# CO-OPTIMIZING SOLUTIONS: WATER AND ENERGY FOR FOOD, FEED AND FIBER

wbcsd

# CONTENTS



*Readers may use the hyperlinks embedded in this document to easily navigate to the various co-optimized solutions highlighted in the report. Links are generally denoted by underlined text.*

*An executive summary of this document is available in the water section of* **www.WBCSD.org** *along with a companion piece on the challenges of the water, food and energy nexus.*

# FOREWORD:
# CHALLENGES AND OPPORTUNITIES

Over the next 40 years we will face major challenges in meeting demand for food, fiber and feed sustainably. According to the Food and Agriculture Organization (FAO) of the United Nations, demand for food will rise by 60% and fiber by 80-95% by 2050.[1] These increases will occur at a time of growing pressure on water quality and quantity, with agriculture using the majority of water globally.[2]

Climate change, including extreme weather events and higher temperatures, will impact food production in several ways. For instance, increasingly unreliable rainfall, new weed infestations, and a larger incidence of pests may slow down agricultural productivity. At the same time, greenhouse gas emissions from agriculture – already 14% of the global total – are likely to increase unless farming is transformed.[3]

Sustainable agriculture, water stewardship and energy production are essential elements of the transformation that is required if a global society of over 9 billion people is to live well and within the limits of the planet. This is the high level goal that the World Business Council for Sustainable Development (WBCSD) set out in its 2010 publication *Vision 2050: The new agenda for business*.

WBCSD's Action2020 initiative takes this vision and develops business solutions that deliver tangible outcomes towards its achievement. Action2020 concentrates on addressing nine, science-based actionable priorities by developing business solutions that can result in measurable positive impact. The work is led by the WBCSD in collaboration with member companies and leading international organizations, and seeks to engage companies across the globe to implement innovative and scalable business solutions that will also improve the business case for sustainability.

[1]FAO 2012, [2]WWAP 2009, [3]IPCC 2007

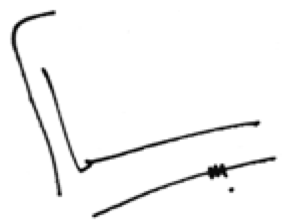
For each of the nine priority areas a societal goal, a "Must-Have", was defined that we all need to work towards achieving by 2020 if we are to put ourselves on a path where Vision 2050 can become a reality. These Must-Haves require urgent attention if progress is to be made, and this publication sets out some of the challenges and solutions that we are working on in the closely related areas of Water, Ecosystems & Land Use, and Climate & Energy.

Action2020's growing set of Business Solutions are addressing issues such as reducing shared water risks, increasing water efficiency in agriculture, restoring productivity to degraded land, and halving food waste from field to fork. These issues are all linked to the co-optimized solutions detailed in this publication.

Working on the food, water, energy nexus will co-optimize production increases, reduce pressure on water and land, and achieve higher resource efficiency while not just minimizing, but avoiding negative side effects.

Business is a central part of the solution. It has great reach and enormous resources: with that power comes the responsibility to formulate ideas and innovations that will drive changes at scale. This is the premise behind the WBCSD's engagement in the Nexus Program – scoping the interconnectedness of water, food, fiber and energy, and finding efficient solutions.

The WBCSD is the leading voice in support of business scaling up true value-adding solutions and creating the conditions where more sustainable companies will succeed and be recognized. The landscape of co-optimized solutions is rich and promising and offers wide-ranging exciting opportunities for leading companies to push forward solution development and implementation.



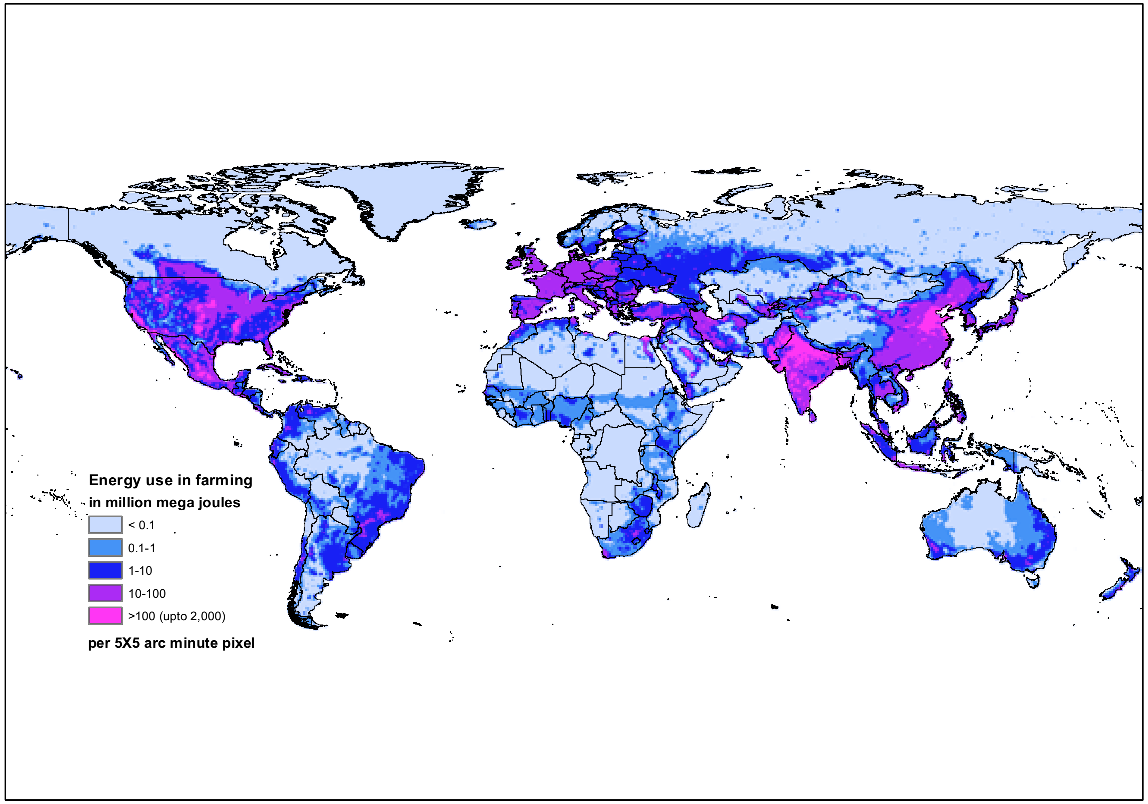
**Peter Bakker**
President and CEO, WBCSD

# 1
# INTRODUCTION

Agriculture is one of the world's largest economic sectors, contributing on average to 6% of gross national product,[4] and probably more if non-monetized transactions – common in smallholder farming in particular – are taken into account. It is also a sector where much of the value comes from direct resource use (land, water, minerals), and hence where planetary boundaries are felt more markedly.

Energy use in agriculture is 3-8% of global consumption, and this estimate more than doubles if food processing is taken into account. Energy consumption in agriculture will increase by 84% by 2050 in a business-as-usual scenario,[5] much of it because of the fossil fuels that are required to make fertilizers and run farm equipment. Figure 1, showing the geographical distribution of energy use intensity in agriculture, clearly points out where agriculture is energy-intensive and where opportunities for improvement exist.

Figure 1
## Energy use in farming




Source: WBCSD Nexus Model, prepared by Resourcematics Ltd., 2013

[4]U.S. Central Intelligence Agency *World Factbook 2013*, [5]Pimentel and Pimentel 2008

Increasing demand for food, fiber and feed will put great strains on land, water, energy and other resources. The expected increase in agricultural production will bear heavily on greenhouse gas emissions and climate change. Agricultural commodity markets may also change: the price spikes of 2008 and 2011 are a reminder of how sensitive agricultural commodity markets can be.

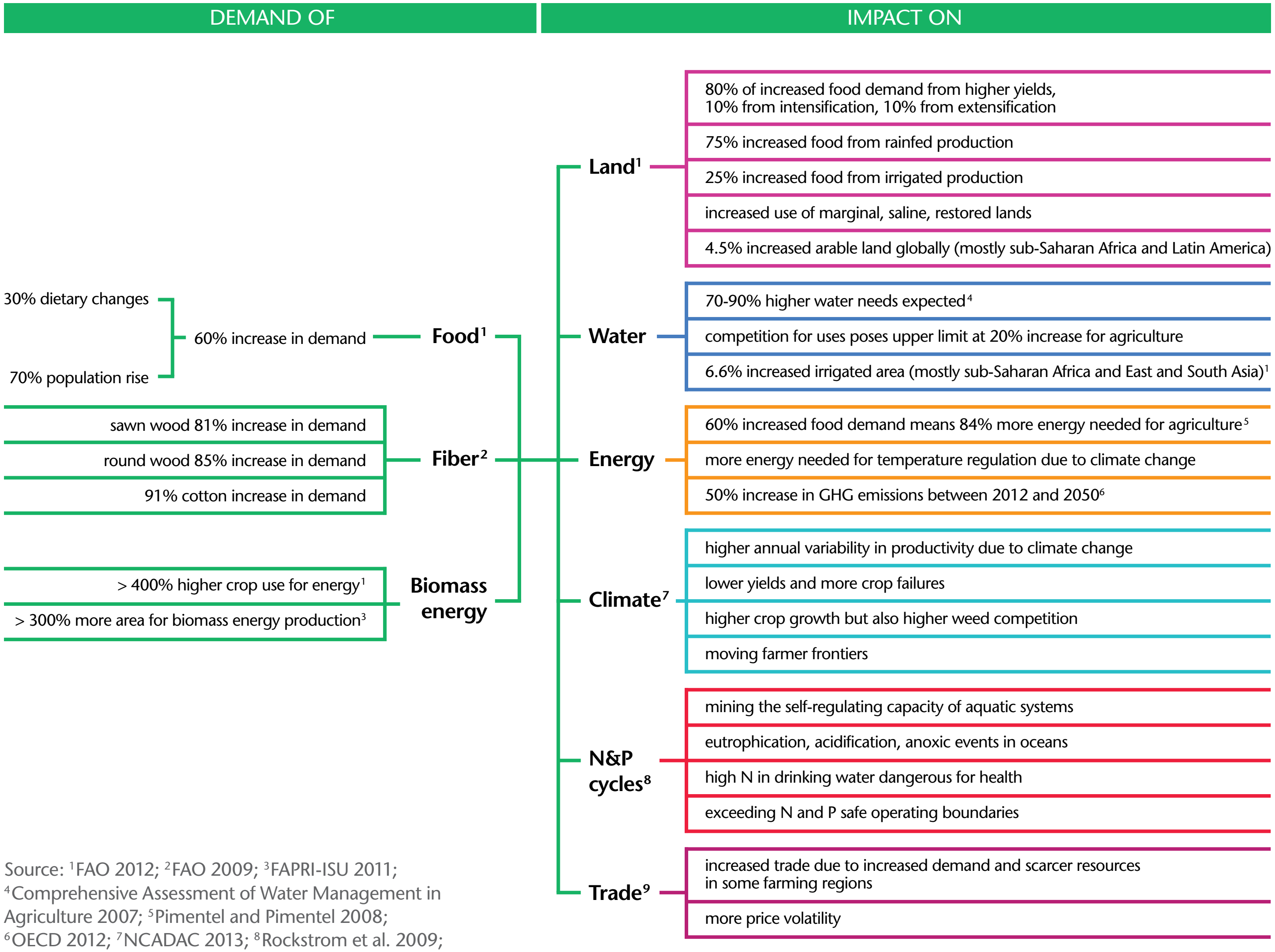
The main challenges are:

- 60% increase in demand for food by 2050 caused by population growth and increased per capita consumption of meat and dairy;
- Increased demand for fiber for wood panels, roundwood and paper;
- Threefold increase in demand for biofuels;
- Impact on land from increases in production yields, including land-use change;
- Impact on water resources and water quality from increased irrigation and domestic and industry water use will, along with competition over water resources that will reduce overall water availability and salinity and cause high concentrations of nitrates, nitrites, phosphorous and nitrogen compounds;
- Impact of climate change on agriculture, including increased water requirements and decreasing yields;
- Impact on energy consumption from intensified agriculture;
- 50% increase in greenhouse gas emissions;
- Volatile agricultural commodity markets due to increased demand and scarcity of agricultural products, rising oil prices leading to higher production costs, especially for fertilizers, and fluctuations in production due to climate change.

Figure 2 provides a map of challenges, which is also a map of opportunities.

Increasing demand for food, fiber and feed will put great strains on land, water, energy and other resources.

Figure 2
## Map of challenges ahead to 2050




Source: [1]FAO 2012; [2]FAO 2009; [3]FAPRI-ISU 2011; [4]Comprehensive Assessment of Water Management in Agriculture 2007; [5]Pimentel and Pimentel 2008; [6]OECD 2012; [7]NCADAC 2013; [8]Rockstrom et al. 2009; [9]Allan 2011; Baffes 2007 and 2009; OECD-FAO 2011.

There is both a need and a business case for the identification and implementation of a broad spectrum of solutions that will reinforce and complement one another. The pressure on the water-food-energy nexus asks for both short- and long-term solutions that will contribute to balancing and optimizing the future on all fronts. There is an ecological, social and economic inclination towards co-optimization. The most appropriate, scalable solutions are available and can be implemented with multiple benefits on yields, energy, water, climate change, resource use and other factors. Many of these benefits translate into direct financial opportunities and present a sound case for business action. There is indeed much to gain with co-optimization. For instance, gains on the energy side may pay for water use savings: if crop production is increased through better water management, water will be saved and less energy will need to be generated, yet the world will still be able to feed a growing population.

Box 1

## The Nexus model

The solutions areas are complemented by the Nexus Model. The Nexus Model aims to provide an understanding of and document the global linkages between water, energy, food/feed/fiber/fuel and climate change and to develop policy and technology options to address the challenges identified. In specific, the nexus model focuses on:

i) Water demand for food, feed, fiber and fuel

ii) Energy demand for water supply to agriculture

iii) Energy demand for farming

iv) Energy demand for fertilizer use (production to application).

The model draws on various sources, such as the Food and Agriculture Organization of the United Nations (FAO), Land Use and the Global Environment (LUGE), and the Water Footprint Network (WFN). The aim of the Nexus Model is to provide first indications that can guide business decisions by answering generic "what-if" type questions with reference to comprehensive nexus perspectives. Once the problem is quantified with reference to the energy, water and food nexus, various solution pathways will be applied by adjusting water, energy and food indicators. This paper integrates some outputs of the Nexus Model – baseline visualizations of water and energy use patterns as well as potential impacts of specific solutions. The maps and analysis presented in this report are a mere glimpse of the Nexus Model and not an exhaustive output.

There are many examples of possible co-optimization. The use of enzymes can make crops grow faster and the uptake of phosphate fertilizer more effective, thus saving on energy and reducing pollution. Biodegradable plastic mulch contributes to avoiding water losses through evaporation, increased soil temperature and accelerated natural nitrogen fixation. By fundamentally changing the philosophy with which we grow rice, we could increase yields, save water for other uses and reduce methane emissions. On the consumer side, changing behavior at the retailer and consumer levels to control food waste will significantly reduce demand for water and energy embedded in products that never reach an end-user. Value chains can even be taken a step further to set up water- and energy-efficient production systems.

Addressing the challenges of providing food and fiber to a growing population that lives well while staying within the boundaries of the planet in terms of water, energy and climate impact will require change and initiative. Agriculture worldwide is likely to develop constantly, while natural resources dwindle and demand for food, fiber, feed and biofuels increase. Innovation in crops, farming systems, and value chains are all required and constitute must haves towards an agriculture that is sustainable in terms of people and planet.

Farmers and businesses have always been adapting, experimenting and improving, and the contours of new forms of agriculture are becoming visible. If the 10 solution areas are the shape of things to come, then the world must move towards global farming that is more precise and less wasteful, has a better understanding of and respect for natural, biological and ecological cycles and makes the best use of them, is more stress- and climate-resilient yet maintains productivity, and addresses the resource base at the landscape level.

To reach this new state of agriculture requires closing the knowledge gap and new ingenuity – including clever crop agronomy, smart seeds, zero-energy farms and integrated logistical systems. Care must be paid to avoid a dichotomy between innovative and productive farm systems on the one hand and marginalized, resource-poor backwater systems on the other. It is as important to promote breakthroughs as it is to work on improving the productivity of very small farms and making them viable businesses in their own right. For centuries, farming has been the pursuit of basic subsistence, and still is in many areas. In the future, it will become more and more entrepreneurial and knowledge-intensive.

The business sector has a large role to play here by:

- Applying its capacity to innovate towards higher water and energy productivity and sustainable harvests;
- Applying its capacity to invest in a demanding future and not draw back, for instance, from more marginal areas;
- Strategically anticipating future challenges and risks and investing in long-term agro-solutions; and
- Using its organizational skills to strengthen supply systems and marketing logistics to better source products and reduce waste.

There is also great opportunity for businesses to work together all along the value chain – connecting input suppliers, producers, commodity traders, processors and retailers.

Business is a large part of the solution. It wields enormous power, and hence the responsibility to formulate ideas and innovations that will drive changes and the use of its processes and outreach to achieve scale. But business needs to work in a conducive and supportive context. It can make long-term investments only if there are suitable and enabling policy frameworks.

Governments have to play the role of “stable enabler”, as they have done in countries that now lead in agriculture, sometimes irrespective of a limited resource base. Price and resource buffers act as enablers, too. Price buffers are adequate reserves of commodities to prevent sudden price surges or collapses, and resource buffers are well-managed landscapes and water resource systems.

There are many solution areas, and if these are triggered and combined, the challenges towards 2050 can be met. All solution areas are part of a larger co-optimization, where multiple benefits synchronize and where investments in R&D lead to energy and water savings while increasing yields and creating better quality products.

# 2
# CO-OPTIMIZING AGRO-SOLUTIONS

Some of the most promising, innovative, and scalable solutions to the interconnected water, energy and food/feed/fiber challenges allow for combined co-optimization. The 10 main solution areas – **1) smart varieties**; **2) smart crop management**; **3) mixed farming systems**; **4) better blue water management**; **5) better green water management**; **6) efficient farm operations and mechanization**; **7) bridging the yield gap**; **8) efficient fertilizer production**; **9) making use of trade**; and **10) reducing waste** – impact food supply and reduced water and energy demands, both in terms of the environmental implications, such as water quality and climate change, and geographically.

These solution areas – covering a range of opportunities from seed to food and from food to fork – capture a large part of the options at hand to address the co-optimization challenges and balance the inevitable demand for food, feed and fiber within the limits of water and energy availability at minimum or zero environmental impact. These solution areas concern broad categories, each of which have a myriad of more specific innovations, and many are integrated, thus enabling, reinforcing or multiplying each other.

Without considering the social implications and the investment required, one impression that emerges from exploring the different solution areas is that from a resource perspective, considerable gains are possible. Most agro-solutions will address several challenges at once. Looking at current baselines for energy and water productivity, and the variation therein, and considering current loads on climate and pollution, it appears that there are great margins for improvement in several regions.

For instance, overuse of phosphates and nitrates could be reversed by using best available technologies (BAT). Climate effects are a major factor, especially in agriculture, but there are also untapped opportunities to adapt to these. Several agricultural solutions can even mitigate climate impacts by reducing greenhouse gas (GHG) emissions and by sequestering carbon.

Table 1 below provides an overview of the solution areas at stake and their impact on the water and energy nexus and climate change.

The different solution areas are explored in more detail in the next section. All these areas need business initiative and enablers from government to move forward, which is discussed in section 4.

