new agricultural land. In South East Asia and Northern Australia these soils are mostly the result of drainage activities.

The acid sulphate soils contain pyrite (FeS_2) or ferrous sulphide (FeS). These sulphides were formed through anoxic oxidation of organic matter in which process the ferric iron (Fe^{3+}) and sulphate (SO_4^{2-}) were reduced to ferrous sulphides. The South East Asian sulphidic soils were formed in marine environments while the Nordic sulphidic soils were formed in a brackish sea by an anaerobic microbial flora. When these soils become exposed to oxygen the reverse reaction occurs releasing sulphuric acid:

$$FeS_2 + 15/4O_2 + 7/2H_2O \Rightarrow 2SO_4^{2-} + 4H^+ + Fe(OH)_3$$

This reaction results initially in a pH below 3. The main side effect is the dissolution of aluminium in concentrations that are toxic to most crops. The dissolution follows the following reaction formula:

$$Al(OH)_3 + 3H^+ \leftrightarrow Al^{3+} + 3H_2O$$

The dissolution of aluminium has the effect of disturbing the phosphorus supply to crops by precipitating an almost insoluble aluminium phosphate ($AlPO_4$).

In South East Asia most of the acid sulphate soils are still used for wetland rice (paddy) cultivation. This implies that the rice plants are partly standing in water which disfavours weeds in a convenient way without much work needed for weed removal. Paddy rice can be suitable for acid sulphate soils as most of the soil remains anaerobic. Any raised part of a paddy field in acid sulphate soils may suffer from aluminium toxicity and the death of the rice plants. The rice plants can manage to grow in an anaerobic soil as they have air channels all the way through the shoot to the root tips. The air channels (aerenchyma) keep the close surroundings of the roots aerobic, causing formation of ferric iron precipitates around the roots. These precipitates act as adsorbents for trace metals like zinc and can therefore cause zinc deficiency. On the other hand, a more anaerobic soil may cause iron toxicity due to a high concentration of Fe^{2+} ions in the water. The handling of acid sulphate soils is thus a delicate matter, which can be regarded as a balancing act between different redox states. Acid sulphate soils may also cause problems in the surrounding environment through acidic water drainage, with elevated levels of metals. As mentioned above the metals may damage the aquatic fauna. This also includes fish. The latter effect has been a major problem in Finland and Sweden where occasional acid surges occur at the onset of rains or snowmelt after extended periods of lowered groundwater levels.

What can be done?

In view of the wide extent of irrigated agriculture it is of the utmost importance to find remedies to alkalinisation and salinisation. As already mentioned, proper drainage is crucial for saline soils. Underground drainage , which requires less land to be sacrificed, has been proven useful in India. In closed basins, like around Tuz Göl (Salt Lake) in the southern part of the Anatolian high plateau in Turkey, drainage has been diverted to low lying areas. There new salt lakes have been formed, while the upland is saved from the salinity problem.

In view of the wide extent of irrigated agriculture it is of the utmost importance to find remedies to alkalinisation and salinisation.

As regards alkalinity, quite a number of remedial measures are proposed and shown to be functional. The overall aim is to increase the concentration of dissolved calcium ions in the soil water. This is possible through the addition of gypsum ($CaSO_4 \cdot 2H_2O$) or even sulphuric acid, the latter causing a dissolution of $CaCO_3$. Gypsum is commonly found in semi-arid areas and is generally a cheap amendment. Tree plantation has also been proposed and found functional in field tests. Mycorrhizal associations which promote the dissolution of calcium carbonate presumably explain this effect.

Trace element deficiency in alkaline soils may be combated by fertilisation but the added trace metals like zinc tend to be tied up in unavailable forms. Another way may be to use trace metal efficient species that can extract the trace metals concerned even from deficient soils. Traditional selection of such species or genetic modification may be used.

For management reasons, fluoride removal from groundwater has not been very successful in India. However, water harvesting in the vicinity of water supply wells has been found to function well in Andhra Pradesh.

Acid sulphate soils in Southeast Asia are generally used for paddy cultivation, which may be sustainable if the soils can be kept largely anaerobic even during the dry season (provided that irrigation water is available). Regulated drainage, keeping a more or less constant groundwater level, is practised in Finland and has decreased acid surges in the downstream water.

Liming of acid sulphate soils may be possible but this depends on the original amount of sulphides.

Liming of acid sulphate soils may be possible but this depends on the original amount of sulphides. It may work if the pyrite-sulphur content is in the order of a few tenths of one per cent, while for instance a 2 % pyrite-sulphur content would need more than 60,000 kg $CaCO_3$ /ha.