# OVERVIEW OF SOLUTION AREAS, GEOGRAPHICAL SPREAD, AND IMPACTS

## SMART VARIETIES

- Increased maximum potential yield
- Pest smart
- Resource smart

find out more

## EFFICIENT FARM OPERATIONS AND MECHANISATION

- Retrofitting and replacement of inefficient operations
- Integrated planting systems
- Closing the energy loop

find out more

## SMART CROP MANAGEMENT

- Efficient fertilizer use
- Smart fertilizers
- Rock dust and bio-fertilizers
- Bio-stimulants
- Improved disease control
- Nanotech pesticides

find out more

## BRIDGING THE YIELD GAP

- Best management practices; farmers' inclusion in innovation systems; access to relevant information and technology; better linkage to markets and service providers; uses new communication technology

find out more

## MIXED FARMING SYSTEMS

- Multiple cropping
- Agroforestry

find out more

## EFFICIENT FERTILIZER PRODUCTION

- Overhauling, BATs, natural gas

find out more

## BETTER BLUE WATER MANAGEMENT

- Precision irrigation
- Conjunctive water use and drainage
- Water-saving rice systems

find out more

## MAKING USE OF TRADE

- Trade based on water/energy productivity

find out more

## BETTER GREEN WATER MANAGEMENT

- Conservation agriculture
- Bio-degradable plastic mulching
- Landscape restoration and watershed improvement

find out more

## REDUCING FOOD LOSS AND WASTE

- Improving harvest, post-harvest, and processing
- Rebalancing consumption at retailer and consumer level

find out more

Table 1
## Overview of solution areas, geographical spread, and impacts

| Solution area | Geographical spread | Yields | Effects on Energy | Effects on Water | Effects on Climate |
|---|---|---|---|---|---|
| **1 Smart varieties** | | | | | |
| Increased maximum potential yield | Global/Asia/sub-Saharan Africa | 40-70% higher | | | |
| Pest smart | Global/Latin America/Asia | 7-30% higher | Less fuel for chemical applications | Up to 50% reduction in pesticides, less pollution | 100 million tonnes (t) $CO_2$ saved/year from fuel reduction |
| Resource smart | Global/Asia/sub-Saharan Africa/ Latin America | Drought-tolerant maize yields 6-15% higher in water-stressed conditions; saline-tolerant rice yields 30% higher in saline environments | New maize 11% higher nitrogen-use efficiency than old varieties | Aerobic rice 30-60% savings | Aerobic rice 80-85% less methane emissions than lowland rice |
| **2 Smart crop management** | | | | | |
| Efficient fertilizer use | Global/Asia | Increased quantity and quality | 20-30% fertilizer savings | Less leaching, less pollution | Reduced nitrous oxide emissions |
| Smart fertilizers | Global | 10-40% higher | 20-30% fertilizer savings | Less leaching, less pollution | Reduced nitrous oxide emissions |
| Rock dust and bio-fertilizers | Modest and dispersed; near mines and quarry sites | 10-15% higher | Less fertilizer | 5% higher water retention capacity | Serpentine and olivine sequester 0.5 and 0.67 t $CO_2$/t weathered rock |
| Bio-stimulants | Global | 10% higher | | | |
| Improved disease control | Global | 10 to more than 200% higher | 60-90% less pesticides | Less pesticide leaching, less pollution | |
| Nanotech pesticides | Modest geographical scope | 20-50% higher | 50% less pesticides | Less pesticide leaching, less pollution | |

Table 1
**Overview of solution areas, geographical spread, and impacts (continued)**

| Solution area | Geographical spread | Yields | Effects on: Energy | Effects on: Water | Effects on: Climate |
|---|---|---|---|---|---|
| **3 Mixed farming systems** | | | | | |
| Multiple cropping | sub-Saharan Africa/ Asia/Latin America/ marginal lands | Higher yields/unit area; 89% higher for glutinous rice | Up to 50% nitrogen savings in legume-cereal systems | 18-99% water savings | |
| Agroforestry | Asia/sub-Saharan Africa/Latin America/marginal lands | 20-60% higher productivity in silvo-arable systems | | Soil moisture conservation and groundwater recharge | Carbon sequestration |
| **4 Better blue water management** | | | | | |
| Precision irrigation | Asia/Latin America | 10-54% higher in vegetables | 29-44% energy savings | 30-70% water savings but also less recharge | |
| Conjunctive water use and drainage | Asia/sub-Saharan Africa | 20-130% higher for rice; 54% for sugarcane, 64% for cotton, 136% for wheat | | 20% savings | |
| Water-saving rice systems | Asia/sub-Saharan Africa | 5-15% higher | 60% energy savings with direct seeding; 26% higher nitrogen-use efficiency | 20-60% water savings with direct seeding; 15-30% savings with alternate wetting and drying | 18-50% less methane emissions |

Table 1
## Overview of solution areas, geographical spread, and impacts (continued)

| Solution area | Geographical spread | Yields | Effects on: Energy | Effects on: Water | Effects on: Climate |
|---|---|---|---|---|---|
| **5 Better green water management** | | | | | |
| Conservation agriculture | Global/Asia/sub-Saharan Africa/ Latin America | 20-90% | 40-70% energy savings | 25-70% reduced runoff | 11 t/hectare (ha)/year $CO_2$ sequestration |
| Bio-degradable plastic mulching | Global/China | 10-60% higher | 1,400% energy savings for production compared with petroleum-based plastic | 40-60% water savings | Sugar beet-based plastics reduce fossil fuel use by 65% compared to low-density polyethylene (LDPE) plastic mulch |
| Landscape restoration and watershed improvement | sub-Saharan Africa/Latin America/Asia | 30-70% higher with mosaic landscapes | | Groundwater recharge, moisture retention, less irrigation | Carbon sequestration with reforestation projects (1-10 t $CO_2$/year/ha) |
| **6 Efficient farm operations and mechanization** | | | | | |
| Retrofitting and replacement of inefficient operations | Global/Asia/Latin America | More timely and precise operations and solving age/labor gap mean higher yields | 35-60% savings with pump retrofits in India | | 50-96% less NOx and PM10 with new diesel engines |
| Integrated planting systems | Global/Asia/Latin America | 15% higher with PLENE technology (Syngenta's integrated solution that combines plant genetics, chemistry and new mechanization technology) for sugar cane | Less fuel used by the smaller machines in Syngenta's PLENE system | | |
| Closing the energy loop | Modest | | Can turn farms into energy providers | | |

Table 1
## Overview of solution areas, geographical spread, and impacts (continued)

| Solution area | Geographical spread | Yields | Effects on: Energy | Effects on: Water | Effects on: Climate |
|---|---|---|---|---|---|
| **7 Bridging the yield gap** | | | | | |
| Best management practices; farmers' inclusion in innovation systems; access to relevant information and technology; better linkage to markets and service providers; uses new communication technology | Sub-Saharan Africa/Latin America/Asia | Rice: 15-85%<br>Maize: 30-165%<br>Wheat: 25-35%<br>Coarse grain: 85% | More fertilizers needed | | Likely more greenhouse gas emissions |
| **8 Efficient fertilizer production** | | | | | |
| Overhauling, BATs, natural gas | Global/China | | 10-25%; 37% if bulk of plants replaced by BATs | | 57% less green-house gas emissions = 164 million t/year |
| **9 Making use of trade** | | | | | |
| Trade based on water/energy productivity | Modest geographical scope | | 5-6% higher energy productivity | 5-6% higher water productivity | |

Table 1
**Overview of solution areas, geographical spread, and impacts (continued)**

| Solution area | Geographical spread | Yields | Effects on: Energy | Effects on: Water | Effects on: Climate |
|---|---|---|---|---|---|
| **10 Reducing waste** | | | | | |
| Improving harvest, post-harvest, and processing | Sub-Saharan Africa/Asia/Latin America | 10% less food demand | 2% production energy savings | 10% water savings for production | 10% less greenhouse gas emissions along the food chain |
| Rebalancing consumption at retailer and consumer level | North America/ Europe | 10% less food demand | 8% energy savings along the food chain | | 10% less greenhouse gas emissions along the food chain |

# 3
# TEN SOLUTION AREAS

# SOLUTION AREA 1
# SMART VARIETIES

Continuously increasing the potential yields of major crops owes much to plant breeding for increased harvest indexes and biotechnology. However, the great yield gains reached over the last decades are slowing down as the ceiling of physiological yields for major crops is being reached.[6]


[6]Bruinsma 2010

## SMART VARIETIES

Though there are various estimates of what is still possible to achieve, the consensus lies between a 50-100% increase over current maximum yields:

- For wheat, potential maximum yields are estimated at 13 tonnes per hectare (t/ha) under average conditions and 19 t/ha under optimum conditions – a 50% increase over what is currently possible.
- For rice, within the International Rice Research Institute's (IRRI) Chinese Green Super Rice breeding program, varieties are already nearing 12 t/ha – similar yields are also attained by hybrids grown in eastern China. A 50% increase in rice biomass is deemed possible if the photosynthetic path is re-engineered.[7]
- For maize, potential yield projections are not consistent but range between 17-25 t/ha.
- There are still great opportunities to improve maximum yields of coarse grain cereals, such as barley, sorghum and millet – important crops for many poor populations though largely neglected by breeding and crop engineering programs.

Projections based on the Nexus Model suggest that 5 billion tonnes of grain could be produced if potential maize, wheat and rice yields are pushed up to 24, 19, and 18 t/ha respectively,[8] and if these improved varieties are cultivated on 40% of the aggregated cultivated area of maize, wheat and rice[9] by 2050. This is far beyond the projected global cereal demand of 3 billion tonnes in 2050[10] needed to keep up with a world population of 9.6 billion. More details on the methodology underpinning the Nexus Model are available in **Annex A**.

The development of new varieties can be obtained by conventional breeding or by genetic crop engineering. The latter technology involves incorporating the desired exogenous genes from other organisms or plant species into a certain crop. Developing new varieties takes time. On average, it could take about 10 years from when the research starts to the point when a new variety is commercially available.

Projections based on the Nexus Model suggest that 5 billion tonnes of grain could be produced if potential maize, wheat and rice yields are pushed up to 24, 19, and 18 t/ha respectively

[7]Sheehy et al. 2007, [8]Fischer et al. 2010, [9]Monfreda et al. 2008, [10]FAO 2012

## SMART VARIETIES

Table 2
**Potential and impacts of smart varieties**

| | Crop | Spread | Yield | Energy | Water | Climate |
|---|---|---|---|---|---|---|
| **Increased potential yield** | | | | | | |
| Hybrids; re-engineering photosynthesis | Wheat, rice, maize, barley, coarse grains | Asia/sub-Saharan Africa | 40-70% higher[i] | | | |
| **Pest-smart varieties** | | | | | | |
| Insect and herbicide resistant | Maize, cotton, canola, sugar beet, soybean | Global/Latin America/Asia | 7-20% higher[ii] | Less fuel for chemical applications | Up to 50% reduced pesticides, less pollution[ii] | 100 million $CO_2$ saved/year from fuel reduction |
| Bacterial disease resistant | Rice | Asia | 20-30% higher[iii] | | | |
| **Resource smart varieties** | | | | | | |
| Drought tolerant | Maize | Global/sub-Saharan Africa | 6-15% higher in water stressed conditions[iv] | | Adapted to water stressed conditions | |
| Nitrogen efficient | Maize | Global | | 11% higher nitrogen use efficiency than old varieties[v] | | |
| Saline tolerant | Rice | Asia | 30% higher in saline environments[vi] | | | |

Sources: [i]Qaim and Matuschke 2005, Sheehy et al. 2007, Bruinsma 2010, Syngenta 2012b; [ii]Brookes and Barfoot 2011, Edgerton et al. 2012; [iii]Li et al. 2012; [iv]WBCSD 2009; [v]Ciampitti and Vyn 2012; [vi]DuPont Pioneer n.d.

A second main direction for breeding and genetic engineering is developing crops that are more resilient to non-optimal conditions.

A first main direction for breeding and genetic engineering is pushing potential crop yields. Much is expected from re-engineering the photosynthetic process to make it more efficient in converting carbon dioxide into biomass. This can be done by genetic modification, for instance by including specific genes from algae and bacteria into commodity crops.[11] Ongoing research focuses on improving the photosynthetic efficiency of rice.

High growth rates and crop hardiness are competing characteristics, however. For a crop to invest disproportionate energy in one single aspect, i.e., its biomass, means that less energy is left for other functions, such as dealing with pest attacks. Rapid growth needs optimal conditions for nutrients, water and plant protection. This is at the expense of general hardiness.[12] For instance, hybrid rice is more prone to diseases than local inbred varieties and requires greater fertilizer and pesticide investments.[13] Moreover, the cost of purchasing hybrid rice seed each growing season may be prohibitive and tedious for many small farmers.

A second main direction for breeding and genetic engineering is developing crops that are more resilient to non-optimal conditions. Crops have been engineered to resist several pests and diseases (see **Annex B**). For example, insect resistance, the most common trait, has been engineered into major crops such as cotton, soybean, maize and potato. This has reduced the use of insecticides.[14] The latest biotechnologies have also enabled striking advances in the control of harmful bacterial pests.

Another important line is the work on herbicide-tolerant crops. This allows fewer applications of broad-spectrum herbicides instead of higher volumes of more harmful selective herbicides. Herbicide-tolerant rice varieties are an example.[15] Considering that one of the main reasons for inundating paddy fields is weed control, this could lead to considerable water savings. Herbicide-resistant rice opens opportunities for resource conservation technologies, such as direct-seeded rice (see **Solution Area 4**) with zero tillage.

[11] Hahlbrock 2009, [12] Ibid., [13] Sahai et al. 2010, [14] Qaim and Matuschke 2005, [15] Kumar et al. 2008

Still, research on the impacts of pest and herbicide resistant varieties on the environment is too contradictory to generalize.[16] For example, the development of herbicide-resistant weeds is a concrete and already observed risk related to the cultivation of herbicide-resistant crops.[17]

With present climate uncertainty and resource constraints, developing and selecting varieties that are more resource efficient and adapted to a wider range of climatic and soil conditions is increasingly important. Varieties that can grow in saline, low nutrient, hyper-arid or waterlogged conditions make it possible to increase production on marginal lands.

While genetic engineering has been relatively successful in delivering traits such as pest or herbicide resistance, it has proven much more challenging to deal with abiotic stresses, such as tolerance to drought or salinity.

The areas of breeding that accommodate tolerance to water stress are: early leaf growth to cover soil and reduce moisture evaporation; osmotic adjustment; waxy leaves and improved root structure; and managed sensitivity to drought at flowering by storing more water in root systems.

Box 2 describes drought-tolerant engineered corn developed by BASF and Monsanto, which is currently being tested in Africa. DuPont Pioneer and Syngenta, in collaboration with the International Maize and Wheat Improvement Centre (CIMMYT), have also made strides in breeding corn that can yield 15% more than conventional hybrids in water-stressed conditions and equal or even more under optimal conditions.

Box 2

## Drought-tolerant corn for changing climates

In the coming decades, the effects of climate change on agriculture are likely to materialize in the form of reduced yields for major crops – the consequence of increased rainfall variability and dry spells. In the U.S., 4-5 million hectares of corn may be affected by at least moderate drought.[18] Biotechnology-derived drought-tolerant varieties can help stabilize yields, securing an income for farmers faced with unfavorable environmental conditions. Drought-tolerant corn, pioneered by BASF and Monsanto, can yield more than conventional hybrids in situations of water stress. Having discovered the genes responsible for drought tolerance in the bacterium *Bacillus subtilis*, researchers at these two companies have incorporated these traits in staple crops like corn. Field tests show that drought-tolerant maize yields 6-10% more than conventional hybrids in drought-prone areas.[19]

[16] Qaim and Zilberman 2003, [17] Owen and Zelaya 2005; Owen 2009, [18] WBCSD, 2009, [19] WBCSD, 2009,

## SMART VARIETIES

Ongoing research is also seeking to develop crop varieties that use nitrogen more efficiently, reducing the need for fertilizer and saving energy. An example is plant breeding for enhanced soybean bio-fertilization. The greater challenge, however, is to incorporate nitrogen-fixing capacity into non-leguminous crops.[20] In the case of maize, great advances have been made in grain yield formation in relation with nitrogen uptake. New hybrids have a larger yield response per unit of nitrogen, and new genotypes have been documented to be more tolerant to nitrogen-deficiency stress, leading to higher yields when no or limited nitrogen is applied.[21] In Africa, a project launched in 2010 and led by CIMMYT, DuPont and various African research institutes, is aiming to develop a maize variety that yields more with the same amount of nitrogen. DuPont is also currently testing the combination of drought tolerance with nitrogen-use efficiency, as these two traits have synergistic relationships. The architecture of rooting systems has to be understood better in order to achieve gains in both water and nitrogen-use efficiency.

Worldwide, more than 34 million hectares of land are affected by some degree of salinity. Abundant research has been conducted to improve the salt tolerance of staple crops like wheat and barley.[22] Salt tolerance, however, is a complex genetic trait (multiple gene transformations required) and bioengineering has not yet delivered salt-tolerant cultivars of conventional staple crops (wheat, maize or rice).[23] Halophytes that have developed salt tolerance are being studied for "3rd generation" biofuels, feed and fibers.[24] However, domestication is needed to convert them to viable crops. Salinity-tolerant rice hybrids have been developed by DuPont Pioneer to allow rice-shrimp farming in South-East Asia without compromising rice yields due to the use of salt water. These advances help small farmers coping with adverse and changing climate conditions.

Ongoing research is also seeking to develop crop varieties that use nitrogen more efficiently, reducing the need for fertilizer and saving energy.

[20] Hahlbrock 2009, [21] Ciampitti and Vyn 2012, [22] Colmer et al. 2006, [23] Rozema and Flowers 2008, [24] Ahmad and Malik 2002; Khan and Ansari 2008; Abideen et al. 2011

## SMART VARIETIES

Mainstream international research and agricultural development have historically focused on several major crops that undoubtedly have played a crucial role in human development and food security. Yet it is also extremely important to acknowledge that a great diversity of local, traditional crops are still waiting their turn. This is the case for a wide range of cereals native to Africa that have been and still are crucial to sustaining local livelihoods. Despite their incredible performance in terms of hardiness and resilience to extreme environments, not to mention their often very high nutritional value and the fact that they are deeply embedded in local diets and habits, their potential is still largely untapped. These crops could have a huge role to play in solving some of the greatest food security challenges, especially in Africa where the promises of the "green revolution" might not be able to take root for a number of reasons.[25]

Genetic diversity and traditional varieties bear enormous relevance in both building resilient cropping systems and sustaining local livelihoods, especially when it comes to adaptive mechanisms in addressing climate change (see **Annex B**). For instance, Ethiopia has a unique genetic diversity of cultivated, semi-wild and wild *Arabica* coffee varieties with different types of disease resistance, environmental adaptation and quality characteristics. The genetic diversity of coffee in Ethiopia is of global importance in breeding varieties that are adapted to future variable environmental conditions and that are disease resistant.[26] Another example is the foxtail millet that, due to its excellent drought resistance, allows farmers in dry areas of Northern Karnataka, India, to make a living.[27] Dryland varieties generally have lower water requirements with similar or higher production than higher yield varieties in harsh environments.[28]

[25]National Research Council 1996, [26]GIZ 2011, [27]GTZ 2006, [28]GIZ 2010

# SOLUTION AREA 2
# SMART CROP MANAGEMENT

There is much to be gained with smart crop management. A first big improvement is the more efficient use of resources, such as solar radiation, water and nutrients through the improved management of external inputs, including fertilizers and pesticides.

The overuse of fertilizer is problematic in some areas, resulting in energy loss, pollution and no extra yield, while in other parts of the world more nutrients should be applied from a range of sources. There are also breakthroughs in better application and better dosing – through chemigation (applying pesticides and fertilizer through the irrigation system used to distribute the water), smart fertilizers and nanopesticides. Some of these techniques are well known, others are experimental.

Finally, there is a range of farming techniques that mimic and strengthen natural processes and do not just add nutrients but improve soil structure or reinforce growth processes. These include bio-fertilizers using rock dust minerals and bio-stimulants. These methods do not add a missing ingredient to the soil system on a short-term basis but help build up a more sustainable long-term new resource base by making biochemical soil processes perform better. These techniques are expected to become more central to farm operations.

Table 3

**Potential and impacts of smart crop management**

| | Spread | Yield | Energy | Water | Climate |
|---|---|---|---|---|---|
| **Efficient fertilizer use** | | | | | |
| More timely and precise use; sensor-based application; chemigation; integrated nutrient management (INM) | Global – areas with overuse (e.g., China) | Higher yields and higher quality | 20-30% fertilizer savings[i] | Less leaching, less pollution | Reduction of nitrous oxide emissions |
| **Smart fertilizers** | | | | | |
| 1) Slow control mechanisms 2) nitrification inhibitors and 3) urease inhibitors (4) phosphorous availability enhancers | Global – especially in high value crops | 10-40% higher[ii] | 20-30% fertilizer savings[iii] | Less leaching, less pollution | Reduction of nitrous oxide emissions |

Sources: [i]Bumb and Baanante 1996, Scharf et al. 2011; [ii]Abdul Wahid and Mehana 2000, Song et al. 2005, Trenkel 2010; [iii]Trenkel 2010

## SMART CROP MANAGEMENT

Table 3

**Potential and impacts of smart crop management (continued)**

| | Spread | Yield | Energy | Water | Climate |
|---|---|---|---|---|---|
| **Rock dust and bio-fertilizers** | | | | | |
| Use of rock dust and bio-fertilizers to re-mineralize the soil | Close to quarries and in some countries by crushing | 10-15% higher[iv] | Less fertilizer | 5% higher water retention capacity | Serpentine and olivine sequester 0.5 and 0.67 t $CO_2$/t weathered rock[v] |
| **Bio-stimulants** | | | | | |
| Strobilurines | Global | 10% higher[vi] | | | |
| **Improved disease control** | | | | | |
| Less and more precise use; integrated pest management; pest monitoring systems | Global/Asia/ Africa | 10% to more than 200% higher[vii] | 60-90% less pesticides[vii] | Less pesticide leaching, less pollution | |
| **Nanotech pesticides** | | | | | |
| Increased efficacy of nanoactive ingredients and controlled release by nanoencapsulation | Global | 20-50% higher[viii] | 50% less pesticides[ix] | Less pesticide leaching, less pollution | |

Sources: [iv]Samobor et al. 2008; [v]Schuiling and Krijgsman 2006; [vi]Beck et al. 2002; [vii]Dasgupta et al. 2007, Dhawan et al. 2009, Pretty et al. 2011, Khan et al. 2011; [viii]Agro Nanotechnology Corporation (n.d.), Sheykhbaglou et al. 2000; [ix]Nano Green Sciences Inc. (n.d.)

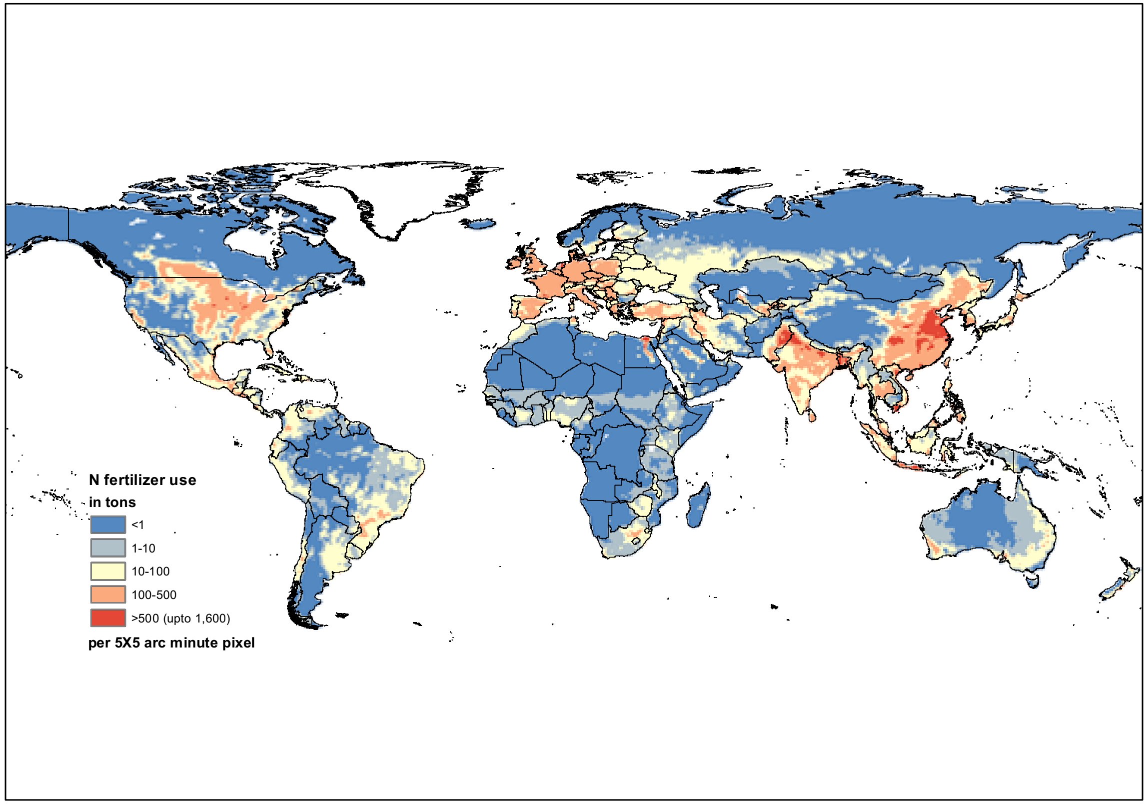
## Efficient fertilizer use

Fertilizer use is important to crop yields, energy use in agriculture and effects, such as pollution. Most (89%) of the increased agricultural production over the coming decades is expected to come from agricultural intensification, bringing along more intensive use of fertilizer. In several regions, nutrient limitations set the major ceiling on yields.[29]

Fertilizer use is particularly low in many parts of Africa (see figures 3a and 3b) and this constrains land and water productivity (in sub-Saharan Africa, only 9 kg/ha of external nutrients are used as compared to 73 kg/ha used in Latin America, 100 kg/ha in South Asia and 135 kg/ha in East and Southeast Asia).[30] Therefore, particularly in sub-Saharan Africa, the world's major agricultural frontier, a system of sustainable intensification is advocated.[31] With current rainfall patterns, improved soil fertility could double productivity in Africa.[32] It is noted that this could be achieved by using chemical fertilizers, but bio-fertilizers and other nutrient sources, if properly used, are also a credible alternative.

Figure 3a

**Spatial patterns of nitrogen fertilizer use**



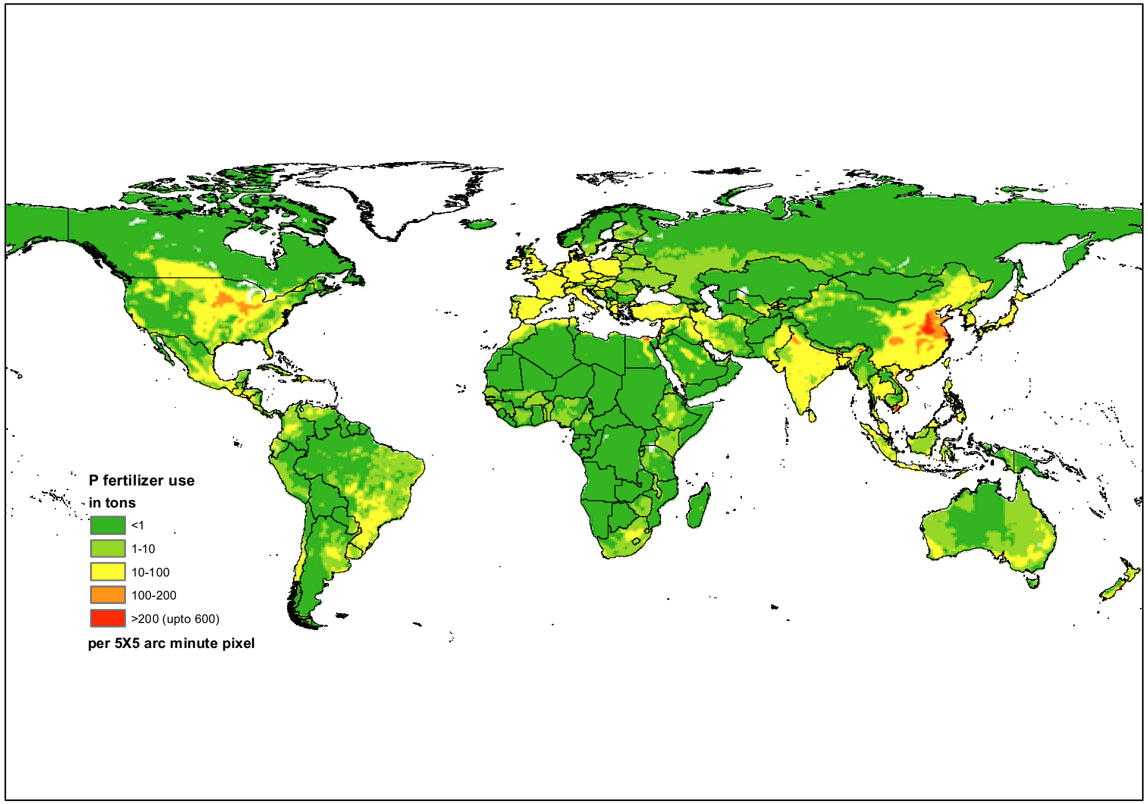

Source: WBCSD Nexus Model, prepared by Resourcematics Ltd., 2013

[29] Bindraban et al. 1999; Breman et al. 2001, [30] Kelly 2006, [31] Pretty et al. 2006; Pretty et al. 2011; Tilman et al. 2011, [32] Molden et al. 2010

# SMART CROP MANAGEMENT

Figure 3b

## Spatial patterns of phosphorous fertilizer use




Source: WBCSD Nexus Model, prepared by Resourcematics Ltd., 2013

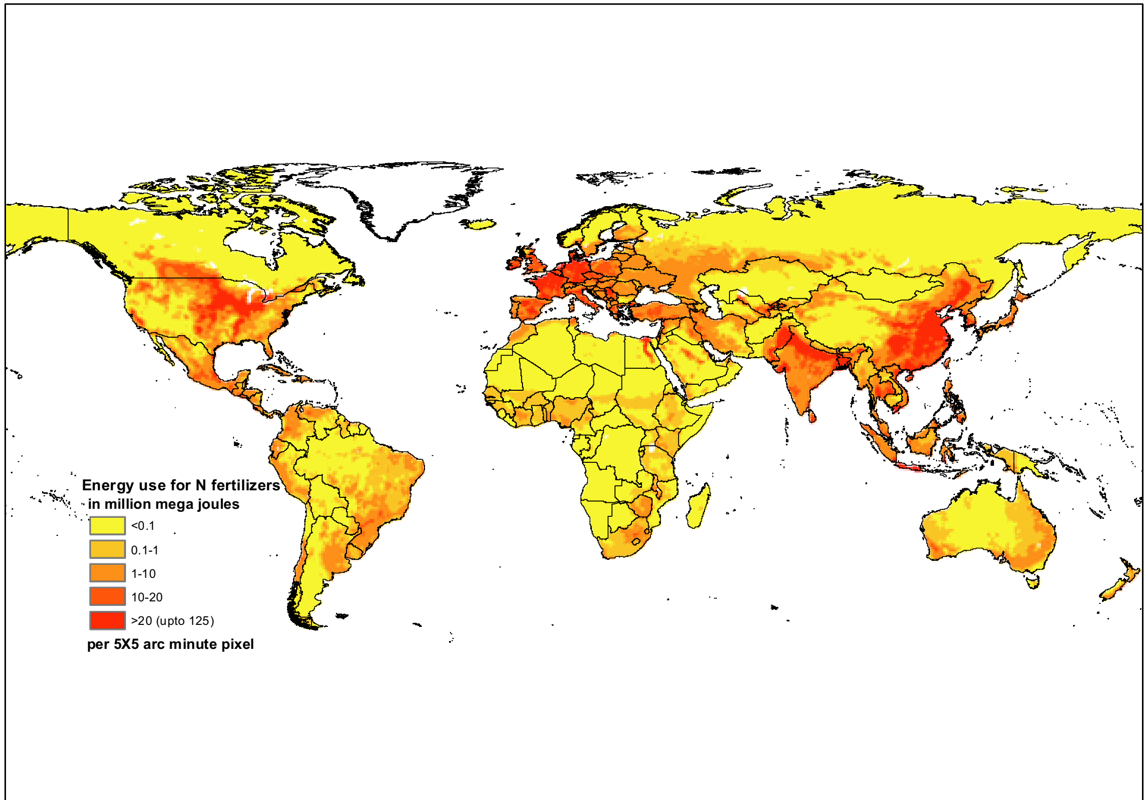
Meanwhile, in several parts of the world, fertilizer is overused, particularly in parts of China, India, North America and Europe (see figures 3a and 3b). As fertilizer production uses significant amounts of energy (1.1% of global energy consumption[33]), using fertilizer more efficiently will reduce agricultural energy consumption. Figure 4 shows energy-use spatial patterns for nitrogen production through application at field level.

[33]Dawson and Hilton 2011

# SMART CROP MANAGEMENT

Figure 4

## Spatial patterns of energy use for nitrogen fertilizer




Source: WBCSD Nexus Model, prepared by Resourcematics Ltd., 2013

What change is expected in energy consumption if fertilizer use is reduced by 30% and 60% by 2025 and 2050 respectively in the regions where it is over consumed, coupled with increases in fertilizer use in sub-Saharan Africa and Latin America? In sub-Saharan Africa, the FAO[34] estimates increases in fertilizer consumption of 78% and 143% by 2025 and 2050 respectively. In Latin America, increases of 63% and 88% are expected by the same years. Results based on the Nexus Model[35] are quite striking. Despite consistent increases in fertilizer use in sub-Saharan Africa and Latin America, fertilizer reductions in over-consuming regions would result in global energy savings of around 1,000 and 2,000 billion megajoules (MJ) by 2025 and 2050 respectively. Global savings in energy use for fertilizers by 2025 could be equivalent to Spain's current yearly electricity consumption, whereas the energy saved by 2050 could be compared to that of Germany's annual electricity consumption. In China alone, energy saved from a 30% reduction in fertilizer consumption corresponds to the total yearly electricity consumption in Mexico.

[34]FAO 2012, [35]Calculations based on spatial data of fertilizer use from Potter et al. 2010

## SMART CROP MANAGEMENT

What is even more important is that overuse of fertilizers contributes to anthropogenic influxes of nitrogen and phosphorus. These are negatively affecting many Earth systems in the form of groundwater pollution, eutrophication, reduced or depleted oxygen in water bodies causing extinction of species and land degradation.[36] The heavy use of nitrogen fertilizers has also caused widespread soil acidification in China. A study comparing two soil surveys – from the 1980s and 2000s in China – found that in many areas soils have become too acidic to grow maize, tea and some other tree crops.[37] Similarly, the widespread use of fertilizers in India has been blamed for soil deterioration. Moreover, efficient fertilizer use will also reduce nitrous oxide emissions, which are among the most active greenhouse gas emissions. Also, mixed farming (**Solution Area 3**) and better soil moisture management (**Solution Area 5**) can go a long way towards capturing natural nitrogen in the soil rather than applying fertilizer.

Studies in developed economies have estimated that up to 45% of fertilizer use can be reduced by more precise application (in terms of time, quantity and type) and by applying alternatives. In rice systems, on average about 65% of the applied nitrogen is lost to the environment.[38] Moreover, greater returns are achieved with first increments in added nitrogen, but at higher applications the curve turns negative,[39] suggesting that further applications are not as effective at increasing yields.

In many instances, integrated nutrient management (INM) appears to be a viable way forward. INM uses complementary measures – both natural and man-made sources of soil nutrients and mechanical measures – while considerable attention is paid to timing, crop requirements and agro-climatic considerations.[40] Real-time crop sensors for site-specific application of nitrogen are a breakthrough in precision agriculture[41] and allow for significant improvements in nitrogen use efficiency (see box 3).

The combination of mineral and organic fertilizers shows sustained yields in the long run compared to just mineral fertilization, as well as increased crop production per unit of synthetic fertilizer applied.[42] Inorganic fertilizer combined with green manure leads to increased yields in rice-groundnut cropping.[43] They registered yield increases of 1.6 t/ha and 0.25 t/ha for rice and groundnut respectively.

[36]Rockström et al. 2009, [37]Guo et al. 2010, [38]Pathak et al. 2010, [39]Tilman et al. 2002, [40]Gruhn et al. 2002, [41]Singh et al. 2006, [42]Gruhn et al. 2000, [43]Prasad et al. 2002

## Chemigation allows for a more precise application of agro- chemicals, thus reducing energy use (fewer chemicals, less tractor movements) and increasing yields.

Chemigation is a technique developed over the last three decades that consists of incorporating any chemical (e.g., fungicide, insecticide, herbicide, fertilizer, soil and water amendments) into the irrigation water. As such, it is often combined with **Solution Area 4: better blue water management**. Chemigation allows for a more precise application of agro-chemicals, thus reducing energy use (fewer chemicals, less tractor movements) and increasing yields.[44] A chemigation system typically includes an irrigation pumping station, a chemical injection pump, a reservoir for the chemical, metering and monitoring devices, a backflow prevention system and safety equipment. Progress in equipment technology leads to increased precision and effectiveness. The latest chemigation systems are designed to work with different chemicals simultaneously. The chemical's distribution uniformity is directly related to irrigation uniformity, which is dependent on a number of factors (i.e., wind, pressure differences in the emitting lines, clogging of emitters, unlevelled soils and soil infiltration rate).

With fertigation, fertilizers can be applied with irrigation water on demand during periods of peak crop demand at or near the roots and in smaller doses, which ultimately reduces losses while increasing yields and quality of product.[45] If properly designed and scheduled and also taking into consideration soil properties,[46] fertigation systems allow for the more efficient application and use of nitrogen,[47] thereby reducing its leaching and runoff. This is of particular relevance amid rising concerns about environmental degradation and water pollution by nitrates and other nutrients, such as phosphorus. However, micro-irrigation systems should be carefully managed and maintained to not contribute to water pollution if water and nitrogen doses are excessive.[48]

[44]Burt 2003, [45]Tilman et al. 2002, [46]Gärdenäs et al. 2005, [47]Singandhupe et al. 2003; Hou et al. 2007, [48]Hanson et al. 2006

Box 3

## Crop sensors for real-time and site-specific fertilizer application

The underlying premise is that canopy reflectance in the red and near-infrared varies according to the plant's nutrient status among several other factors.

Crop sensors measure the optical reflectance of crop canopy and a nitrogen-sufficient reference strip in an area of corn plants that has been well fertilized since planting. A sensor controller receives, stores and analyzes data received from the sensors, including position data. According to the difference in sensor measurements between the nitrogen-sufficient reference and the crop, the sensor controller sends signals to the fertilizer applicator that releases the amount of fertilizer needed in a specific site. Sensors can be carried by either a center pivot system to apply the fertilizer through the irrigation system, or sensors can be mounted on a tractor-drawn fertilizer applicator. Field tests carried out on corn by DuPont show increased gross income and 50% higher nitrogen use efficiency in sensor treatments with respect to the nitrogen-sufficient reference.[49]

## Smart fertilizers

Considerable research is devoted to the development of smart fertilizers. A smart nitrogen fertilizer incorporates a mechanism controlling nitrogen release based on crop requirements. This reduces unproductive losses, such as leaching and atmospheric emissions, while increasing nutrient-use efficiency and yields. The major mechanisms used are: 1) slow and control mechanisms; 2) nitrification inhibitors; and 3) urease inhibitors. Based on these mechanisms, a wide variety of smart fertilizers have been developed.

Improving the efficiency of nitrogen fertilizers reduces the total amount of nitrogen applied and, by doing so, reduces the energy input in agriculture (see **Annex C**). Nitrogen inhibitors also reduce GHG emissions in the form of nitrous oxides. Advances in biochemical research and development may produce smart fertilizers that increase soil's organic matter and water retention capacity, thus limiting the leaching of water and nutrients. Increasing soil's organic matter also reduces $CO_2$ emissions into the atmosphere.