The management problems in acid sulphate soils become even more complicated when crops are grown on raised beds. A raised bed is a dyke that consists of acid sulphate soil material. The construction of raised beds often implies that the original soil is placed 'upside down'. This means that the original pyrite layer may be placed on top of the dyke (i.e. in a fully aerobic environment), which causes acceleration of the acidification due to sulphuric acid formation. By using suitable soil amendments such as lime, organic matter and NPK fertilizers, the growth and yield of some acid tolerant crops are promoted. In Vietnam, for instance, sugar cane and pineapple are two of the crops that are often grown on raised beds. One of us (IN) has recently started a research project where we try to grow a cucumber species (*Momordica cochinchinensis*, called 'gac' in Vietnamese) on raised beds. Gac is a valuable fruit crop which is tasty and contains high concentrations of carotenoids.

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System of Rice Intensification
– more rice with less water

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The traditional paddy cultivation of rice uses large amounts of water. The System for Rice Intensification, where the crop is never continuously flooded, has evolved as a set of six practices which also reduce the need for seed, pesticides and fertilisers. Results from many field trials have looked promising, with high increases in yields and reduction in water requirements. The system should be accessible to many poor farmers, who are restricted to rice cultivation using scarce resources.


SRI farming in Chattisgarh, India.

Introduction

The critical relation between paddy cultivation and water use is traditionally known. This is because rice has traditionally required standing water to be cultivated. So far, rice is the only cereal that can withstand water submergence, which explains the long and diversified linkages between rice and water. For hundreds of years, natural selection pressures such as drought, submergence, flooding, and nutrient and biotic stresses led to a great diversity in rice ecosystems.

The new millennium has posed two critical challenges to humanity: one, the increasing scarcity of water and two, the increasing demand for cereals such as rice, accompanied by galloping prices. This is all the more critical in Asia, where 90 per cent of the world's rice is grown and consumed. Eventually, the demand for paddy cultivation arising out of an increasing demand for rice has led to an increased need for water, thereby creating an upward consumption pressure on the scarce resource. In many parts of the world, and more prominently in South Asia, the increased demand for water for paddy has even led to conflicts between rice-producing units.

Against this background, System of Rice Intensification (SRI) claims to offer unprecedented opportunities by meeting both the conflicting ends of rice production and water management. It all started with the practice of intermittent irrigation of lowland rice in Madagascar in the 1980s, where scarcity of water did not allow the rice field to be kept flooded. Fr. Henri de Laulanié from France observed that this did not decrease the yield. He published his findings in the journal *Tropicultura* in 1993, and in many places tests were initiated in response.

Since 1997, almost a flood of publications have appeared, verifying the initial findings as well as doubting the established results. And, in scientific publications an unusually harsh debate can be observed with words such as "nonsense and no science". Norman Uphoff, director of the International Institute for Food, Agriculture and Development at Cornell University (Ithaca, New York), cooperated with Fr. Laulanié and his NGO Association Teffy Saina to become one of the first promoters of the practice. He transferred SRI to Asia, and it was first picked up in north east China where water is a scarce resource. Eventually, it spread to parts of South Asia, including India.

SRI: A set of six practices

SRI has evolved as a set of six practices:

- **Transplanting very young seedlings in the age group of 8 to 15 days to preserve potential for tillering and rooting:** This results in quick recovery and establishment and production of more tillers.

- **Planting seedlings by inverting root tips individually and carefully rather than plunging clusters in the soil as in conventional practice.**

- **Widely spacing out the seedlings, at least 25x25 cm and in some cases even 50x50 cm, and placing them in a square pattern rather than in rows:** This allows sufficient amount of sunlight to reach the leaves, thereby reducing the competition for water, space and nutrients, resulting in the spread of roots and healthy growth of plants.

- **Using a simple, mechanical hand weeder ('rotary hoe') to aerate the soil and control weeds.** The utility of the simple hoe lies in replenishing the nutrients in the form of green manure, and due to aeration of the soil, there is vigorous growth of root.

- **Using less water:** The soil is kept moist and never continuously flooded during the ' vegetative' growth phase, up to the stage of flowering and grain production.

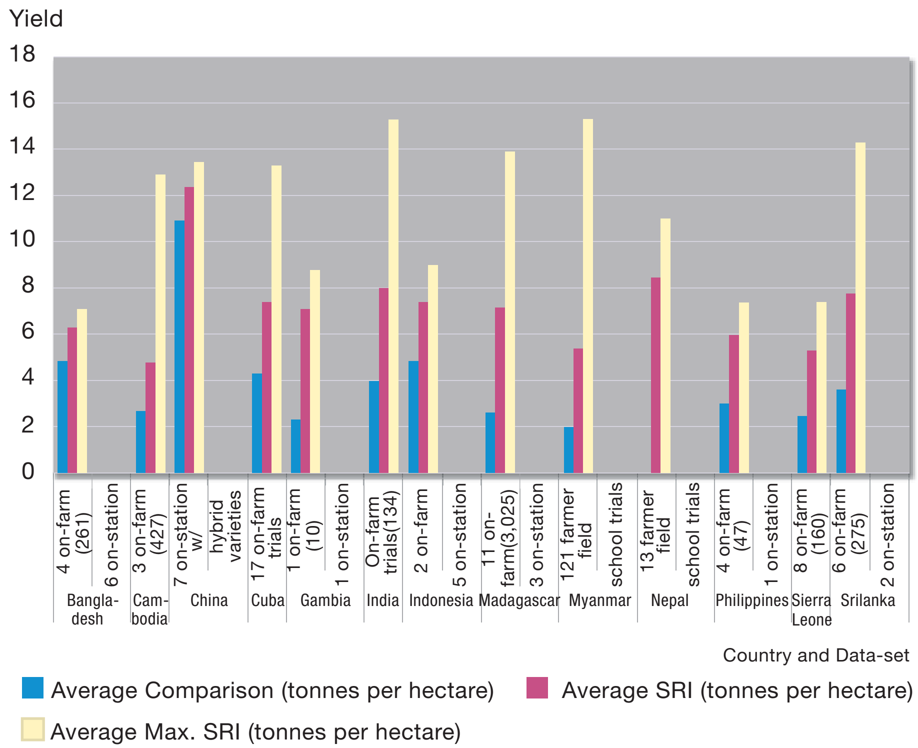
- **Using organic manure or compost to improve soil quality:** Organic manures perk up soil aeration and microbial activity. This further helps in decomposing organic matter into nutrients that are essential for plant growth.

These principles, perfected over a period of time in Madagascar, surprisingly gave very high yields, in some instances close to 20 tonnes per hectare, with much reduced inputs of seed, water, fertilisers and pesticides.

Some established results: experiences in a few countries

Various agricultural universities, research centres and NGOs in several countries around the world have attempted the SRI experimentation. Some initial results are presented in Fig. 1, as reported by one of the leading exponents of the practice, Norman Uphoff.

Fig. 1. Avarage and Maximum Yield with SRI vs. Comparison Yield (in tonnes per hectare) from 13 countries



Source: Adapted from Uphoff et al. (2002)

The results presented in Fig. 1 are unweighted averages of data reported from a variety of on-farm and on-station trials, giving a representative range of outcomes to date where SRI methods have been utilized mostly as recommended. In all the 13 countries, the experiment with SRI shows a phenomenal average increase over the comparison yield.

As claimed by its proponents, farmers do not need new rice varieties with SRI as all cultivars respond positively. The best SRI yields have, however, been achieved with high-yielding varieties or hybrids, but even traditional varieties can produce 6–8 tonnes/ha, and can even go to the extent of 10–12 tonnes/ha. Since SRI reduces seed requirements by 80–90 %, it slashes the otherwise significant hybrid seed cost. With low water requirements in soil that is not always flooded, it is also claimed that SRI may reduce greenhouse gas emissions, though this cannot be assessed unless SRI is used on a larger scale.

Productivity of land, water and labour

It is obvious that SRI improves the productivity of water and land. Less water consumption in SRI is a great advantage, especially for dry, tropical countries whose economy depends essentially on rice production. A study carried out in Madagascar has yielded the following results concerning the economy of SRI

Table 1

	Conventional cultivation	SRI	SRI changes
Labour requirement (in man days/ha)	193	247	54 (+28 %)
Yield (kg/ha)	3 359	6 365	3 006 (+89 %)
Cost of labour/ha x 5000 FMG/day	963 500	1 233 950	270 450 (+28 %)
Revenue in FMG x 1000 FMG/kg	3 359 000	6 365 000	3 006 000 (+89 %)
Net revenue/ha (in FMG)	2 395 500	5 131 050	2 735 550 (+114 %)
Returns to labour (in FMG/day)	17 430	25 790	8 360 (+56 %)

The study shows that although labour requirement increases substantially, there is a lower land and water requirement. Interestingly, even with increased labour requirement, the productivity of labour has shown a substantial rise (to the tune of 56 %).

However, some of the initial studies inferred that higher labour requirements for SRI have been responsible for the low adoption rate of the technology in various places. SRI initially seemed well suited to Madagascar due to the unavailability or high cost of fertilizer and the inability of most farmers to grow enough rice to feed their families. Despite its promise, farmer adoption of SRI in the areas where it was promoted has been low, "dis-adoption" (abandonment) of the method has been high, and those who continue to practise the method rarely do so on more than half of their land. To help explain this phenomenon from an economic perspective, a study was conducted in five communities in Madagascar in 2000 by Moser and Barrett, using both participatory research methods and a household survey of over 300 farmers. The study concluded that it was difficult for most farmers to practise SRI because of significant additional labour inputs at a time of the year when liquidity is low and labour effort is already high. Thus, the poorer the farmer and the more dependent his income is on rainy season crops, the less able he is to take advantage of the technology.