[49] DuPont Pioneer 2013, unpublished

Box 4

## A fungus to enhance phosphorus availability

JumpStart, developed by Novozymes, offers a solution to low phosphorus availability in the soil. It contains a naturally occurring fungus, *Penicillium bilaii*, which helps increase the amount of phosphorus readily available to plants by releasing bound phosphorus from the soil. By increasing the availability of soil and fertilizer phosphorus, it improves the efficiency of conventional fertilizers while improving plant health and increasing yields. Increases of 6-7% have been reported. It works effectively in soils within a wide pH range and at low soil temperatures when phosphorus availability is increasingly limited. JumpStart has been shown to offer the equivalent of an extra 8 kg/ha of phosphate.[51]

Much attention is being paid to the phosphorus cycle. Phosphorus is a non-renewable and limited resource[50] that is essential for agricultural productivity, and its use has to become more efficient. Only a small part of the phosphorus pool in the soil is now readily available to plants; the rest is precipitating or being adsorbed by colloids. The efficiency of phosphate fertilizer use is generally low: 10-25%. Technological advances in phosphorous fertilization include, for instance, products that contain a natural fungus that releases bound phosphorus from the soil, making it available to plants (see box 4). Other solutions involve phosphorus coating with polymers that reduce precipitation or adsorption and improve plant phosphorus recovery over a longer period.

[50]Fischer et al. 2010, [51]WBCSD 2009

## Use of rock dust bio-fertilizers

Using alternative sources of nutrients can further reduce fertilizer use in agriculture. A promising option, already known in ancient times, is the application of stone meal or rock dust. In Brazil, rock dust is used at scale to re-mineralize intensively exploited lands. This has served as an example for other parts of the world.

Phosphorus deficiency is the most limiting factor for legume productivity in tropical soils. Rock phosphate deposits in environments that favor biological or chemical mineralization have been found useful in parts of Africa.[52] Apart from rock phosphate, there are a large number of other mineral deposits that can be used beneficially, such as basalt or granite dust.

Rock dust (or stone meal) is best used in combination with bio-fertilizers. The combination is able to supply a range of micronutrients (e.g., S, Ca, Mg, B, Cl, Cu, Fe, Mn, Mo, Ni, Zn), in addition to the macronutrients (N, P and K) required for optimal crop growth, while also improving the physical, chemical and biological quality of the soil.

At field level, these effects bring a number of benefits, such as improved workability of heavy clay soils, improved water holding capacity of the soil (sandy and clay soil), increased quality of yields of cultivated crops and decreased spending on conventional fertilizers. Rock dust addresses four global challenges:

1 It increases production and food quality;

2 If rock dust is obtained as a byproduct of mining and quarry sites, its production is energy neutral;

3 In the case of some parent rocks (e.g., olivine and serpentine), it sequesters carbon;[53]

4 It reduces water consumption due to better soil water retention, though in relatively small amounts, with the exception of the use of zeolites or bituminous soils (see **Annex D**).

The use of rock dust in combination with bio-fertilizers is particularly promising where other sources of nutrients are unavailable. A case in point is Africa, where there are no fertilizer plants but mines or quarries that can provide the source minerals. Some key figures on the impact of rock dust applications include:

- Serpentine and olivine are able to dispose of 0.5 and 0.67 t $CO_2$/t weathered rock respectively; and
- The nutrient delivery capacity of the soil is enlarged: the application of 10 t/ha of basalt dust on clay soils reduces the phosphorous application requirement by 170 kg/ha of super phosphate.

[52] Inter Academy Council 2004, [53] "Mineral $CO_2$ sequestration" is an alternative sequestration route in which $CO_2$ is chemically stored in solid carbonates by the carbonation of minerals. The process utilizes a solution of sodium bicarbonate ($NaHCO_3$), sodium chloride (NaCl), and water, mixed with a mineral reactant, such as olivine (Mg2SiO4) or serpentine [Mg3Si2O5(OH)4. Carbon dioxide is dissolved into this slurry, by diffusion through the surface and gas dispersion within the aqueous phase. The process includes dissolution of the mineral and precipitation of magnesium carbonate ($MgCO_3$) in a single unit operation.

There is a large body of literature underscoring the potential and benefits of organic fertilization as a means of improving soil structure and fertility, reducing soil erosion and stimulating biodiversity.

The most common alternative to chemical fertilizer use is greater reliance on intercropping, green manure, the use of manure and compost teas, nitrogen fixing rotations and better soil water table management to stimulate biochemical processes. There is a large body of literature underscoring the potential and benefits of organic fertilization as a means of improving soil structure and fertility, reducing soil erosion and stimulating biodiversity. Research also shows yield gains from organic fertilization. A study on the impacts of composting on several pulses and cereals found that yields more than doubled.[54] Undoubtedly, the employment of organic fertilization methods depends on the local availability of manure, the inclusion of legumes in the cropping pattern, labor availability, etc. Newly developed technologies allow for the re-use of nutrients contained in municipal organic waste and agricultural residues through composting or biogas digestion. Much innovation is expected to come in the near future from biogas technology. The use, for instance, of digested bio-plastic as a fertilizer is a very promising, though still embryonic, new option to be developed.

## Bio-stimulants

There is a range of elements that stimulate plant growth if applied in the right doses. The positive stimulation of plant stress resilience has been reported for a number of fungi-based compounds, particularly the class of strobilurines produced by the fungus *Strobilurus* that have a suppressive effect on other fungi. Such products are already marketed in a number of areas but are unknown and untested elsewhere. One claim is that they contribute to higher resistance to drought-induced stress. Yield increases of up to 10% under water-stressed conditions can be achieved according to field trials.[55]

Another bio-stimulant is the use of micronutrients, such as zinc and boron. This method is considered a major winner leading to more vigorous growth and higher quality, more resistant crops. Again, while the management of micronutrients is popular in North America and Europe, for instance, they are not well-known elsewhere.

[54] Edwards et al. 2007, [55] Beck et al. 2002

## Improved disease control

Integrated pest management (IPM) as opposed to single pest control methods is a strategy that combines a larger range of cultural, biological, mechanical and chemical tools and practices. It relies on a deep understanding of pathogen life cycles and plant-pathogen interactions. By rationalizing chemical interventions and doses, IPM aims to use resources more efficiently, reducing costs and environmental and health externalities. IPM includes four steps: 1) setting an action threshold; 2) monitoring and identification of pests; 3) prevention; and 4) control. Prevention methods encompass several practices using pest-resistant crops, including rotations, intercropping and using certified and pest-free planting material. These methods can be very effective and cost-efficient while preserving the environment and human health. Similarly, any method for early monitoring and pest detection is crucial in preventing the outbreak of devastating diseases and avoiding cost-intensive measures.

An example of this is an early warning system developed by Syngenta in collaboration with Manchester University and Rothamsted Research (see box 5).

Once the threshold for action has been reached, various control methods are available, starting with the least risky pest control methods, such as pheromones for pest mating or mechanical control. If these are not working, then, targeted pesticides may be applied. Broadcasting and non-specific pesticides are the last resort.[56] Several studies confirm the potential and profitability of this approach.[57] IPM has found wide application in Asia and Africa, often promoted in farmer field schools as part of programs aimed at social and human development. Rice yields in Mali have been reported to rise from 5.2 to 7.2 t/ha and in Senegal from 5.19 to 6.84 t/ha, with up to 90% reductions in pesticide use.[58]

By rationalizing chemical interventions and doses, IPM aims to use resources more efficiently, reducing costs and environmental and health externalities.

[56] US EPA n.d. [57] Dasgupta et al. 2007; Dhawan et al. 2009; Pretty et al. 2011 [58] Pretty et al. 2011

Box 5

## Networked mimic sensors for crop enhancement and disease control

SYIELD networked mimic sensors are an early warning system consisting of a network of sensors that can monitor diseases carried by the wind 24 hours a day, seven days per week. Based on knowledge of host-pathogen interactions, Syngenta engineered environmentally tolerant mimic surfaces that trick the pathogen into germination on the sensor cartridge. This occurs at the same time or prior to disease progress in the bulk crop. The mimic surface, together with detection of a specific pathogen's factors, forms the basis of the biosensor specificity. This technology is now being tested in a pilot project known as SYIELD, in consortium with Manchester University and Rothamsted Research, to detect the fungus sclerotinia, which causes stem rot in oilseed rape. Setting up a network of devices to detect this disease would help provide an early alert along British shores. U.K. technology companies will manufacture the in-field nodes, which house the disposable sensor cartridge, micro air sampler, intelligent interface electronics and telecoms modules. These will link, alongside satellite crop-usage data, to a geographic information system web portal accessible as a commercial service to farmers, agronomists, government and other agri-food stakeholders. The project will enable growers to produce more food from fewer inputs through an integrated farm management strategy. Syngenta is in discussions on how to develop SYIELD to combat other diseases. These could include the wind-spread fungi that cause chestnut blight, feared to be a major threat to trees in the U.K., and pine pitch canker.

## Nanotech pesticides

Despite global pesticide use of 2.5 million tonnes every year, production losses as a consequence of plant pests remain in the order of 20-40%.[59] Oerke[60] estimates total[61] losses of 28% for wheat, 37% for rice and 31% for maize.

Conventional pesticides are strongly associated with environmental degradation and health hazards. This is due to pesticide toxicity, non-biodegradability, the impreciseness of some formulations, and leaching and other losses during application. This combination of side effects and low efficiency is the imperative for rethinking conventional pesticide use, the aim being to halve current losses.

Breakthroughs in pesticide control are expected in the field of nanotechnology. Nanotechnology refers to a range of techniques for manipulating materials, organisms and systems at a scale of 100 nanometers or less.[62] Nanopesticides contain nanoscale chemical substances. The theoretical advantages are: 1) increased efficacy, stability or dissolvability in water as compared to larger-scale molecules of the same chemical substances and 2) controlled release of pesticides due to the nanoencapsulation of pesticide substances (see **Annex E**). Some smart pesticides can release their active ingredient only when inhaled by insects.[63] Nanopesticides are also better combined with genetically engineered insecticide-producing crops and genetically engineered herbicide-tolerant crops. Nanopesticides are still in the experimental stage: one issue to be resolved is precautionary concerns on the release of the particles in a larger environment.


[59] FAO 2011a, [60] Oerke 2006, [61] Globally, cereal crops losses from weeds are estimated at 8-11%; from animal pests 8-15%; from pathogens 9-11% and from virus strains 1-3%.
[62] One nanometer is equivalent to one billionth of a meter. [63] Kuzma and VerHage 2006

# SOLUTION AREA 3
# MIXED FARMING SYSTEMS

# MIXED FARMING SYSTEMS

The focus of research and agricultural development in recent decades has been on increasing yields and improving farming technologies for a reduced number of crops, preferably those grown in monocultural systems. This has largely overlooked the benefits and potential of multiple cropping and agroforestry systems, not only for ecosystem services provided by increased biodiversity, but more importantly in terms of pest control, improved resource-use efficiency and resilience in resource-limited environments (see **Annex F**). Moreover, in the face of increasing demands for food, by intensifying crop production in time and space, multiple cropping systems are a means to maximize land productivity.[64]

Table 4

**Potential and impacts of mixed farming systems**

| | Spread | Yield | Energy | Water | Climate |
|---|---|---|---|---|---|
| **Multiple cropping** | | | | | |
| Intercropping for disease control and enhanced fertilization | Sub-Saharan Africa/ Asia/Latin America | Higher yields/unit area; 89% higher for glutinous rice[i] | Up to 50% nitrogen savings in legume-cereal systems[ii] | 18-99% water savings[iii] | |
| **Agroforestry** | | | | | |
| Bioenergy-wood-food production systems | Sub-Saharan Africa/ Asia/Latin America | 20-60% higher productivity, expressed in land equivalent ratio (LER)[iv] | | Soil moisture conservation and groundwater recharge | Carbon sequestration |

Sources: [i]Zhu et al. 2000; [ii]Venkatesh and Ali 2007; [iii]Gliessman 1985, Morris and Garrity 1993, Tsubo et al. 2003; [iv]Werf et al. 2007, Smith 2010, Dupraz and Talbot 2012.

[64]Gliessman 1985

## Multiple cropping

Multiple cropping systems build diversification within a field, with the purpose of optimizing ecological synergy between crops. Diversification can be done either in time (i.e., rotations) or in space (i.e., intercropping). When properly designed, this leads to improved nutrient uptake and nitrogen use, increased soil fertility, increased water-use efficiency and reduced incidence of pests. Ecological approaches to pest reduction become important in view of the vulnerability of monocultured crops to pest and diseases.[65] For instance, the simultaneous use of different rice varieties (glutinous and hybrid rice) was tested in China with promising results. Yields of glutinous rice were 89% greater and pest incidence was 94% lower than in monoculture systems. Hybrid (non-glutinous) rice yields were nearly equal to those of monocultures.[66]

Another successful example of mixed cropping comes from mechanized wheat farming in the U.S. By using multiple wheat cultivars and wheat and barley intercropping, disease reduction was larger than with the application of fungicides.[67]

Biological nitrogen fixation by leguminous crops is of great importance. Intercropping of cereal and legumes makes it possible to use significantly less fertilizer without having an impact on yields. In India, nitrogen fertilizer savings of 35-44 kg/ha were registered when a leguminous crop preceded rice or wheat. Intercropping of soybean with maize saved 40-60 kg of nitrogen per hectare.[68] Crops with different nutritional requirements, timing of peak needs and diverse and deeper root structures are grown on the same land simultaneously,[69] thus optimizing nutrient and water use.

Because of the efficient use of residual moisture, water-use efficiency in intercropping is often 18% higher, and sometimes as much as 99% higher, than in sole crops.[70] By optimizing plant architecture and different light requirements, multiple cropping ensures the best use of available light and increases photosynthetic potential.[71] Ultimately, by making the best use of space and labor, multiple cropping systems can offer greater profit per unit area to smallholders. In sub-Saharan Africa and China, one-third of the total cultivated area and half of total yields already come from multiple cropping systems – an opportunity to build on traditional methods.

[65] Waddington et al. 2010; Hartman et al. 2011; Ratnadass et al. 2012, [66] Zhu et al. 2000, [67] Vilich-Meller 1992; Kaut et al. 2008, [68] Venkatesh and Ali 2007, [69] Gliessman et al. 1985, [70] Morris and Garrity 1993, [71] Ibid

Box 6
## The benefits of mixed cropping systems

Researchers at the Centre for Crop Systems Analysis at Wageningen University believe that breeding for combinability in mixed cropping systems is a new agricultural frontier. This means, for instance, synchronizing crop cycles for simultaneous ripening and harvesting, and finding cultivars and species that best exploit synergistic benefits. Labor constraints are a major challenge to the scalability of mixed cropping systems in view of an aging and diminishing farm population. New forms of mechanization will have to provide an answer, such as the use of robotic machines that can handle multiple crops.

### Agroforestry

Agroforestry systems, if well managed, produce food, feed and fiber in proper balance. In agroforestry, trees are included in the cropping system or combined with livestock production in agrosilvopastoral systems. Benefits include biodiversity conservation, water and soil quality enhancement and carbon storage. By supporting a variety of complementary products (i.e., food, feed, fuel wood, timber and energy), agroforestry is an important means to increase smallholder incomes. The case study by ITC presented in box 7 exemplifies this.

Most importantly, agroforestry systems are moldeled to maximize eco-efficiency – reducing the need for external inputs while enhancing nutrient cycling. The observed competition effect between trees and crops for radiation, topsoil water and nutrients, which might translate into lower crop yields, is outpaced by positive effects on soil moisture and nutrient improvement and the reduction of pest pressures. Recent studies on the productivity of temperate silvoarable agroforestry systems show 20-60% higher productivity relative to the respective monocultures.[72] Productivity in multiple cropping systems is expressed by land equivalent ratios (LER), which is the ratio of the area under sole cropping to the area under intercropping needed to give equal amounts of yield at the same management level. It is the sum of the fractions of the intercropped yields divided by the sole-crop yields.

[72] van der Werf et al. 2007; Smith 2010; Dupraz and Talbot 2012

Box 7

## ITC's agroforestry model: Addressing the food-fiber conflict

ITC's paper mill at Bhadrachalam is located in Khammam District, Andhra Pradesh, India, where there are large tracts of land that are unsuitable for agriculture, leading to low productivity and poor returns from traditional cash crops. Here, marginalized smallholders constitute the majority of the population. ITC developed a Social and Farm Forestry Program that assists small landowners in converting their wastelands into pulpwood plantations. The program covers 140,000 hectares so far, engaging 37,000 farm families, sequestering 4,300 kilotonnes (Kt) of $CO_2$, and reducing pressure on public forests.

To ensure the commercial viability of these plantations, ITC's R&D team developed a high-yielding clone stock with shorter harvesting cycles – four years instead of seven years for standard saplings. In partnership with non-governmental organizations (NGOs), households are mobilized to form community-based wood-producers' associations. Through these associations, ITC provides long-term, interest-free loans, a package of extension services, and training in financial management. ITC offers a buy-back guarantee at prevailing market prices, although plantation owners are free to sell to buyers of their choice. The plantations are a life-changing proposition for these low-income households as they generate average net incomes between US$ 460-740/ha/year. Owners are required to repay their loans to their association after the first harvest to build a Village Development Fund used to extend loans for further plantations and invest in community assets. Recently, another innovation is the development of a mixed agroforestry model. In India, the predominant practice of growing pulpwood trees sees 2,200 trees planted per hectare. In this practice, intercropping is possible in the first year of the four-year cycle only. ITC's new mixed agroforestry model is designed to accommodate a slightly lower number of trees (2,000) per hectare with wider spacing by adopting paired row design. In the new design, the land allocated to forestry is only 25% and the remaining 75% is available for agricultural crops. This new design also allows for intercropping throughout the tenure of the tree life cycle. Through agroforestry, the leaf litter increases the carbon content and replenishes soil nutrients, improving soil fertility.[73]

[73] ITC Limited, 2013, unpublished

# SOLUTION AREA 4
# BETTER BLUE WATER MANAGEMENT

## BETTER BLUE WATER MANAGEMENT

The 2007 *Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture,* International Water Management Institute report suggests that 25% of the demand for new food will come from irrigated areas. However, the general consensus is that opportunities to use more "blue water" (either surface water or groundwater) are limited as there is very little renewable untapped water left. The main exception is the use of groundwater and some surface water in parts of Africa and South America. Elsewhere, drying rivers and declining groundwater tables are common. Higher blue water productivity, rather than tapping into new sources, will therefore be the key in the coming decades. More productive irrigated agriculture will enable the availability of water for other uses. Water productivity varies largely across crops and locations: for wheat, the range is 0.66-4.0 Kcal/m$^3$ water; for rice 0.5-2.0 Kcal/m$^3$ water; for corn 1.0-7.0 Kcal/m$^3$ water; for lentils 0.8-3.2 Kcal/m$^3$ water; for groundnut 0.8-3.2 Kcal/m$^3$ water; and for apples 0.52-2.6 Kcal/m$^3$ water.[74] Much of the variability relates to different management practices, suggesting substantial room for improvement.

Advances in blue water use can achieve several outcomes at the same time. For instance, precision irrigation saves water, reduces fertilizer use and increases yields. Effects not related to water savings are often the most interesting as they have more economical impacts (greater yields and savings on agrochemicals).

In improving the productivity of blue water, some of the most promising options are:

- Increasing the use of pressurized and precision irrigation;
- Improving the management of large irrigation schemes, including the conjunctive use of surface water, groundwater and drainage;
- Adopting water-saving technologies in irrigated rice.

Several of these water management improvements are energy neutral or energy positive while contributing to higher yields.

**More productive irrigated agriculture will enable the availability of water for other uses**

[74] Molden et al. 2010

Box 8

## The big unknown: Desalination as new agricultural water?

Besides managing conventional water sources better, the use of non-conventional sources, such as saline water, is gaining increasing importance. At present, the high energy costs related to desalination limit its broad application in agriculture to high-value horticulture in extremely water scarce situations.