SRI productivity under various conditions

Despite Uphoff's claims in favour of SRI in his various writings as presented in Fig.1, literature is replete with examples revealing that SRI is not an unmixed blessing. A study published by McDonald et al. in 2006 in *Field Crops Research* compared results from field trials of SRI productivity to accepted best management practices (BMP) in a common database with average yield values reported for both management systems. In some cases, this average represents the mean value of several replicates, whereas for others it is the response from a single field. BMP practices varied from site to site, reflecting local conditions; an overview of what commonly constitutes best management for rice is available from International Rice Research Institute (IRRI). Among the site-year or site-year-variety records, five are from Madagascar and the remainder from nine different Asian countries. Sources for these data ranged from peer-reviewed literature to informal reports from non-governmental organizations (i.e. 'grey' literature). It, thus, shows that different results were obtained under varying conditions, conducted by various scientists at several points in time. Interestingly, the data in Table 2 often contradicts the claims cited in Fig. 1 as in many cases the productivity through SRI has been lower than that of BMP, as shown in Table 2. Table 2 also reveals that all the experiments conducted in Madagascar have been quite successful, while the same is not true for other countries (barring a few like India and Sri Lanka, where one should not get into conclusive evidence based on results of only one experiment given in the table). It is clear that in the case of most countries, the results are quite mixed because of varying agro-climatic and soil conditions.

Table 2. SRI concurrently evaluated against accepted best management practis (BMP)

Location	Setting	SRI yield (tons/ha)	BMP yield (tons/ha)	SRI Yield deviation (%)	Comment
Madagascar (Anjomakely)	Farmer Field	10.4	3.0	245	Good soil
Madagascar (Anjomakely)	Farmer Field	6.4	2.0	213	Poor soil
Madagascar (Morondava)	Exp. Station	6.0	2.1	182	Trad. Cult.
Madagascar (Morondava)	Exp. Station	6.8	2.8	140	HYV
Madagascar (Beforona)	Exp. Station	6.3	4.9	27	
Bangladesh (Comilla)	Exp. Station	5.3	4.4	22	
China (Anqing)	Exp. Station	12.2	10.0	21	
India (Pondicherry)	Exp. Station	6.4	5.4	19	
Laos	Unreported	3.9	3.5	11	
Sri Lanka (Hinguraggoda)	Farmer Field	7.6	6.9	10	
China (Jiangsu)	Exp. Station	9.9	9.1	9	
Indonesia (S. Sulawesi)	Farmer Field	7.1	6.6	9	
China (Yunshun Co.)	Unreported	12.0	11.7	2	Pei'ai cult.
China (Jiangsu)	Exp. Station	9.3	9.1	2	
China (Nanjing)	Exp. Station	11.8	11.5	2	Hybrid
Bangladesh (Rajshahi)	Exp. Station	10.0	9.8	2	2002 Boro
China (Guangdong)	Exp. Station	7.2	7.2	-1	
Nepal (Bhairawa)	Exp. Station	5.4	5.7	-5	
China (Nanjing)	Exp. Station	7.9	8.3	-5	
China (Jiangyin)	Farmer Field	8.4	8.9	-6	
Bangadesh (Comilla)	Exp. Station	7.1	7.6	-7	
China (Nanjing)	Exp. Station	9.8	10.6	-7	Indica cult
China (Hunan)	Exp. Station	6.7	7.4	-9	
Thailand (Chiang Mai)	Exp. Station	4.4	4.8	-10	Dry Season
Bangladesh (Vagurapara)	Farmer Field	6.0	6.8	-11	
Laos	Unreported	2.5	2.9	-14	
Bangladesh (Matiara)	Farmer Field	5.9	7.0	-16	
Bangladesh (Joydebpur)	Exp. Station	7.4	8.9	-17	2003 Boro
Bangladesh (Joydebpur)	Exp. Station	6.4	7.8	-18	2002 Boro
Bangladesh (Rangpur)	Exp. Station	6.2	7.7	-20	2003 Boro
Nepal (Khumultar)	Exp. Station	4.7	6.3	-25	
Philippines (Los Banos)	Exp. Station	3.0	4.1	-27	Wet season
Thailand (Chiang Mai)	Exp. Station	3.8	5.9	-36	
Laos	Unreported	2.2	3.5	-37	2 site ave.
Thailand (Chiang Mai)	Exp. Station	2.6	4.2	-38	Rainy season
Thailand (Chiang Mai)	Farmer Field	3.2	5.4	-40	8 farmers
Philippines (Los Banos)	Exp. Station	1.4	3.1	-55	Dry season

Mean yields are reported for SRI and BMP, with SRI performance judged as relative deviation from BMP1. Records are listed in descending order of SRI performance with respect to best management.

Relative SRI productivity deviations from BMP: deviation (%) = ((SRI t ha^{-1}/BMP t ha^{-1}) -1) x 100)
Source: Adapted from McDonald et al (2006)

However, lately some experiments with SRI in India have shown positive results in terms of productivity. Interestingly, it is now becoming popular in the south Indian states of Karnataka and Tamil Nadu, which have been engaged in conflict over water for decades. The conflict over the waters of the Cauvery river has primarily been because of paddy cultivation in the basin districts of the two states. SRI might be a potential solution to the problem.

SRI: Too good to be true?

Constraints and Costs

There are quite a few limitations on the use and adoption of SRI. The most critical one is the **need for good water control** to get the best results. Water savings can be made only if farmers apply a limited quantity of water rather than keeping their paddies continuously flooded. Most farmers do not have such water control as they operate in field-to-field systems of distribution.

SRI methods require **more labour**, which needs to be trained properly. This has already been discussed earlier. However, with a higher productivity of labour under SRI, the extra labour input is well repaid. Uphoff (2004), however, feels that in the long run, SRI can be labour saving.

The other important requirement is **motivation and skill**. Farmers have to become conscientious and knowledgeable managers of the plants, soil, water and nutrients. The bulk of the requirements and costs centres on water management. For farmers with the knowledge of growing irrigated rice and with the motivation to learn SRI, adopting SRI has not really taken much time and effort, as reported by Uphoff. However, this might not be the case for the rain-fed paddy cultivation.

One of the major constraints on adopting SRI is that it is labour-intensive and therefore **suitable only for small-scale production** processes. This is still a debatable point as there are proponents of SRI who claim that SRI need not be so labour-intensive as to impact planning, coordination and management of the paddy production process.

It has also been stated that SRI **can lead to gradual soil depletion.** However, there is no confirmed evidence of such a phenomenon to date.

Criticisms against SRI

Sinclair perceived SRI as the latest addition to the family of unconfirmed field observations (UFOs) "…that have several features in common with their space UFO cousins. While there is an abundance of 'sightings,' they are anecdotal, and are reported by people who have minimum understanding of the basic scientific principles being challenged by such reports." Of course, Sinclair's statements have emerged from the traditional school, which believes that there are at least three components of SRI that run against the well-established principles for high crop growth. "These principles were developed over many years of careful testing and scrutiny by scientists worldwide, and they have stood the test of time."

The points of contention arose on three counts. First, SRI suffers from poor light interception because of low plant densities. Second, the traditional school is unwilling to accept the hypothesis that the relationship between growth and plant water use can be changed. Third, SRI is supposed to face a serious challenge in obtaining sufficient mineral nutrients from organic sources to achieve high yields. Sinclair has referred to the study by Sheehy et al. published in *Fields Crop Research* in 2004, which revealed that SRI offers no yield advantage.

Hence, there remains the serious question on whether SRI is really "too good to be true." As revealed by data obtained from various sources, the results have so far been mixed. Evaluation of SRI is difficult as it is still evolving, and remains more of a set of ideas than a complete technology. Even data on SRI have not been collected uniformly, as it is being undertaken by a diverse set of NGOs, government agencies, research institutions, universities, farmer groups and individuals with no central support or funding. This has really made comparison impossible, and offers an explanation for the wide variations in the results.

Conclusion

The debate rages whether SRI is indeed a boon "too good to be true" or an "agronomic UFO" with anecdotal evidence of its claim to fame. Nonetheless, SRI is spreading because of its versatility and capacity to more than double the farmers' income. It is a work in progress; only since 1999 have institutions outside Madagascar taken interest in SRI by evaluating its potential and understanding how its results are obtained. In that sense, SRI stands as an emerging and incomplete innovation. In that sense, SRI should not be treated as a technology, but as a set of evolving principles and ideas. Thus, SRI will evolve with improvements continually being made, including better implements and techniques that can further reduce labour and water requirements. Farmers are encouraged to make their own improvements in SRI methods and to share their experience within the farming community. Higher yield and less water usage are the most evident features of SRI, but many other considerations are also driving its spread around the world.

Against the background of an increasing demand for food and its inextricable linkage with dwindling water resources, process innovations like SRI need to be encouraged. In that sense, with an interdisciplinary knowledge base, SRI reduces water demand and emerges as a concept adequately embedded in *Integrated Water Resources Management* (IWRM). As Uphoff puts it in his article entitled, 'System of Rice Intensification responds to 21st century needs' published in 2004 in *Rice Today*, 3, "…With respect to the agricultural- and food-security needs of the new century, SRI is a 'designer' innovation that efficiently uses scarce land, labour, capital and water resources, protects soil and groundwater from chemical pollution, and is more accessible to poor farmers than input-dependent technologies that require capital and logistical support."