Dow Chemical believes seawater desalination holds great promise in taking potable water to cities and villages (it strives to purify 97% of the world's water locked in salinity). Today, reverse osmosis provides about 2% of potable water. Dow has developed more cost-efficient technologies, making desalination a more affordable and appropriate option in developing countries, such as Ghana.[75]

Advances in membrane technologies by Dow Chemical have slashed costs from US$ 2.43 to \$0.65/m$^3$ water. The cost for agricultural use is still mainly prohibitive, but this may change. If so, it would cause a minor revolution, but it would also increase the energy footprint of agriculture considerably.

Compared to desalination, wastewater treatment is much cheaper and consumes less energy just because wastewater and brackish water contain less salt than seawater. Wastewater, if appropriately treated, constitutes an important source of irrigation water that could free large shares of freshwater for other, more valuable uses.

[75] WEF 2011

Table 5
**Potential and impacts of better blue water management**

| | Spread | Yield | Energy | Water | Climate |
|---|---|---|---|---|---|
| **Precision irrigation** | | | | | |
| Precision systems – i.e,. drip, micro-sprinkler combined with fertigation | Still on less than 2% of irrigated area; groundwater systems (40%), horticulture | 10-54% higher in vegetables | 29-44% energy savings[i] | 30-70% water savings but also less recharge[i, ii] | |
| **Conjunctive water use and drainage** | | | | | |
| Balanced delivery of surface and groundwater, reduced water logging | Asia (22% under conjunctive use)/ sub-Saharan Africa | 20-130% higher for rice;[iii] 54% for sugarcane; 64% for cotton; 136% for wheat[iv] | | 20% savings[v] | |
| **Water-saving rice systems** | | | | | |
| Aerobic rice; alternate wetting and drying irrigation (AWDI); direct seeding | Asia/sub-Saharan Africa/Latin America | 5-15% higher[vi] with AWDI; aerobic rice yields 20-30% lower than lowland varieties, but water productivity is 32-88% higher[vii] | 60% savings with direct seeding;[viii] 26% higher nitrogen use efficiency[v] | 20-60% saving with direct seeding;[viii] 15-30% savings with alternate wetting and drying;[ix] 30-60% savings with aerobic rice[vii] | 18-50% less methane emissions;[x] aerobic rice 80-85% less methane emissions than lowland rice[vii] |

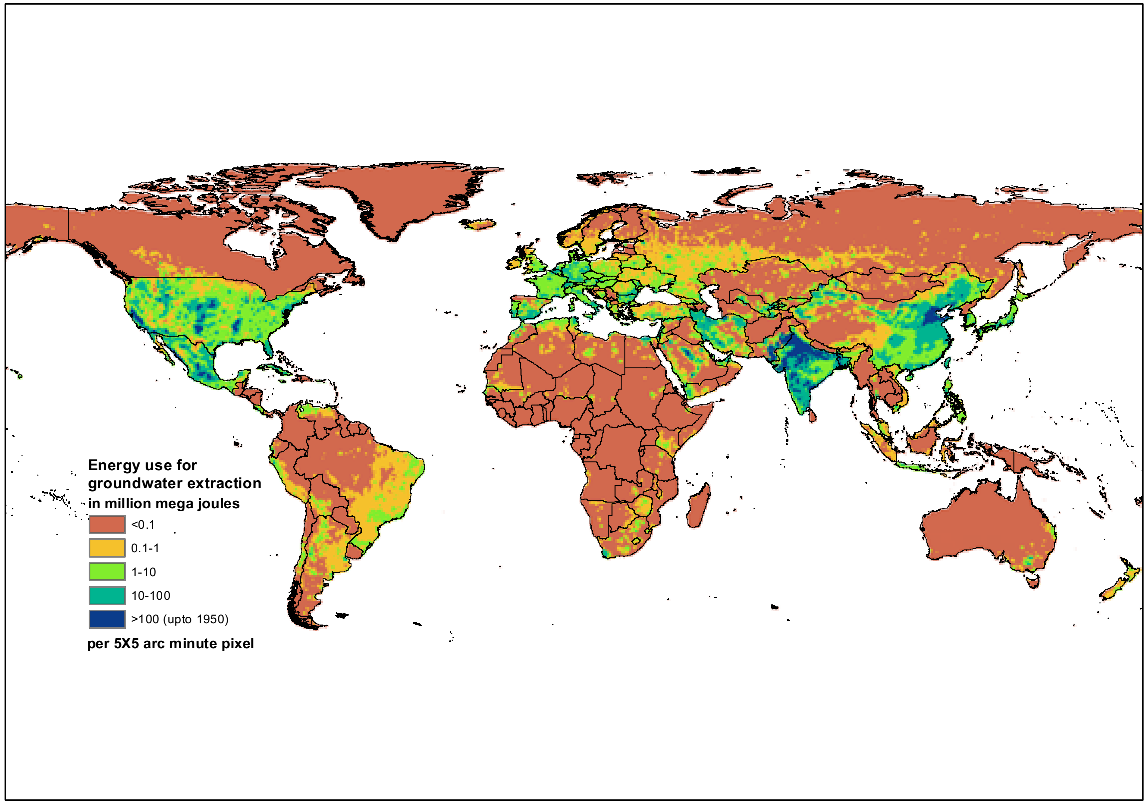
Sources: [i]Narayanamoorthy 2007, Radstake and van Steenbergen 2013; [ii]Lamont et al. 2002; [iii]Borgia et al. 2012; [iv]Ritzema et al. 2008; [v]Gohar et al (forthcoming); [vi]Jothimani and Thiagrajan 2005; [vii]Pinheiro et al. 2006, Parthasarathi et al. 2012; [viii]Gupta et al. 2006, CA 2007, Pathak et al. 2011; [ix]Tabbal et al. 2002, Belder et al. 2004; [x]Li et al. 2002, Wang et al. 2001, Kumar et al. 2008.

## Precision irrigation

Conventional field irrigation methods, though largely embedded in local practices, tend to over use water as they have an average application efficiency of 40-50%, depleting ground and surface water. They also use a huge amount of energy for the pumping of irrigation water. Energy use for groundwater pumping is particularly intense in India, China and parts of the U.S. (see figure 5). In contrast, pressurized irrigation technologies have field-level application efficiencies of 70-90% as surface runoff, deep percolation and evaporation losses are minimized.

Figure 5

**Spatial patterns of energy use for groundwater extraction**




Source: WBCSD Nexus Model, prepared by Resourcematics Ltd., 2013

Drip and sprinkler irrigation are common technologies, yet there are other available systems, like root zone irrigation, micro-sprinklers, spring and bubbler irrigation. Studies on corn show water savings of 40% without substantial effects on yields when using subsurface drip irrigation, probably one of the most advanced field irrigation technologies available. Micro-irrigation allows for optimal management of the root zone: water, fertilizers and pesticides are used more efficiently, which ultimately reduces non-point source pollution (see Annex G). Box 9 exemplifies the benefits of micro-irrigation systems developed by Jain Irrigation System Ltd.

Box 9

## A micro-irrigation solution to macro water depletion in India

Agriculture in India consumes 28% of national electricity production,[76] much of it for irrigation water pumping. As an alternative to conventional surface irrigation methods at the field level, Jain Irrigation System Ltd. developed micro-irrigation systems (MIS) that are tailored for small farmers and allow for substantial water and energy savings and increased yields. Water savings can range between 12% and 84% per hectare, depending on the crop used.[77] This system has gained wide popularity in areas of acute water scarcity and in areas where horticultural and commercial crops are grown.

Additionally, Jain developed on-demand irrigation systems that minimize canal irrigation losses. In this system, field-level canals are equipped with small water-storage ponds, and water is conveyed to the field through a piped network and applied to the crops' root zone through a micro-irrigation system. Solar pumps married with drip irrigation can be a powerful option in arid and semi-arid areas for crops, such as cotton, and in orchards that require water at critical stages for survival and to attain optimum yield. Jain believes that rather than giving free electricity to farmers, a more sustainable option could be to subsidize solar pumps. Jain is also engaging closely with the governments of Andhra Pradesh, Rajasthan and Karnataka in the development of innovative irrigation solutions that could create renewed interest among many stakeholders.

[76]GOI 2008, [77]Narayanamoorthy 1996

Pressurized systems work well in groundwater irrigation, but their application with surface water sources is less straightforward.

At present, pressurized systems cover less than 2% of the global irrigated area – around 40 million hectares. Therefore, there is great scope to expand the area using this technology. In the North China Plain, for instance, where groundwater tables are rapidly declining, the Asian Development Bank is promoting irrigation-efficient technologies for small farmers and the results are promising.[78] According to the Nexus Model, by 2025, the total volume of water saved in China if pressurized irrigation were to double[79] from 2000 levels corresponds roughly to the country's industrial water use or about one-third of its agricultural water use.[80] Similarly in India, the largest consumer of water for agriculture in the world, water savings by 2025 could amount to twice the total industrial and domestic water consumption combined, and about one-third of its agricultural water use.[81] These numbers emphasize the incredible potential gains in water productivity by adopting water-saving technologies and informed policymaking and investment.

Yet context-specific considerations are important. Pressurized systems work well in groundwater irrigation, but their application with surface water sources is less straightforward. There is also a difference between "gross benefits" and "net benefits" depending on what fraction of the water loss can be easily recovered and reused. Efficient pressurized systems have a bonus added value where seepage is to non-usable groundwater sources (very deep or saline groundwater systems). In some cases, the introduction of efficient irrigation triggers even more water consumption as it becomes possible to irrigate land that earlier could not be reached.

The large gain with micro-irrigation may come less from water savings and more from the higher yields associated with more precise water applications, particularly in horticulture, where 10-54% higher yields are possible.[82] Precision irrigation reduces the incidence of fungi in vegetables or losses at early fruit development stages. However, in salt-affected lands or in the presence of saline irrigation water, drip irrigation leads to the accumulation of salts in the root zone with negative impacts on crop growth and yields.

[78]Radstake and van Steenbergen 2013, [79]Projections based on ICID 2012, [80]FAO-AQUASTAT 2013, [81]World Bank 1999, [82]CA 2007; Knoop et al. 2012

## Conjunctive water use and drainage

There is considerable scope to improve water management in large surface irrigation systems that are common in Asia and North Africa. Water logging is estimated to affect 24% of the global irrigated area.[83] This is very much the result of inadequate irrigation management or insufficient investment in drainage. As opposed to irrigation, drainage and its effects on scheme performance has so far received little attention[84] despite its primary role in guaranteeing the sustainable use of irrigated land, avoiding water logging and salinization.[85] Insufficient drainage was found to be a primary cause of low and variable yields in large irrigation systems in the Sahel.[86]

An important breakthrough would be the conjunctive management of surface and groundwater – balancing surface water deliveries with groundwater (re)use and leaching requirements. In most large irrigation systems in South Asia there is now a "conjunctive reality" with more than half of the supplies coming from groundwater – essentially seepage water brought back into productive use.[87]

The combined use of ground and surface water in the world's largest irrigation systems can significantly contribute to higher crop yields (see **Annex H**).

For instance, the drought that affected Pakistan and India between 1999 and 2003 meant a decrease of 20% in surface water supplies. At the same time, as more use was made of groundwater, it resulted in an increase in production of 5-10% that reduced the negative effect of water logging on yield. In the southern Pakistani province of Sindh, the area facing water logging problems shrank from 40% to 5% of the irrigated area. The same has also been reported in parts of India, such as the Krishna Delta in Andhra Pradesh. Thus, the argument for conjunctive management concerns higher yields, water savings and reduced methane emissions from waterlogged lands.

[83] FAO 2011b, [84] Smedema and Ochs 1998, [85] Smedema et al. 2000, [86] Vandersypen et al. 2006 2007; Borgia et al. 2012, [87] Shah 2006

## Water-saving rice systems

Irrigation is the largest water consumer (70% of the world's freshwater withdrawals). Within irrigation, the cultivation of paddy fields is the largest single user (between a quarter and a third of total freshwater withdrawals)[88] and where the largest gains are possible. A common cultivation practice is keeping rice fields perpetually inundated. This practice suppresses weeds, yet in many circumstances this function can be substituted by better weed control. If paddy fields are alternately wetted or dried, roots will develop deeper without jeopardizing yields. In fact, in alternate wet and dry systems – promoted for instance in the System of Rice Intensification (SRI) – yields may be higher (5-15%) with significantly reduced water consumption (20%) and much higher nitrogen-use efficiency (26%).[89] Yet more weed development and a wider weed spectrum may require increased use of herbicides[90] or more and better weeding. The technique of direct seeding (see Annex I) will also improve the effective use of rainfall and reduce irrigation needs[91] (see box 10).

Box 10

### Direct seeding saves water and reduces methane emissions

India, with its 44 million hectares of land under rice cultivation, is one of the world's largest rice producers. Traditional growing involves rice seeding in nurseries and transplanting seedlings in 10 centimeters of standing water. This system is labor and water intensive. In addition, the presence of biomass immersed in water over a longer period leads to 4.5 million tonnes of methane emitted yearly from India's paddies. In direct seeding, dry seeds are sown onto the dry or wetted soil, thus avoiding puddling, transplanting and standing water. Since 2004, PepsiCo has successfully supported direct-seeded rice in a number of initiatives with farmers in India, covering 4,000 hectares total. PepsiCo has also introduced a special tractor coupled with a direct seeding machine that is adjustable according to seed variety, planting depth, and plant-to-plant spacing.

**Key benefits**

- 30% water savings compared to transplanted rice;
- Curbs methane emissions because direct seeding does not require standing water at the base of the crop.[92]

[88] CA 2007, [89] Jothimani and Thiagrajan 2005, [90] CA 2007, [91] Cabangon et al. 2002, [92] PepsiCo 2010

Although there are varieties of rice that consume less water and are to a certain extent drought tolerant, such as upland varieties, these do not yield nearly as much as lowland rice.[93] Aerobic rice is not drought tolerant, although it consumes less water than traditional lowland rice, and because of this it can be irrigated instead of flooded. Additional research is needed to understand drought tolerance mechanisms and rice response to water. Ongoing research is seeking to transform rice into a crop that consumes the same amount of water as other cereals (box 11).

Box 11

## Growing rice like wheat

Most of the arguments for flooding rice are agronomic (i.e., soil labor, weed control, valorization of monsoon areas) rather than physiological. So why not transform rice into a plant like wheat, reducing the total amount of water used from 2,000-5,000 to just 1,000 liters?

This is the ambitious research carried out by the Plant Research International Group at Wageningen University, together with the International Rice Research Institute, the University of Guangzhou and the University of Bangalore.

The program consists of two basic approaches. The first involves making a morphological and physiological comparison of wheat and three types of rice with varying water requirements (the sawah type, dry rice, and a new hybrid type known as aerobic rice) with a number of closely related types of rice. Desired features are then related back to specific genes. A second approach will analyze the genetic characteristics of a wide population of rice species and selections. Genetic differences are then related to certain phenological and physiological features. Looking at these transformations is important for business as the amount of water potentially "freed" if rice were to be grown like wheat could be invested in other, more valuable uses, or for diversification into cash crops.

[93] van der Hoek et al. 2001

## BETTER BLUE WATER MANAGEMENT

Beyond new varieties or water-saving technologies, water productivity can be improved if best management practices are applied to increase yields. For this, training and access to products, services and information are crucial. As an example, in 2012 Syngenta set up a project to provide smallholder rice farmers in India with the products and services needed to increase their productivity and profitability. Together with a local partner, Syngenta provides training and information technology tools to young extension workers who work closely with farmers, capturing their needs and data. Farmers then work with Syngenta's agronomic advisory teams, a local financial institution, or Syngenta's Centre of Excellence to make sure the required products are delivered to farmers.[94]

Inundated rice not only uses more water than physiologically required, it also accounts for 15-20% of human-induced methane emissions,[95] amounting to approximately 50-100 million tonnes of methane emissions per year. The warm, waterlogged soil of rice paddies provides the conditions for methanogenesis, and although some of the methane produced is oxidized in the shallow overlying water, the vast majority is released into the atmosphere. Dry rice cultivation and the use of aluminum sulfate may reverse the process of methane emissions.

[94] Syngenta 2012a10, [95] Sass and Fischer Jr. 1997

# SOLUTION AREA 5
# BETTER GREEN WATER MANAGEMENT

Rainfed systems produce 58% of global food. By 2050, the area under rainfed cropping is expected to increase by some 70 million hectares,[96] making an increasingly important contribution to soaring demand for food. Yet much of this depends on how well soil moisture, i.e., green water, is managed. A series of breakthroughs have already been made – some already applied at scale and others with the potential to make a significant impact. Most of these are energy neutral – they will increase yields with no additional energy inputs.

[96] FAO 2012

## BETTER GREEN WATER MANAGEMENT

Table 6

**Potential and impacts of better green water management**

| | Spread | Yield | Energy | Water | Climate |
|---|---|---|---|---|---|
| **Conservation agriculture** | | | | | |
| Reduced/zero tillage, cover crops/mulch, rotations | Already widespread but not in sub-Saharan Africa and less in Asia and Europe | 20-90%[i] higher | 40-70% savings[ii] | 25-70% reduced runoff[iii] | 11 t/ha/year $CO^2$ sequestration[iv] |
| **Biodegradable plastic mulching** | | | | | |
| Bio-based and degradable plastic soil cover to reduce evapotranspiration | Widespread; China: biodegradability to be improved | 10-60% higher[v] | 1,400% savings for production compared with petroleum-based[vi] | 40-60% savings[vii] | Sugar beet-based plastics reduce by 65% fossil fuel use compared to LDPE plastic mulch[viii] |
| **Landscape restoration and watershed improvement** | | | | | |
| Landscape measures for water storage and moisture retention | Latin America/Asia/sub-Saharan Africa | LER = 1.2-1.6 with mosaic landscapes[ix] | | Groundwater recharge, moisture retention, less irrigation | Carbon sequestration with reforestation projects (1-10 t/year/ha of $CO^2$) |

Sources: [i]Pieri et al. 2002, Clay 2004; [ii]Jones et al. 2006, Derpsch et al. 2010; [iii]Jordan and Hutcheon 1997, Jones et al. 2006; [iv]Derpsch et al. 2010; [v]Ashrafuzzaman et al. 2010, NCPAH 2011; [vi]Bos et al. 2011; [vii]Feibert et al. 1992, Radstake and van Steenbergen 2013; [viii]Wageningen UR 2011; [ix]Dupraz and Talbot 2012.

## Conservation agriculture

Conservation agriculture is a set of principles[97] whose adoption depends very much on time and space considerations. There are three fundamental principles in conservation agriculture:

1 Reduced tillage (i.e., minimum or no plowing), which increases the biotic activity in the soil. In the long term, it improves soil structure, resulting in improved infiltration and water retention capacity of the soil.

2 Diversified crop rotations, which reduce pest pressure and keep the soil nutrient balance stable. Incorporating nitrogen-fixing legumes in the rotation reduces the need for external fertilizer inputs.

3 Keeping a permanent vegetative cover on bare land, which helps reduce the erosive impact of rain and wind, reduces evaporation, and enhances the structure and fertility of the soil. This can be achieved either by leaving crop residues on the land or by planting a cover crop.

Conservation agriculture can deliver multiple benefits (see **Annex J** and box 12). For the farmer, these are less expenditure for labor, energy and agrochemicals, although this may occur at the expense of yields. With no-tillage, 60-90% of soil erosion could be avoided[98] and runoff could decrease by 40-69%, meaning less diffuse water pollution from nitrates, herbicides and soluble phosphates.[99]

However, the use of herbicides to suppress weeds is often part of conservation agriculture. Some of the most popular herbicides contain Atrazine, an herbicide that persists in water and accumulates. Energy savings of as much as 40-50%[100] are gained through reduced fuel consumption for mechanized labor. Economic benefits are directly linked to reduced energy costs and labor requirements and higher yields observed in many studies. Not all soil types are equally suitable: heavy soils may become compacted when not plowed. Although hailed by many, the carbon sequestration potential of conservation agriculture has yet to be studied and proven thoroughly.[101]

[97] Jones et al. 2006, [98] Ibid., [99] Jordan et al. 1997, [100] Jones et al. 2006, [101] Baker et al. 2007; Govaerts et al. 2009

The area using no-till techniques has expanded enormously and was estimated at 110 million hectares in 2009, most of this in Latin America. However, many existing practices are "discovered" as conservation agriculture but in reality reflect a strong trend toward zero-tillage. The popularity of the method has much to do with labor savings in conservation agriculture matching well with an aging farm population in many rural areas. The uptake of conservation agriculture in Europe, Asia and particularly in sub-Saharan Africa, is modest compared to the rest of the world. Constraints on the adoption of conservation agriculture by farmers in sub-Saharan Africa[102] range from access to inputs, such as herbicides, trade-offs in the use of crop residues (mulching vs. livestock feeding), to increased labor requirements for weed suppression if herbicides are not available.[103] A range of small-scale cultivation techniques, such as seed drills and weeders, are now on the market, removing some of the barriers.