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Genetic options for crop improvements to meet water deficiency

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The current food crisis and predictions of increase in temperature make it important to investigate the potential for plant breeding and gene technology to create drought tolerant crops. Some plant breeding techniques have already proved successful, such as drought tolerant rice in Africa. However, to genetically engineer crops towards drought resistance is much more difficult. Many genes, complex traits and mechanisms become involved when crops experience water shortage. The development of the techniques is also slowed down by legal issues concerning the ownership of genetic material of interest for the experiments.

Seed of the drought tolerant, open-pollinated variety ZM521, developed by CIMMYT and partners in southern Africa, has been widely distributed to farmers through NGOs and community-based seed production initiatives and is being used by seed companies.

Introduction

We are writing this chapter when the world is experiencing a food crisis. TV is showing scenes where, because of sky-rocketing food prices, citizens are hoarding staple foods such as rice in USA and there are daily struggles for food in Mexico, Bangladesh and elsewhere. This is a situation created by the open market situation as well as unexpected crop failures in high producing areas, increased demand of meat besides armed conflicts. Some experts claim that in the near future an Asian rice cartel will replace OPEC in international economical importance. After World War II vast investments were made to increase food production to cope with the population growth. The result, and particularly the marked increase in cereal-grain yields in the late 1960s and onwards, is known as the "green revolution". On this joint international effort numerous pro and con articles have been published. To review this subject is not the focus of this article but clearly without all the international initiatives that started during this era we would be in a much worse situation today. Impacts of global climate change will doubtless give rise to further changes and constrains in the supply systems vital for human wellbeing in the near future. The expected increase in temperature as a result of increasing carbon dioxide levels will create both much dryer and more humid or flooded regions in both local and global perspectives. How can we meet these new challenges to feed a growing population under more stressful and constrained production conditions? This chapter will look into potential contributions to water-saving agriculture production from plant breeding and gene technology aspects. First we need to understand the events taking place in a plant under dry conditions and then consider what can be changed regarding plant architecture to avoid major crop failures.

Plant responses under dry conditions

It is important to understand that many primary events of the photosynthesis machinery such as electron transport capacity and other photoreactions are hampered under dry conditions. This spans from leaf level and diminished carbon fixation due to stomatal closure to whole plant level where total carbon uptake is reduced due to inhibition of growth. A reduced photosynthesis capacity leads directly to fewer photosynthetic products, i.e. products that we harvest (seed, roots etc). Also, water deficits in the soil environment affect solute transport (nutrient uptake) to a large extent, which influences photosynthetic reactions. In addition, a dryer climate can under certain circumstances cause accumulation of ions or heavy metals in the soil, leading to toxic responses, which have already been seen regarding aluminium and cadmium. Under field conditions plants are commonly subjected to multiple stresses in addition to drought, such as high light and heat. These factors put further constrains on the plant, often leading to restricted CO_2 fixation. The effect on the metabolism incited under drought due to CO_2 pkt scarcity is however not yet clarified. Plants have developed a redox system that in many respects can take care of the toxic compounds generated as a result of over-reduction of components within the electron transport chain in the photosynthetic machinery. This redox system, together with sugar and the hormone abscisic acid (ABA) and under certain circumstances ethylene, comprises major players in a complex signalling network impacting a range of secondary responses which influence growth, biotic stress responses, lipid and nitrogen metabolism and resource allocation between root and shoot. When a plant encounters too much drought stress these protection systems cannot function properly. The entire organism becomes overheated, which initiates senescence and wilting processes. However, there exist a handful of species that have learnt to endure such constrains, for example our desert flora. Such species, like the resurrection plants *Craterostigma plantagineum*, and *Xerophyta humilis*, are now used in order to dissect drought and desiccation mechanisms on molecular levels.

Contributions by plant breeding

One example of what improvements breeding efforts can achieve is the success story of high yielding and drought tolerant NERICA rice (New Rice for Africa) popularly termed "a technology from Africa for Africa". NERICA was produced at the Africa Rice Center (WARDA) by combining the best of the two rice species, *Oryza sativa* a native of Asia that gives very high yields but is poorly adapted to rain-fed uplands and other stresses in Africa, with *Oryza glaberrima*, a native of Africa which although highly adapted in Africa, is very low yielding. This work started in 1992 and required a number of back-crosses and anther culture steps to overcome the sterility and other drawbacks that are linked to the nature of interspecific hybridisation (crosses between two species). NERICA varieties have now been disseminated in various parts of Africa for field trials. Recently, in Uganda, the National Agricultural Research Organization (NARO)

NERICA rice.

released NERICA-3. This variety has received wide adoption by both small and medium scale farmers. NERICA has brought promises to most African famers who for long had depended on wetlands to grow rice which has become very unreliable because of erratic rainfalls and high temperatures and hence their continued existence hangs in the balance. The NERICA initiative demonstrates the large possibilities of breeding but also the long time-span required. To meet a rapidly changing climate, tools to speed up the breeding process are required.

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Since several essential and complex regulated mechanisms are targeted by water deficit there are no fast or simple solutions to drought stress, irrespective of the technology applied. The challenge here is to introduce or otherwise manipulate sets of genes that govern quantitative traits. Development of breeding strategies employing molecular assisted selection (MAS) is initiated in many places worldwide and on many crops. Marker assisted selection is a process whereby a molecular marker (based on DNA/RNA variation) is used for indirect selection of a genetic determinant or determinants of a trait/traits of interest. The main advantage of MAS is that it can considerably speed up the selection step of desired traits in the breeding material. Today there are many different types of marker systems to choose from but a common requirement is that they must be tightly linked to the trait of interest without causing effects on the trait itself. The markers should furthermore be easy to recognise in a high-throughput manner. As long as genetic diversity is available, the MAS strategy will certainly improve many crop species in the future.

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We depend heavily on access to genetic resources in order to improve crops, an issue that has become a delicate domain. There are several international agreements regarding ownership and accessibility of crop genetic resources. The convention on biological diversity (CBD) from 1992 declares that each country has supreme ownership rights on its flora. This protocol has partially created a lock up phenomenon and several more recent international agreements are in place to facilitate possession of plant material harbouring important traits. This important issue concerning ownership of genes and natural resources is still not entirely solved which slows down both fundamental research and more directly applied breeding achievements.

Possible routes for gene modifications

Genetic engineering solutions so far have generally had a bias towards introducing single major genes into a selected plant species, but the golden rice is an example of a combination of several genes into a valuable GM product. There are many routes to take in order to improve productivity and one drawback of drought stress is, as earlier mentioned, reduced photosynthetic capacity. One solution is to make photosynthesis more effective. There are three photosynthetic pathways used by plants. In most species, CO_2 is fixed by the Rubisco enzyme to generate a three-carbon compound. These plants are referred to as C_3 in contrast to C_4 species that can form a four-carbon compound and thereby increase their photosynthetic efficiency. Therefore, many attempts during the years have been aimed at moving C_4-encoding genes into C_3 plants. An alternative would be to improve the specificity of Rubisco, the enzyme that regulates the CO_2 vs. O_2 affinity in the photosynthetic reactions. However, none of these approaches have been very successful so far, but new attempts to convert rice into a C_4 crop plant are now being made in order to increase future yields.

A farmer from Mbingwa Village, southern Malawi, shelling maize. Farmers in Malawi depend heavily on maize and have suffered terrible droughts and hunger, but policy changes and government support for use of inputs like fertilizer have improved harvests in recent years.

Strategies employed to enhance drought tolerance have been to regulate stomatal closures, not least via ABA signalling or making overall changes to ABA signalling and related transcription factors. In this huge complex of possibilities it is important to fine-tune the changes to avoid negative drawbacks. One gene that is being exploited in this context is "Enhanced resistance to ABA1" (*ERA1*). This gene is controlled by ABA and when *ERA1* is suppressed (silenced) the stomata close and thereby reduce the water loss in the plant. Other alternatives are to adjust the osmotic potential in the cells. The aim of such work is to maintain water absorption and cell turgor at lower water potentials. This can be achieved by engineering sugars like mannitol, fructans, threhalose and similar molecules to increased levels. Several attempts along this line are ongoing.

Another group that has received attention in this context is the late embryogenesis abundant (LEA) proteins and other dehydration response proteins that are linked to changes in hyper-osmotic conditions in the cell. Several attempts are now ongoing in cereal crops to modulate such genes. Furthermore, water molecules have to cross numerous cell membranes in a plant. This water movement is regulated by specific membrane-intrinsic proteins, the aquaporins. Engineering of their cognate genes has so far not generated significant improvements, most likely due to their dual roles in other processes including plant mineral nutrition. But further fine-tuning attempts have the potential to result in a positive outcome in combination with modifying ABA signalling. There are also proteins that are important for protein stability and refolding when denatured upon stress. These are the so-called heat shock proteins (HSP) which have also been shown to contribute to drought tolerance.

Modulation of reactive oxygen molecules that take active roles in various redox processes involves another set of important genes that impacts various physiological events, not least an array of environmental processes including carbon assimilation. These genes mainly have their function locally, making them a difficult choice for alterations. This category of traits could however be indirectly targeted by altering linked genes present in the inter-connected signalling networks.