Box 12

## Conservando La Tierrita with conservation tillage

The Conservando La Tierrita program is a joint initiative of Syngenta and the Universidad del Bosque, Colombia, aiming at comparing integrated sustainable agricultural practices – including conservation agriculture – with conventional farming.

Five demonstration plots were established where practices such as reduced tillage, good quality seed use, cover crops and integrated crop management were compared with conventional production systems. The program engaged closely with local farmers and peasant organizations, as well as students, in demonstrations and events that facilitated learning exchanges and the dissemination of results.

Field experiments on different potato production systems showed 67% soil loss reduction and 25% water loss reduction in conservation plots relative to conventional plots. Moreover, costs were 14% less under the conservation system than with conventional practices.[104]

[102]Giller et al. 2011, [103]Giller et al. 2009, [104]Syngenta 2011a

## Biodegradable plastic mulching

Plastic mulching is a technique by which polyethylene (mainly low-density polyethylene (LDPE) films) are applied as a thin foil over the soil surface. This creates a microclimate allowing better control of crop growth factors. Plastic mulching reduces evaporation, controls weeds, protects the soil against erosion and stimulates nitrogen-fixing microbial activity. It also protects the crop from soil contamination (see **Annex K**). Most importantly, it helps retain nutrients in the root zone, allowing for more efficient nutrient use.[105] Moreover, in temperate areas, the control over temperature makes it possible to start cultivation earlier. In some very dry areas, the control over soil moisture evaporation allows for crop growth where it was impossible before. Plastic films are applied in horticulture but can also be applied to field crops, such as maize, sorghum and sugar.[106] A variety of plastics – size, thickness and color – mean the grower can select the right plastic for the right crop and conditions.

Plastic mulching is widely applied in the U.S., Australia and China but far less elsewhere. The area under plastic mulch in China was estimated at 12 million hectares in 1999 – a figure that must have at least doubled by today. Water savings from plastic mulch are substantial – up to 26-50% compared with furrow irrigation – or even more if combined with drip irrigation. Crop yields are significantly higher, 50%, but in exceptional cases a factor of four or five is possible.[107]

The current challenge is to develop commercially attractive photodegradable and biodegradable plastic mulches, ones that do not disintegrate too fast or too slow and are not too "flaky". Farmers may even add plant nutrients or seeds to the thin films.

When biodegradable plastics are made from bio-based material, it is important to consider possible competition with food and feed for land and resources. This is especially true for first-generation feedstock. Second-generation feedstock and byproducts from agriculture and forestry to produce bio-based plastics do not compete with food and feed.

Organic polymers, such as hydrogels (polyacrylic acids), are a related synthetic product. Added to the soil, these polymers improve the moisture-holding capacity. The niche for polymers is now in specialized uses: tree nurseries, turf grass and gardening (see box 13). The challenge is to adapt these polymers to large-scale vegetable and field crop uses. Field trials have shown that depending on crop, soil type and water availability, yield increases of 5-30% are achievable. For irrigated crops, the choice would be to reduce irrigation water deliveries while maintaining similar yields by using soil modifiers.

[105]Kasirajan and Ngouajio 2012, [106]Ibid., [107]van Steenbergen et al. 2011

## Land restoration and watershed improvement

There has been considerable degradation of land worldwide, but the picture is mixed. The Global Land Degradation Information System (GLADIS) survey by FAO and the International Soil Reference and Information Centre (ISRIC)[108] established that land degradation was still increasing in the period 1991-2008 – it now concerns almost a quarter of the global land area. There are areas where land quality has declined (24% of the global land surface) but also areas where land quality has improved (16%).

Box 13

### Water-retention polymer for effective reforestation

Organic polymers added to the soil are already used today to enhance the viability of plants during seeding and planting. As some trees may be difficult to transplant effectively in harsh environments, such as degraded or water scarce lands, Evonik has developed STOCKOSORB, an organic synthetic polymer that is added to pre-hydrated soil before transplanting tree seedlings and increases soil water-holding capacity.

STOCKOSORB was tested in a reforestation project with Argan trees in Morocco. The area with Argan trees, an endemic species that has been used by local people for centuries for multiple purposes, especially highly valued cosmetic oil, was endangered by intensified land use and farming.

**Key results**

- Effective reforestation rates: increased survival of seedlings by 29-50%;
- No need for irrigation at transplanting: 360 liters of water/tree/year saved.[109]

A large range of measures are helping to store and retain water in agricultural landscapes while improving the productivity of marginal and deteriorated lands.

The measures concern the conservation of moisture at field level (field bounding, windbreaks, use of invertebrates), the control of runoff on hilly areas (terracing, trenching, half-moons, swales, ridges), the recharge and retention of water in shallow aquifers (flood water spreading, planting pits, recharge wells, subsurface dams) or in surface storage. When such land restoration measures are applied at scale and density, they also affect the microclimate and soil moisture in the entire landscape. In fact, tn some parts of the world landscapes have been entirely transformed. In other areas there is still a lot to do. Landscape management is often combined with large-scale agriculture and forestry. Examples are mosaic landscapes combining eucalyptus plantations and grazing areas. Productivity gains of 20-60%, expressed in LER, are common.[110]

[108]Bai et al. 2008, [109]WBCSD 2010, [110]Dupraz and Talbot 2012

# SOLUTION AREA 6
# EFFICIENT FARM OPERATIONS AND MECHANIZATION

# EFFICIENT FARM OPERATIONS AND MECHANIZATION

Farm equipment has a large role to play in co-optimized future agriculture. As rural populations in many countries stagnate and age, there is a growing need for small-scale mechanization, especially in the poorest parts of the world, to keep up with the demand for food and fiber and intensified production. Also, new farm equipment will be required to support new co-optimized farming operations: from special tillers that help build up productive soil profiles within short periods of time to robots working in multiple cropping farms. Integrated farming systems with farm equipment tailored to the agronomy at hand are another important breakthrough, as is the fact that farms can be sources of energy instead of being energy sinks.

Farm mechanization now accounts for approximately 10-30% of agricultural energy consumption. As mechanization is expected to increase, energy-efficient operations become an important factor. There are several methods to reduce energy consumption in farm operations. The most basic methods are retrofitting and replacing energy-inefficient farm equipment and modes of working. The second route is integrated planting systems sustained by tailor-made equipment. The final route is zero-energy farms, including new generation greenhouses.

Farm mechanization now accounts for approximately 10-30% of agricultural energy consumption.

# EFFICIENT FARM OPERATIONS AND MECHANIZATION

Table 7

**Potential and impacts of efficient farm operations and mechanization**

| | Spread | Yield | Energy | Water | Climate |
|---|---|---|---|---|---|
| **Retrofitting and replacement** | | | | | |
| | South Asia, China/ sub-Saharan Africa/ Latin America | More timely and precise operations and solving age/ labor gap mean higher yields | 35-60% savings with pump retrofits in India[i] | | 50-96% less nitrogen oxides (NOx) and atmospheric particulate matter (PM10) with new diesel engines[ii] |
| **Integrated planting systems** | | | | | |
| | Asia/Latin America | 15% higher with PLENE technology for sugar cane[iii] | Less fuel used by PLENE's smaller machines[iii] | | |
| **Closing the energy loop** | | | | | |
| | Modest/ experimental | | Can turn farms into energy providers | | |

Source: [i]Bom et al. 2002, Nelson et al. 2009; [ii]US EPA 2010; [iii]Syngenta 2011b.

# EFFICIENT FARM OPERATIONS AND MECHANIZATION

## Retrofitting and replacement of inefficient operations

The most basic area of improvement is retrofitting existing farm machinery, including pumping equipment. Work in India established that diesel pump energy consumption could be reduced by 34%[111] through a set of low-cost modifications to the prime mover: reducing the governor speed so as to avoid overcapacity, replacing the foot valve with a hand pump for priming and controlled cooling (see **Annex L**). Another study in India suggests that the energy consumption of electric bore wells could be improved by placing pumps at the right depth – pumps are often set too low, requiring additional lift.

Replacing inefficient farm operations with increasing levels of mechanization could have benefits beyond gains on the energy side, such as removing labor constraints and the need to operate within limited time windows. For instance, planting practices in rice systems can be made more efficient through technological innovation. This is true for the Tegra Rice Transplanter, which was developed by Syngenta for rice growers in Asia and Latin America. These machines plant young seedlings in a row at two seedlings per hill and can cover 4-5 hectares in eight hours.[112] The results are increased yields, because younger seedlings produce more tillers (or shoots) per hill, and time, cost and labor savings, thereby overcoming labor shortages.

[111]Bom et al. 2002, [112]Syngenta 2012c

## Integrated planting systems

One step further in improving farm equipment efficiency and mechanization is the development of integrated planting systems whereby innovative agronomic practices are combined with specially developed equipment, reaching yields that were not possible earlier (see box 14). The development of intelligent machines that treat crops and soils selectively thanks to a high level of automation is a promising frontier in precision agriculture. For multiple cropping systems, where several crops have to be managed at the same time, this can shift labor-intensive manual practices to smart mechanization.

The idea of robotic agriculture is not new but strides have been made recently in developing smaller and smarter machines that act unattended and are precise. These new, smaller robots generally require less fuel (70%) than earlier generation robots and can, for instance, be used easily in conservation tillage.[113] Moreover, smaller machines are more weather independent[114] than large machines. They can operate in a wider range of field conditions, which makes it possible to increase fertilizer efficiency by applications at the right time and location and in the right quantity. This also reduces diffuse water pollution.

Box 14

### Syngenta's PLENE technology for sugar cane

Brazil is the undisputed market leader in sugar cane production: 8 million hectares under cultivation, 2% of the country's arable land. Current sugar cane production is close to 500 million tonnes. Brazil produces 40% of the bioethanol in the world.

The production of sugar cane is under pressure as increasing demands for sugar and bioethanol are outpacing the ability to produce it under manual operations. Planting can be done mechanically, but the equipment is generally very heavy and causes compacting of the clayey soils.

PLENE's breakthrough technology, developed by Syngenta, is an integrated solution that combines plant genetics, chemistry and new mechanization technology. Whereas the traditional planting method uses 30-40 cm long cuttings, PLENE uses much smaller cane cuttings, less than 4 cm long, that are coated with seed treatment. This allows for the use of newly developed small-size plant equipment that does not compact soils, uses less fuel and helps to overcome labor shortages. Thanks to this technology, sugar cane can be replanted more frequently, and younger plants mean higher yields, probably as much as 15%. At the same time, costs per hectare are projected to decrease by 15%.[115]

[113]Chamen 1994, [114]Blackmore et al. 2005, [115]Syngenta 2011b

## EFFICIENT FARM OPERATIONS AND MECHANIZATION

### Closing the energy loop

Apart from saving energy through retrofitting, energy neutral and energy positive farm concepts are being developed – though these are still in experimental stages. The experimental zero-energy farm, La Bellotta, in Italy applies a series of techniques: hydrogen-fuelled tractors, energy co-generation from biogas plants, use of biogas digestate to fertilize crops and energy generation from photovoltaic roofs. At present, fully energy-independent farms are futuristic and experimental, but they indicate the shape of things to come.

A related field for major improvement is the management of greenhouses. In temperate climates, greenhouses consume substantial quantities of energy. For example, 10% of all natural gas in the Netherlands is used to heat greenhouses. Energy consumption, however, can be reduced by windbreaks and improved internal cooling systems, including the shift to low kinetic-value energy.

And there are novel developments that move a lot further – from greenhouses that use energy to greenhouses that produce energy.[116] An innovative project in the Netherlands combines closed greenhouses with sun heating and heat and cold storage in aquifers, avoiding the use of natural gas as a heat source. In further phases of development, the aim is to have district biogas digesters that dispose of organic waste from greenhouses and households. These closed cycles produce energy, dispose of waste, return excess $CO_2$ produced during anaerobic digestion to greenhouses to stimulate plant growth, and re-use the digestate to fertilize fields.

In temperate climates, greenhouses consume substantial quantities of energy. For example, 10% of all natural gas in the Netherlands is used to heat greenhouses.

[116] See Kristinsson 2006

# SOLUTION AREA 7
# BRIDGING THE YIELD GAP

## BRIDGING THE YIELD GAP

There is substantial promise of increasing crop productivity by bringing management practices and input use in line with tested best practices – in other words, closing the yield gap. There are different ways to measure the yield gap. The one adopted here is the difference between actual yields in farmer fields and those attained on-farm under optimum conditions. Rather than considering yield gap relative to potential yields in highly controlled on-station experiments, this definition is more relevant because it represents the economically recoverable yield gap.[117] It is a prime solution area, applying what is already known. Table 8 presents yield gaps for major crops expressed in percentage over lowest actual yields.

Yield gaps exist because best practices are not used at farmer level. The underlying reasons may be several and concurrent: the inability to access basic or improved inputs, insufficient awareness and training, and/or risk-minimizing behavior. In some cases, yield gaps occur because the available technology set is inappropriate in dealing with specific circumstances in a given locality.

All farming cannot be expected to operate at optimum conditions. A yield gap of 25% may, in fact, be normal. Beyond this, however, improved practices and input supply should make it possible to increase yields. The most potential for yield-gap-related increases occurs in developing countries where poverty, inadequate input use, uncertain access to markets and low yields come together. The socioeconomic impact of reducing yield gaps is also much larger when yields go from 1 to 2 t/ha than when they rise from 7 to 8 t/ha.[118] In some cases, a small farmer producing 1 t/ha might not be able to cover production costs. In that case, doubling production would allow that farmer to pay off costs and purchase production inputs for the next cropping season.

Yield gaps exist because best practices are not used at farmer level.

[117]Fischer et al. 2010 [118]Molden et al. 2010

# BRIDGING THE YIELD GAP

Table 8
**Potential and impacts of bridging the yield gap**

| | Spread | Yield | Energy | Water | Climate |
|---|---|---|---|---|---|
| Best management practices; farmers' inclusion in innovation systems; access to relevant information and technology; better linkage to markets and service providers; using new communication technology | Examples of major gains for maize and coarse grains in sub-Saharan Africa; millets in India; rice in India and the Philippines. | Rice: 15-85%[i] increase Maize: 30-165%[i] increase Wheat: 25-35%[i] increase Coarse grain: 85%[ii] increase | More fertilizers needed | | More fertilizers, likely more greenhouse gas emissions |

Sources: [i]Fischer et al. 2010, [ii]CA 2007

The yield gap for some main crops:[119]

- Wheat: Yield gaps amount to 35-50% in India, 50% in eastern China, 50% in the U.S. and 45% in South Australia;
- Rice: Yield gaps are 15% in Egypt, 55% in Japan, 60-100% in the Philippines and 110% in Punjab, India. Yield-limiting factors for irrigated rice in South Asia stood at 37% and rank in order of importance as: nutrients (10%), diseases (7%), weeds (7%), water (5%) and rats (4%). For rainfed rice, yield-limiting factors amounted to 68% – the most important ones being nutrients (23%), diseases (15%) and weeds (12%).
- Maize: Yield gaps are less clear-cut but very high. They are estimated at 193% in sub-Saharan Africa.
- Coarse grains (millet and sorghum): Yield gaps are less researched, but they are considered to be very high. For instance, the yield gap for millet in India is 110%.[120]

[119]As presented in Fischer et al. 2010, [120]See also Comprehensive Assessment of Water Management in Agriculture, 2007

## BRIDGING THE YIELD GAP

The potential to increase crop yields with existing knowledge seems considerable (in both irrigated and rainfed agriculture).

For this solution area, a scenario was developed using the Nexus Model to match the impacts of reducing the yield gap with projections of increased cereal demand. If yield gaps for maize, rice and wheat, the three major crops, were closed by 60% in 2050, then based on calculations with the Nexus Model,[121] the yearly production of grain would be 3.9 billion tonnes, a 230% increase over the year 2000. This would exceed the 3 billion tonnes of projected global cereal demand in 2050 by 900 million tonnes.[122]

The largest gains would be obtained in sub-Saharan Africa and South Asia. In sub-Saharan Africa, where population growth is expected to be greatest and levels of undernourishment are highest, closing the yield gap by 60% would translate into a production of around 194 million tonnes of grain against projected cereal demand of 197 million tonnes.[123] Although making a substantial contribution to cereal supplies in sub-Saharan Africa, reducing the yield gaps of these three crops alone is not enough to satisfy demand. It is important to work on other cereals and Solution Areas as well. (For the development of this scenario with the Nexus Model, several assumptions were made: the yield gap was calculated by taking the spatial data of maize, rice and wheat from Monfreda et al;[124] the potential yield for the same crops were obtained from Lobell et al.,[125] Fermont et al.,[126] and Fischer et al;[127] and a yield gap reduction of 60% was applied to all pixels across all regions over the period 2000-50.)

In summary, the potential to increase crop yields with existing knowledge seems considerable (in both irrigated and rainfed agriculture). Based on a series of recent "Crops that Feed the World" articles published in the Food Security Journal, table 9 highlights promising directions to increase the productivity of various commodities that are linked to the Solution Areas described here. In many instances, closing the yield gap will mean a larger reliance on inputs, such as fertilizers and crop protection products, that require larger energy inputs.

[121] See **Annex A** for a detailed explanation of the methodology used in the Nexus Model. [122] FAO 2012, [123] Projected cereal demand for sub-Saharan Africa was calculated based on the growth rate in cereal demand for the period 2005/07-2050 as indicated in FAO 2012 relative to demand in 2000, which is the reference year used in the Nexus Model.
[124] Monfreda et al. 2008, [125] Lobell et al. 2009, [126] Fermont et al. 2009, [127] Fischer et al. 2010

## BRIDGING THE YIELD GAP

Table 9

**Crops that feed the world – important frontiers**

| | Bridging yield gap | Smart varieties | Smart crop management | Mixed farming systems | Efficient operations and mechanization |
|---|---|---|---|---|---|
| **Rice**[i] | Use good agronomic principles, from land preparation to harvest and post-harvest | Development of varieties tolerant to heat, drought, early flooding and salinity; preservation of rice genetic diversity locally should also be supported | Improved crop management increases average yields in the Senegal River Valley from 4 to 6 t/ha and from 2 to 6 t/ha in the Niger Valley; in sub-Saharan Africa, weeds are main biotic factor limiting yields | Diversification of rice systems key to more sustainable management of upland systems | Lack of mechanization hampers development of the rice sector in Africa |
| **Maize**[ii] | Soil fertility, water management and weed control are key to crop productivity | Improved germoplasm[128] for high-temperature and water-limited environments | Precision agriculture tools that allow more efficient use of nitrogen | Irrigation water important to compensate droughts | Availability of equipment for direct seeding or minimal tillage is crucial |
| **Oats**[iii] | | Better lodging and virus resistance; dwarfing and higher-yielding varieties | Good in organic rotations; break crop for disease reduction in cereal crop rotations | Rotation with wheat can reduce disease and increase yields of wheat by 1-3 t/ha | |
| **Soybean**[iv] | Increased yields from better agronomic practices and genetic improvements | Tolerance to water stress, temperature extremes and diseases | Irrigation prevents losses in drought years; diseases are major production constraints | | |

Sources: [i]Seck et al. 2010; [ii]Shiferaw et al. 2011; [iii]Marshall et al. 2013; [iv]Hartman et al. 2011

[128]Germoplasm refers to the genetic material of an organism.