One general but extremely important issue when transgenic plants are designed is the choice of promoter, i.e. the element that controls gene expression. Too strong gene expression or a gene expression at the wrong time or place leads to negative effects on plant growth. Experiments where drought induced promoters have been linked to various genes to further improve drought tolerance have been made with variable outcome. Promoter development is *per se* a special field in plant molecular genetics where new developments are ongoing. Further insight into the role of promoters is certainly required for modulating complex traits like drought.

GM crops at field level

Although GM crops are being produced that target different genes like *ERA1*, sugar regulating genes and other traits, this research area is young and little field data is yet available. However, initiatives aimed at developing crop varieties capable of tolerating drought are taking place in various parts of the world including Africa. For instance, in 2007, Monsanto received permission to carry out trials of drought-resistant GM maize in various locations in South Africa. In East Africa, the Kenya based not-for-profit organisation, African Agricultural Technology Foundation (AATF) recently announced a new public-partnership aimed at developing drought tolerant maize varieties for Africa. This initiative referred to as Water Efficient Maize for Africa (WEMA) includes both MAS strategies and biotechnology and will involve the African countries of Kenya, Uganda, Tanzania, and South Africa. The Bill and Melinda Gates and Howard G. Buffett Foundations are funding this programme that involves other partners with vast expertise in conventional and transgenic maize research, the International Maize and Wheat Improvement Center (CIMMYT) and Monsanto. Besides maize, sorghum is now viewed as an alternative for fighting food insecurity resulting from the effects of drought. This crop is very important in Africa as it is a staple food in most communities and can readily grow in areas receiving rains that cannot sustain maize. Besides various national and company efforts, the Consultative Group on International Agricultural Research (CGIAR) institutes are currently developing varieties with enhanced drought tolerance and those that can withstand other consequences of global warming, flooding and salinity. As a result of a warmer climate, new threats of plant diseases and insect pests are emerging which need to be considered in order to improve yields.

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Near future expectations

The model plant *Arabidopsis thaliana* has generated outstanding information on fundamental processes in plant science over the last 15 years and will most likely continue to open up new avenues. The massive generation of sequence information on various plant crop species today will generate new niches of knowledge. We will soon have both maize and sorghum genomes completely sequenced which together with rice can give us indispensable information to understand and solve agronomically related problems. Advanced comparative genomic approaches would be able to pinpoint genes and loci more specifically related to drought tolerance than ever before. In this context, new genetic tools to assess natural variation in order to specifically identify parental materials of interest will evolve. Such information is of immense importance and provides new opportunities both for plant breeding and genetic engineering strategies. To combat drought is further complicated because of the large influence of genotype by environmental interactions. In the pipeline are also tools under development which will enable us to integrate ecological experiments and reliable meteorological information with population genetics and functional genomic data. This will enable us to model and make improved predictions suitable for selected environments and regions.

Final remarks

We are facing immense challenges to feed a growing human population on decreasing land areas suitable for agriculture.

The confrontations we face are huge and we can most likely not dispense with any suggestion to maintain overall food security.

The latter is due to human expansion like cities and roads, but soil erosion and flooding also take their toll. Climate changes will without doubt generate climate variability and extreme events like cyclones and other natural disasters that will impact regional infrastructure. We have to adapt to these circumstances and reconsider our agriculture systems as well as what crops we grow and when over the seasons. So far we have relied heavily on monocultures in our food and feed production. Such systems are highly producing but vulnerable and are not always the most sustainable solution. But will there be any genuine alternative? The confrontations we face are huge and we can most likely not dispense with any suggestion to maintain overall food security. This implies a combination of improved cultivation practices, advanced breeding and gene technology outputs integrated in ecological monitoring systems, leading to modelling and more secure prediction of alternative choices. Last but not least, a large amount of political courage is needed to avoid national protectionism on food and genetic resources. Global and regional problems require altruistic solutions.

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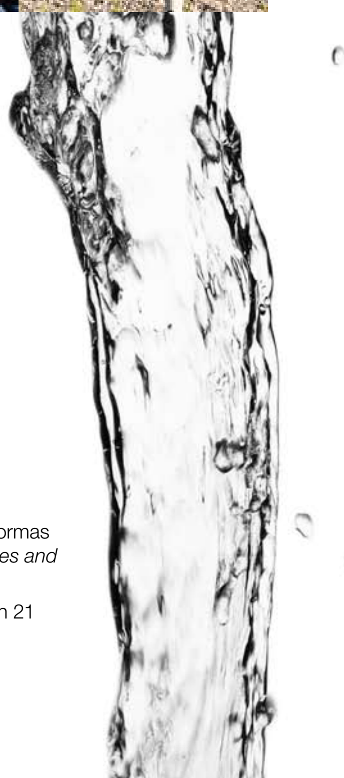

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