## BRIDGING THE YIELD GAP

Table 9
**Crops that feed the world – important frontiers (continued)**

| | Bridging yield gap | Smart varieties | Smart crop management | Mixed farming systems | Efficient operations and mechanization |
|---|---|---|---|---|---|
| **Lentil**[v] | Early sowing with good weed control provides yield gains | Scope to select for improved heat and drought stress, salt tolerance | Seed priming with improved varieties increases yields by 29-38%; cropping systems that include lentils enhance soil moisture retention | Important role as rotation crop to enhance soil fertility; increases yields and protein content of cereals | In countries with mechanized-agriculture, lentils are drilled but elsewhere they are still planted by hand broadcast |
| **Potato**[vi] | Agronomic practices and varieties are to be improved to increase production | Varieties to cope with drought stress are needed | Chemical control measures needed to combat bacterial diseases | | |
| **Sweet potato**[vii] | Yields 20% higher if weed infestation is controlled at early stages | | Time of planting important; irrigation at 60% moisture depletion level increases yield by 24% | China: planted after wheat harvest in June; Indonesia: grown after rice; India: mostly rotated with cereals, pulses or jute | |
| **Yam**[viii] | Use of chemicals to prolong dormancy; use of botanicals to control tuber rot caused by parasitic fungi | Use of disease and drought-resistant varieties | Effective duration of yam crop growth from 6 to 12 months | Often intercropped with maize, cassava and rice; use of leguminous cover crops to maintain soil structure and fertility | |

Sources: [v]Erskine et al. 2011; [vi]Birch et al. 2012; [vii]Mukhopadhyay et al. 2011; [viii]Asiedu and Sartie 2010

# BRIDGING THE YIELD GAP

The yield gap extends to livestock water productivity, both physical and economic. Strategies to enhance water productivity in livestock include improving feed sourcing, increasing animal production (milk, meat, eggs), improving animal health, and promoting grazing practices that avoid land degradation, lessen the amount of water required for grazing and reduce negative environmental impacts, such as erosion.[129] In rangelands, there is scope for increasing stocking rates through controlled intense grazing on savannah grasslands, for instance. Short-term grazing on a small area improves water infiltration and regeneration of perennial grasses and sustains stocking rates that are several factors higher.[130]

A significant part of the increase in production will have to come from the increased productivity of small farmers. Yet these farmers are often excluded from innovation systems, lack access to relevant information to effectively plan and manage production, and are also, in many instances, poorly linked to markets, institutions and service providers. All these factors are holding back small farmers from being more productive while securing their livelihoods.

Having recognized this, the private sector is increasingly engaging in new business models in direct partnership with farmer-customers and in which information and knowledge management are crucial. Modern communication makes it possible to plug the gaps: using popular media, digital expert systems or mobile phones.

There are many opportunities here, and they need to be deployed. Boxes 14 and 15 are examples of effective communication tools to provide farmers with information and training on best agricultural practices that are otherwise hard to get, especially at a time when extension services have decayed in many countries. Businesses are increasingly co-organizing extension services or at least supporting them using the media and its own value chains.

Possible actions to close the yield gap are:

- Including farmers in innovation systems;
- Facilitating farmer access to relevant information and technology;
- Enhancing farmer linkages to markets and service providers using value chains; and
- Using new communication technology.

[129]Molden et al. 2010, [130]Savory and Butterfield 1999

Box 15

## Shamba Shape-Up Project

*Shamba* in Swahili means farm. The "Farm" Shape-Up TV show is an initiative aiming to provide East Africa's rapidly growing rural and peri-urban audience with up-to-date, practical, and simple information and tools to improve their farming practices and productivity.

Mediae, a research-based organization, created the Shamba Shape-Up project. It is supported by a number of organizations internationally, including Syngenta.

The Shamba team typically spends four days with one household and invites experts to give advice on how to improve farming practices. The issues covered encompass access to improved seeds and inputs, improving animal husbandry, water management and irrigation, soil fertility, crop management and disease management, and grassroots partnerships for local and international market linkages, in a range of different agro-ecological zones in Kenya, Uganda and Tanzania.

Sessions are filmed in an entertaining and informative "make-over style" and broadcasted on television in both English and Swahili and used as DVDs for training in the wider region. Viewers are encouraged to send their contact details in order to receive informative material on the topics dealt with as well as to follow updates on the Shamba project through social networks. Altogether, the Shamba Shape-Up Project comprises 40 episodes in three series over 2012-2013, reaching an estimated 11 million people.[131]

[131]Shamba Shape Up n.d.

Box 16

## ITC e-Choupal: The world's largest rural digital infrastructure

The power of information and communication technologies is used to empower small and marginal farmers by setting up Internet kiosks that make a host of services related to know-how, best practices, timely and relevant weather information, transparent discovery of prices and others available. Trained farmers who help the agricultural community access information in their local language manage the kiosks.

**Key elements**

- Leveraging digital technology to bring relevant information and know-how;
- Enabling market access to farmers;
- Providing customized extension services for capacity building;
- Enabling price discovery and better returns, raising rural incomes;
- Transmitting market signals to align production with consumer needs;
- Co-creating off-farm livelihood opportunities with communities; and
- Linking to market institutions for better farm risk management.[132]

There are many more examples of successful partnership with small farmers that include the provision of support, extension services and information services to improve farming practices and livelihoods. For example, Syngenta Foundation India (SFI) has developed a cluster-based approach to agricultural extension. Each extension worker is responsible for a group of villages and is advised by experts. Frequent meetings, field demonstrations and learning sessions facilitate testing and the introduction of latest technologies, inputs and processes. SFI aims to reach 200,000 families by 2014.[133]

[132]ITC Limited 2013, unpublished, [133]Syngenta 2012a

# SOLUTION AREA 8
# EFFICIENT FERTILIZER PRODUCTION

According to the International Fertilizer Association,[134] fertilizer production represents 1.2% of global annual energy consumption and the same percentage of global annual greenhouse gas emissions. The production of nitrogen fertilizer, in particular, is heavy on energy use: it absorbs 94% of all energy consumed by the fertilizer industry.[135] The “nitrogen connection” is also the prime reason that agricultural prices strongly respond to rising energy prices – the price elasticity of agricultural commodities to energy prices is estimated at 0.27 and for fertilizer the elasticity is 0.55.[136]

[134] IFA 2009, [135] IFA n.d., [136] Mensbrugghe et al. 2010

# EFFICIENT FERTILIZER PRODUCTION

Table 10
**Potential and impacts of efficient fertilizer production**

| | Spread | Yield | Energy | Water | Climate |
|---|---|---|---|---|---|
| Overhauling, BATs natural gas | Global/China | | 10-25%;[i] 37% if bulk of plants replaced by BATs[ii] | | 57% less greenhouse gas emissions = 164 million t/year[ii] |

Sources: [i]UNEP, 1998; [ii]Kongshaug, 1998.

As crop production intensifies, the use of fertilizer is very likely to increase. Reducing the energy footprint of agriculture will require producing fertilizers more efficiently. By applying a range of methodologies, fertilizer manufacturers reduce their energy consumption by 10-25%.

- In the short term, overhauling existing less-efficient plants would increase energy efficiency by some 10%.[137]
- In the long-term, closing down poorly performing plants and producing fertilizer with BATs would improve overall energy efficiency by up to 25%.
- In addition, the energy requirement for coal-based plants is significantly higher than for natural gas-fired facilities. A coal-based unit also produces roughly 2.4 times more $CO^2$ per tonne of ammonia than a natural gas-based unit.[138] A drastic shift to gas-based production, however welcome, is not foreseen. Much of the expansion in fertilizer production is expected to be in China, where coal-fired production will continue to prevail.

[137]The cost would be significant, probably exceeding US$ 20 million per site. [138]IFA n.d.

# SOLUTION AREA 9
# MAKING USE OF TRADE

In theory, trade could improve global water and energy productivity by shifting production from areas with low water and energy productivity to areas with high productivity. Then water-rich countries could export water-intensive products to water-scarce countries. This is the idea behind the application of the concept of virtual water to international trade (see **Annex M**). Virtual water refers to the volume of water needed to produce certain commodities. When these commodities are traded, the water "embedded" in their production is also traded.[139] The same applies to energy.


[139]Allan 2003, 2011; Hoekstra 2013

## MAKING USE OF TRADE

Table 11

**Potential and impacts of making use of trade**

| | Spread | Food | Energy | Water | Climate |
|---|---|---|---|---|---|
| Shifting productivity from low- to high-water and energy productivity areas | International trade expected to increase but not as much as production; drivers are land and water scarcity, specific supply and demand (ethanol), new land development | | 5-6% higher energy productivity[i] | 5-6% higher water productivity[i] | |

Sources: [i]Fraiture et al. 2004, Chapagain et al. 2006.

Yet an assessment of current global water savings from international trade shows that global water use, in the period 1997-2001, to produce agricultural products for export equaled 1,250 billion $m^3$ per year.[140] If the importing countries had produced the imported products domestically, they would have required a total of 1,600 billion $m^3$ per year to do so, meaning a water savings of just 350 billion $m^3$/year or 5% of total water used for agricultural production. This figure matches with the 6% water savings estimated for cereals on the basis of 1995 data on international trade of cereals.[141]

The limited application of the concept of virtual water in the practice of international trade has to do with some incomplete assumptions behind international trade theory. According to mainstream theories, trade shall be determined by comparative advantages in factor productivity, e.g., water productivity (Ricardian model) or factor endowment, e.g., water availability (Heckscher-Ohlin model). Yet several studies have proven that both theories fall short when matched against the practice of international trade. Water scarcity is insufficient in explaining the direction and flows of trade.[142]

Other production factors, e.g., capital, land labor and knowledge, might be decisive drivers of trade.[143] In that case, the scarcest factor becomes the limiting factor, shifting the balance of decisions against the concept of virtual water. Public policies applying subsidies or favorable resource pricing to water-scarce regions might also distort production and international trade[144] away from water productivity measures.

[140]Chapagain et al. 2006, [141]Fraiture et al. 2004, [142]Fraiture et al. 2004; Wichelns, 2004, [143]Kumar and Singh 2005; Wichelns 2010, [144]Suranovic 2007

## MAKING USE OF TRADE

The paradox exemplifying this is the case of water-scarce states in China and India exporting food to more water-rich states within their same country. Access to secure markets[145] and local demand for a certain commodity[146] are also important determinants for export/import flows. Nonetheless, water scarcity still influences trade and food imports in countries with extreme water scarcity that simply cannot produce enough food to be self-sufficient. For instance, this is true in several countries in the Middle East and North Africa[147] that have reduced their water footprint by externalizing their production. Thus, projections on future agricultural production and trade must take into account water as a production input and constraint in water-scarce regions.[148]

International trade is estimated to account for 16-25% of all food crop production.[149] Two important questions for the future are: will agricultural trade further increase and what effects will this have on water and energy productivity?

A number of other trends will translate into increased trade. New grain baskets are likely to develop in areas such as the Guinea Savannah Belt, South Sudan, the Zambezi Basin, little developed areas in the Amazon, and parts of Russia and Central Asia. Arable land is expected to expand by 70 million hectares (about 5%), as a combination of an increase of 110 million hectares in developing countries and a reduction of 40 million hectares in developed countries. Another driver is water scarcity. Projections indicate that by 2025 water-scarcity induced cereals trade will increase by 60%.[150] The main regions affected are North China and Punjab, India, where groundwater stocks are being depleted – undermining the agricultural economy in the medium term and possibly turning China into an important importer of food grains. In fact, the latter trend is already developing. Finally, the demand for bioenergy will generate more trade volume – Brazil in particular is expected to export considerable volumes of ethanol, contributing to a six fold increase in international trade.

**Water scarcity still influences trade and food imports in countries with extreme water scarcity that simply cannot produce enough food to be self-sufficient.**

[145]Verma et al. 2009, [146]see Linder 1961, [147]Hoekstra and Chapagain 2008, [148]Liao et al. 2008, [149]Bruinsma 2010, [150]Fraiture 2004

# MAKING USE OF TRADE

Nonetheless, countervailing trends limit a dramatic expansion in the international trade of agricultural products. Production and productivity increases are possible and expected in most agricultural systems across agro-ecosystems and regions, which reduces the need for agricultural imports. The largest increase in food production is expected in currently low-producing rain-fed areas and floodplains in sub-Saharan Africa and Latin America. As a result, some of these countries could turn from being net importers of food to being self-sufficient. The additional production will not translate immediately into increased international commodity flows but might substitute agricultural imports and food aid. Moreover, several countries – including China and India – are pursuing national food security policies through generous subsidies, support to internal food production, and by strengthening national research capacity and the seed industry.

Overall, international trade in agricultural commodities is expected to increase but only moderately. The water and energy savings effect of trade would be modest, too. Table 12 assesses the impact of increased international trade volumes on trade-related water and energy productivity. The picture is mixed.

Table 12
**Impact of increased international trade volumes on trade-related water and energy productivity**

| | Impact on global trade | Impact on trade-related water productivity | Impact on trade-related energy productivity |
|---|---|---|---|
| Closing yield gaps globally | None | None | None |
| Catching up on productivity in rain and flood dependent Africa | None, even decrease | None – no new trade | None – no new trade |
| Development of agricultural frontiers in sub-Saharan Africa, Latin America | Increase | Unknown | Reduce – marginal land requiring fertilizer |
| Water scarcity in China | Increase | Reduce – end of productive groundwater systems | Improve – shift away for energy (pumping) production |
| Export of ethanol from Brazil | Increase | Improve | Reduce – intensive use of fertilizer |

## MAKING USE OF TRADE

The increase in trade, however, appears not to be "pulled" by efficiency gains but more "pushed" by land and water scarcity. The areas for agricultural expansion fall outside the temperate zones where natural productivity is high, so the expansion of relatively intensive farming in these areas may mean a larger use of energy resources. The closure of groundwater-based irrigation in India and North China may mark an end to a system that has high water productivity (though high energy demand as well). The overall effect of a geographical shift in production appears likely to be relatively modest or non-existent in terms of higher water and energy productivity. Nonetheless, higher water and energy productivity could be promoted through different channels using the market chain as a driver. Finally, local niche-production areas may develop that are based on high water and energy productivity for certain crops.

But there are a few considerations. First, food imports depend on the country's foreign exchange availability to purchase the food that would have otherwise been produced domestically. Second, increasing reliance on external food products moves away from food self-sufficiency, weakens the domestic agricultural sector and threatens the livelihoods of subsistence farmers in countries with a high incidence of small farmers. The question is also whether the consequences of weakened local rural economies and endangered smallholder livelihood systems suffering under the competing effect of liberalized trade of agricultural commodities can be borne.[151] Last, concentrating the production of water-intensive products in specialized regions increases the pressure they have on the environment and society.[152]

[151] Mazoyer and Roudart 2002, [152] Hoekstra 2013

## MAKING USE OF TRADE

From the standpoint of the carbon footprint, the commonly held belief that local food systems have lower environmental impact than imported food, the so-called food miles approach, has been challenged by several studies. For instance, a rigorous study using a life cycle analysis (LCA) to quantify a product's carbon emissions rather than just considering the carbon emitted for its transportation, found that lamb, apples and dairy products produced in New Zealand and shipped to the United Kingdom have a lower carbon footprint than if they were produced in the UK.[153] This reflects a less-intensive production system in New Zealand than the UK, with lower inputs, including energy, and lower emissions from electricity generation.

The increased trade flow, however, may affect commodity prices. The lesson gained from the price spikes in 2008 and 2011 is that although most food is consumed locally, domestic prices may be affected by international prices.[154] Global stock-to-use ratios have fallen very far in the last 25 years. In 2010 they stood at 20% of global use – a drastic reduction from 40% in 1986. China contributed to keeping the average high for a long time, but in 2000 it started to reduce its stocks. This increased the volatility of the price system. In the future, there will be a need for global price systems and increases in national or regional strategic food commodity stocks so as to shelter those most at the mercy of price rises, fluctuations and speculation. There is a need to reduce exposure to short-term production shortfalls and to compensate for the effect of possible sharp increases driven by global bioenergy prices.

Another area for overhaul is the systems of farm subsidies. This has a major impact on production. Subsidies come as input subsidies (fertilizer, energy) as well as guaranteed prices and other transfers. The current system of agricultural subsidies is the product of a history of local policies and power games – not an instrument to stimulate resource-efficient production. In many countries it is a major, but blindly directed, drain on public resources. There is a strong case to revisit the current complicated global farm subsidy structure.

In the future, there will be a need for global price systems and increases in national or regional strategic food commodity stocks so as to shelter those most at the mercy of price rises, fluctuations and speculation.

[153] Saunders et al. 2006, [154] Fischer et al. 2010

# SOLUTION AREA 10
# REDUCING FOOD LOSS AND WASTE

An estimated 32% of food produced globally, about 1.3 billion tonnes, is lost or wasted along the food chain yearly, corresponding to a net worth of US$ 750 billion.[155] To put this in perspective, the amount of cereals wasted worldwide was more than three times the amount of cereals transformed into biofuels.[156] Globally, the blue water footprint (i.e., the consumption of surface and groundwater resources) of food wastage is about 250 km³, which is equivalent to the annual water discharge of the Volga River or three times the volume of Lake Geneva.


[155]FAO 2013, [156]Stuart 2009

## REDUCING FOOD LOSS AND WASTE

Fruits and vegetables present the most losses, followed by cereals and roots and tubers. The table below shows the incidence of different food items to total food waste. The waste occurs in equal measure in high- and low-income countries, but the underlying reasons differ. In developing countries, most waste (25-35%) occurs early in the food chain, at harvest, post-harvest, storage and processing. In contrast, in developed countries, most waste (18-24%) happens at the retail and consumer levels.[157] Provided that losses of 15-20% for some items are unavoidable,[158] reducing waste could decrease demand for food by perhaps 10%,[159] saving an equivalent amount of land, energy and water resources (see **Annex N**).

Table 13

**Potential and impacts of reducing food loss and waste**

| | Spread | Food | Energy | Water | Climate |
|---|---|---|---|---|---|
| **Improving harvest, post-harvest and processing** | | | | | |
| | Low-income countries | 10% less food demand[i] | 2% energy saved for production | 10% savings for production | 10% less greenhouse gas emissions along the food chain |
| **Rebalancing consumption at retailer and consumer levels** | | | | | |
| | Mid-/high-income countries | 10% less food demand | 8% savings along the food chain | | 10% less greenhouse gas emissions along the food chain |

Sources: [i]Smil 2001, Connor and Minguez 2012.

[157]Smil 2001; Gustavsson et al. 2011, [158]Smil 2001, [159]Connor and Minguez 2012

## REDUCING FOOD LOSS AND WASTE

Table 14
**Share of different food items to total food loss and waste**

| Commodity group | Total wastage (in 1,000 t) | As percentage of total production (%) |
|---|---:|---:|
| Fruits and vegetables | 492,000 | 38 |
| Cereals | 316,900 | 25 |
| Roots and tubers | 244,700 | 19 |
| Oilseeds and pulses | 43,100 | 3 |
| Fish and seafood | 17,400 | 1 |

Source: Gustavsson et al. 2011

## Improving harvest, post-harvest and processing

Food losses in developing countries are often related to deficient infrastructure, logistics and facilities for harvest, storage, processing and transport. For instance, in the field, an important proportion of production is lost because of harvest failures, often due to lack of labor or machinery at crucial harvest stages. In many cases, waste is the result of a mismatch between supply and demand. Assured agreements between producers and buyers, such as supply contracts, create incentives for producers to invest in the crop and reduce over-production as a form of insurance.

If not properly designed or maintained, storage and processing facilities can lead to as much as 19% in food losses. In some countries, storage facilities are outdated and lack ventilation and temperature control or do not conform to basic standards of hygiene and protection against pests. Additionally, because crops are often harvested under the sun, they need to be cooled down before storage to extend their shelf life.

- Using plastic crates during the handling and storage of perishable products, such as fruits and vegetables, has proven to reduce food losses considerably.
- Small metal silos for use by one household/farmer are an effective option to reduce food loss, especially cereal and pulse losses.
- Purdue Improved Cowpea Storage (PICS) bags have shown promising results in reducing insect damage to cowpeas during storage.[160]
- Effectively designed drying systems help avoid damage to cereals and overheating of oilseeds.
- Fruits and vegetables need high storage standards with humidity, temperature, $CO_2$, ethylene and oxygen controls. Modern storage facilities allow for completely automated control of these parameters.

Finally, transporting food as quickly as possible with the least damage requires planning the entire route, from field to market, as an integrated system and the designing of harvest and transport systems accordingly.[161]

If not properly designed or maintained, storage and processing facilities can lead to as much as 19% in food losses.

[160]Lipinski et al. 2013, [161]IME 2013

## Rebalancing consumption at retailer and consumer level

Although developed countries generally have efficient and well-engineered market logistics and household storage facilities, much food is wasted at retailer and consumer levels. One important waste factor is the supermarket philosophy and the standardization of quality assessment: cosmetic and standard-size criteria leading to trimming and discarding perfectly edible food. The second reason is consumers' limited understanding of the "use-by" date and discarding food prematurely.

Solutions to reduce these wastes require the substitution of the "use-by" date with a "best before" date and avoiding the use of aesthetic criteria for food selection and promotional offers that encourage over purchase. At the same time, at the consumer level, awareness campaigns should be pursued to inform on the health benefits of reduced consumption and more balanced diets. As an example, the cost of a campaign to persuade consumers to waste less food in the UK cost US$ 6 million but saved consumers US$ 450 million.[162]

Box 17

### A chip to reduce waste

Monitoring the quality of perishables from right after they are harvested until they reach the store can reduce food loss and waste. By placing a chip that constantly measures the environmental conditions during the transport and storage of a batch of fruits, vegetables, meat or flowers, the quality and ripening behavior can be determined more accurately and the "use by" dates can be better predicted. Wageningen UR Food & Biobased Research participated in the development of a chip with sensors that measure temperature, humidity, acidity, oxygen and ethylene contents. All this information, combined with information on the product that is being transported or stored, provides details about the state the fresh produce is in.

**Key benefits**

- Tracking the history of the conditions under which the product was kept makes it possible to predict the future quality of the product more accurately;
- This information helps to find the right buyer for the product;
- Thanks to the real time data, the ripening process can be adjusted remotely to ensure that the product has the desired quality when it arrives at the store.

Food redistribution and donation programs need concerted support to overcome legal, transportation and economic constraints.[163] Finally, a closer monitoring of the evolution of product quality, from field to distribution, allows for the extension of their shelf life and differentiation in their markets (box 17).

[162]Stuart 2009, [163]Lipinski et al. 2013

# 4
# ENABLERS, MUST-HAVES AND MEASURES OF SUCCESS

Addressing the challenges of providing food and fiber to a growing population that lives well while staying within the boundaries of the planet in terms of water, energy and climate impact, as is the goal of the WBCSD's Vision 2050, will require change and initiative.

Agriculture worldwide is likely to develop constantly, while natural resources dwindle and demand for food, feed, fiber and biofuel increase. Obviously, innovation in crops, farming systems, and value chains are all required and constitute must-haves[164] towards an agriculture system that sustains the ambition of Vision 2050. Farmers and businesses have always been adapting, experimenting and improving, and the contours of new forms of agriculture are becoming visible.

If the 10 Solution Areas are the shape of things to come, then the world must move towards global farming that:

- Is far more precise and less wasteful (e.g., efficient fertilizer use, smart fertilizers, precision irrigation, retrofitting farm equipment, integrated planting systems, efficient fertilizer production,reducing food loss and waste);
- Has a better understanding of and respect for natural, biological and ecological cycles and makes the best use of them (e.g., rock dust and biofertilizers, biodegradable plastic mulch, conservation agriculture, integrated nutrient management, water-saving rice systems);
- Is more stress- and climate-resilient yet maintains productivity (e.g., smart varieties, mixed farming systems, and smart crop management because resilience to stress and climate (i.e., robustness) goes at the expenses of yields. These are opposite paths of improvement when a crop has to choose where to invest its energy. For instance, a drought-tolerant variety will produce more than a non-tolerant variety under stress conditions but less than an improved one under optimal conditions);
- Addresses the resource base at the landscape level (e.g., conjunctive use in mega irrigation systems; landscape restoration and watershed improvement).

[164] *Vision 2050: The New Agenda for Business* mentions a number of a must haves that should be in place by 2020: training of farmers (Solution Area 1), new crop varieties (Solution Area 2), more agricultural research (Solution Areas 2, 3 and 4), water efficiency (Solution Areas 5 and 6), free and fairer trade (Solution Area 9) and yield gains (almost all solution areas). Other agenda items include energy efficiency in production (Solution Area 7), integrated transport solution (Solution Area 8) and value chain innovations (Solution Area 10).

To reach this new state of agriculture requires the closing of the knowledge gap and new ingenuity (clever crop agronomy, smart seeds, zero-energy farms, integrated logistical systems). Care must be paid to avoid a dichotomy between innovative and productive farm systems on the one hand and marginalized, resources-poor backwater systems on the other. It is as important to promote breakthroughs as it is to work on improving the productivity of very small farms and making them viable businesses in their own right (by making use of current communication technology, working on minor crops, connecting smallholders to value chains and mechanization that is appropriate for small farms). The world is likely to see emerging, productive small farmers catering for global niche crops and local urban markets as well as large-scale providers of main staples and biofuels – both operating in areas where land and water availability allow for it and trade systems encourage it. Though for centuries farming has been the pursuit of basic subsistence, and still is in many areas, it will become more and more entrepreneurial and knowledge-intensive.

The business sector has a large role to play by:

- Applying its capacity to innovate towards higher water and energy productivity and sustainable harvests;
- Applying its capacity to invest in a demanding future and not draw back, for instance, from more marginal areas;
- Strategically anticipate future challenges and risks and invest in long-term agro-solutions; and
- Using its organizational skills to strengthen supply systems and marketing logistics to better source products and reduce waste.

There is also great opportunity for businesses to work together all along the value chain – connecting input suppliers, producers, commodity traders, processors and retailers.

However, business needs to work in a conducive and supportive context. Governments can enable business investment in co-optimized solutions through sound policy frameworks. Examples of government action include:

- Ensure that the basic logistics (transport, storage, processing) are in place or facilitated;
- Ensure that land and water rights are secure and conducive to sustainable and productive use;
- Create, with the business sector, systems that provide knowledge and skills to those who do not have easy access to it;
- Set up educational systems that muster talent and provide fiscal and financial incentives and security for small and large businesses; and
- Define clear land property rights that take into account the heterogeneity of local uses.

Two other important enablers are price buffers, adequate reserves of commodities to prevent sudden price surges or collapses, and resource buffers, well-managed landscapes and water resource systems. Rather than irresponsible subsidies, proper and fair pricing of food should drive investments in agriculture and assure an equitable living for farmers. Finally, more relevance should be given to the role of science and technology in informing and guiding regulations and actions.

Business investment in co-optimized solutions, enabled by smart government policies, can move society toward meeting global challenges, like climate change and water scarcity, by 2050. These solutions will not only reduce our use of natural resources and stress on the nexus of food, water and energy, but also help increase yields and create better quality products for the world's growing population.

# 5 REFERENCES

Abdul Wahid, O.A., T.A. Mehana, 2000. “Impact of phosphate-solubilizing fungi on the yield and phosphorous-uptake by wheat and faba bean plants”. *Microbiological Research* 155(3), 221-227.

Abideen, Z., R. Ansari, M.A. Khan, 2011. “Halophytes: Potential source of ligno-cellulosic biomass for ethanol production”. *Biomass and Bioenergy* 35(5), 1818-1822.

Agro Nanotechnology Corp., n.d. “Nanogrowth”. Viewed 23 December 2011. Available at http://www.agronano.com/nanogro.htm and http://www.agronano.com/trial_UKR.htm.

Ahmad, R., K.A. Malik (eds.), 2002. *Prospects for saline agriculture (Vol. 37)*. Kluwer Academic Publishers, Dordrecht, The Netherlands, 480p.

Allan, J.A., 2003. “Virtual Water-The Water, Food, and Trade Nexus. Useful Concept or Misleading Metaphor?” *Water International* 28(1), 106-113.

Allan, J.A., 2011. *Virtual Water. Tackling the threat to our planet’s most precious resource*. I.B. Tauris &Co. Ltd, London, UK.

Ashrafuzzaman, M., M. Abdul Halim, M.R. Ismail, S.M. Shahidullah, M.A. Hossain, 2011. “Effect of plastic mulch on growth and yield of chill (*Capsicum annuum* L.)”. *Brazilian Archives of Biology and Technology* 52(2), 321-330.

Asiedu, R., A. Sartie, 2010. “Crops that feed the World 1. Yams”. *Food Security* 2(4), 305-315.

Baffes, J. 2007. *Oil spills on other commodities*. World Bank Policy Research Working Paper no. 4333. World Bank, Washington, DC.

Baffes, J. 2009. *More on the energy/non-energy commodity price link*. World Bank Policy Research Working Paper no. 4982. World Bank, Washington, DC.

Bai, Z.G., D.L. Dent, L. Olsson, M.E. Schaepman, 2008. *Global Assessment of Land Degradation and Improvement. 1. Identification by Remote Sensing*. Report 2008/01. ISRIC – World Soil Information, Wageningen, The Netherlands.

Baker, J.M., T.E. Ochsner, R.T. Venterea, T.J. Griffis, 2007. “Tillage and soil carbon sequestration-What do we really know?” *Agriculture, Ecosystems & Environment* 118, 1-5.

Beck, C., E.C. Oerke, H.W. Dehne, 2002. “Impacts of strobilurins on physiology and yield formation of wheat”. *Meded Rijksuniv Gent Fak Landbouwkd Toegep Biol Wet* 67(2), 181-187.

Belder, P., B.A.M. Bouman, R. Cabangon, L.Guoan, E.J.P. Quilang, L. Yuanhua, J.H.J. Spiertz, T.P. Tuong, 2004. “Effect of water-saving irrigation on rice yield and water use in typical lowland conditions in Asia”. *Agricultural Water Management* 65, 193-210.

Bindraban, P.S., A. Verhagen, P.W.J. Uithol, P. Henstra, 1999. *A Land Quality Indicator for Sustainable Land Management: The Yield Gap*. Report 106. Research Institute Agrobiology and Soil Fertility, Wageningen, The Netherlands.

Birch, P.R.J., G. Bryan, B. Fenton, E.M. Gilroy, I. Hein, J.T. Jones, A. Prashar, M.A. Taylor, L. Torrance, I.K. Toth, 2012. “Crops that feed the world 8: Potato: are the trends of increased global production sustainable?” *Food Security* 4, 477-508.

Blackmore, S., B. Stout, M. Wang, B. Runov, 2005. *Robotic agriculture-the future of agricultural mechanisation?* 5th European Conference on Precision Agriculture. J. Stafford, V. (ed.), Wageningen Academic Publishers, The Netherlands, pp. 621-628.

Bom, G.J., I.H. Rehman, D. van Raalten, R. Mishra, F. van Steenbergen, 2002. *Technology innovation and promotion in practice: pumps, channels and wells-Reducing fuel consumption, emissions, and costs*. Tata Energy Research Institute, New Delhi, India.

Borgia, C., M. García-Bolaños, L. Mateos, 2012. “Patterns of variability in large-scale irrigation schemes in Mauritania”. *Agricultural Water Management* 112, 1-12.

Bos, H., S. Conijn, W. Corre, K. Meesters, M. Patel, 2011. *Duurzaamheid van biobased producten: energiegebruik en broeikasgasemissie van producten met suikers als grondstof.* Wageningen UR Food & Biobased Research, Wageningen, The Netherlands.

Breman, H., J.J.R. Groot, H. van Keulen, 2001. “Resource limitations in Sahelian agriculture”. *Global Environmental Change* 11(1), 59-68.

Brookes, G., P. Barfoot, 2011. “Global impact of biotech crops: Environmental effects 1996-2009”. *GM Crops* 2(1), 34-49.

Bruinsma, J., 2010. “The resources outlook: by how much do land, water and crop yields need to increase by 2050?” In Conforti, P. (ed.). *Looking ahead in world food and agriculture: perspective to 2050*. Food and Agriculture Organization of the United Nations, Rome, Italy.

Bumb, L.B., C.A. Baanante, 1996. *The Role of Fertilizer in Sustaining Food Security and Protecting the Environment to 2020*. Food, Agriculture and the Environment Discussion Paper 17. International Food Policy Research Institute, Washington, DC.

Burt, C., 2003. *Chemigation and Fertigation Basics for California*. Irrigation Training and Research Centre, California, U.S.

Cabangon, R.J., T.P. Tuong, N.B. Abdullah, 2002. “Comparing water input and water productivity of transplanted and direct-seeded rice production systems”. *Agricultural Water Management* 57, 11-31.

Chamen, W.C.T., D. Dowler, P.R. Leede, D.J. Longstaff, 1994. “Design, operation and performance of a gantry system: Experience in arable cropping”. *Journal of Agricultural Engineering Research* 59, 145-160.

Chapagain, A.K., A.Y. Hoekstra and H.H.G. Savenije, 2006. “Water saving through international trade of agricultural products”. *Hydrology and Earth System Sciences* 10(3), 455-468.

Ciampitti, I.A., T.J. Vyn, 2012. “Physiological perspectives of changes over time in maize yield dependency on nitrogen uptake and associated nitrogen efficiencies: A review”. *Field Crops Research* 133, 48-67.

Clay, J., 2004. *World Agriculture and the Environment: A Commodity-by-Commodity Guide To Impacts and Practices*. Island Press, Washington, DC.

Colmer, T.D., R. Munns, T.J. Flowers, 2006. "Improving salt tolerance of wheat and barley: future prospects". *Animal Production Science* 45(11), 1425-1443.

CA (Comprehensive Assessment of Water Management in Agriculture), 2007. *Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture*. Earthscan, London, UK/ International Water Management Institute, Colombo, Sri Lanka.

Connor, D.J., M.I. Minguez, 2012. "Evolution not revolution of farming systems will best feed and green the world". *Global Food Security* 1(2), 106-113.

Dasgupta, S., C. Meisner, D. Wheeler, 2007. "Is Environmentally Friendly Agriculture Less Profitable for Farmers? Evidence in Integrated Pest Management in Bangladesh". *Review of Agricultural Economics* 29(1), 103-118.

Dawson, C.J., J. Hilton, 2011. "Fertiliser availability in a resource-limited world: Production and recycling if nitrogen and phosphorous". *Food Policy* 36, Supplement 1, S14-S22.

Derpsch, R., T. Friedrich, A. Kassam, H. Li, , 2010. "Current status of adoption of no-till farming in the world and some of its main benefits". *International Journal of Agriculture and Biological Engineering* 3(1), 1-25.

Dhawan, A.K., S. Singh, S. Kumar, 2009. "Integrated Pest Management (IPM) Helps Reduce Pesticide Load in Cotton". *Journal of Agricultural Science and Technology* 11, 599-611.

DuPont Pioneer, n.d. "The Science Behind Rice Hybrids". Viewed 30 March 2013 http://www2.dupont.com/inclusive-innovations/en-us/gss/global-challenges/food/science-behind-rice-hybrids.html.

DuPont Pioneer, 2013. *Using Crop Sensors to Improve Nitrogen Management for Corn*. Pioneer Agronomy Sciences. Unpublished.

Dupraz, C., G. Talbot, 2012. *Evidences and explanations for the unexpected high productivity of improved temperate agroforestry systems*. 1st EURAF Conference, 9 October 2012, Session 1. INRA, Montpellier, France.

Edgerton, M.D., J. Fridgen, J.R. Anderson Jr., J. Ahlgrim, M. Criswell, P. Dhungana, T. Gocken, Z. Li, S. Mariappan, C.D. Pilcher, A. Rosielle, S.B. Stark, 2012. "Transgenic insect resistance traits increase corn yield and yield stability". *Nature Biotechnology* 30, 493-496.

Edwards, S., A. Asmelash, H. Araya, G. Egziabher, 2007. *Impact of compost use on crop yields in Tigray, Ethiopia*. Food and Agriculture Organization of the United Nations, Rome, Italy.

Erskine, W., A. Sarker, S. Kumar, 2011. "Crops that feed the world 3. Investing in lentil improvement toward a food secure world". *Food Security* 3(2), 127-139.

FAO (Food and Agriculture Organization of the United Nations), 2009. *State of the world's forests 2009*. Food and Agriculture Organization of the United Nations, Rome, Italy.

FAO (Food and Agriculture Organization of the United Nations), 2011a. *Looking ahead in world food and agriculture: perspective to 2050*. Conforti, P. (ed.). Food and Agriculture Organization of the United Nations, Rome, Italy.

FAO (Food and Agriculture Organization of the United Nations), 2011b. *The State of the World's Land and Water Resources for Food and Agriculture (SOLAW) – Managing systems at risk*. Earthscan, London/Food and Agriculture Organization of the United Nations, Rome, Italy.

FAO (Food and Agriculture Organization of the United Nations), 2012. *World Agriculture towards 2030/2050: the 2012 Revision*. ESA Working Paper No. 12-03. Food and Agriculture Organization of the United Nations, Rome, Italy.

FAO (Food and Agriculture Organization of the United Nations), 2013. *Food wastage footprint. Impact on natural resources*. Summary Report. Food and Agriculture Organization of the United Nations, Rome, Italy.

FAO-AQUASTAT. *Country Fact Sheets*. Food and Agriculture Organization of the United Nations, Rome, Italy.

Feibert, E., C. Shock, T. Stieber, M. Saunders, 1992. *Groundcover Options and Irrigation Methods for the Production of Kabocha Squash*. Malheur County Alternative Crops and Marketing Research. Special Report 900. Oregon State University, pp. 26-32.

Fermont, A.M., P.J.A. van Asten, P. Tittonell, M.T. van Wijk, K.E. Giller, 2009. "Closing the cassava yield gap: An analysis from smallholder farms in East Africa". *Field Crops Research* 112 (1), 24–36.

Fischer, T., D. Byerlee, G.O. Edmeades, 2010. "Can technology deliver on the yield challenge to 2050?" In Conforti, P. (ed.). *Looking ahead in world food and agriculture: perspective to 2050*. Food and Agriculture Organization of the United Nations, Rome, Italy.

Food and Agricultural Policy Research Institute (FAPRI) and Iowa State University (ISU), 2011. *World Agricultural Outlook*. Available online at http://www.fapri.iastate.edu/outlook/2011/

Fraiture, C. de, X. Cai, U. Amarasinghe, M. Rosegrant, D. Molden, 2004. *Does International Cereal Trade Save Water? The Impact of Virtual Water Trade on Global Water Use*. Comprehensive Assessment Research Report 4. International Water Management Institute, Colombo, Sri Lanka.

Gärdenäs, A.I., J.W. Hopmans, B.R. Hanson, J. Šimunek, 2005. "Two-dimensional model for nitrate leaching for various fertigation scenarios under micro-irrigation". *Agricultural Water Management* 74, 219-242.

Giller, K.E., E. Witter, M. Corbeels, P. Tittonell, 2009. "Conservation agriculture and smallholder farming in Africa: The heretics' view". *Field Crops Research* 114, 23-34.

Giller, K.E., M. Corbeels, J. Nyamangara, B. Triomphe, F. Affholder, E. Scopel. P. Tittonell, 2011. "A research agenda to explore the role of conservation agriculture in African smallholder farming systems". *Field Crops Research* 124, 468-472.

GIZ (Deutsche Gesellschaft für Internationale Zusammenarbeit), 2010. *Agrobiodiversity in drylands*. Available online at http://conservation-development.net/Projekte/Nachhaltigkeit/DVD_11_China/Material/pdf/en-issue-paper-drylands-2010.pdf

GIZ (Deutsche Gesellschaft für Internationale Zusammenarbeit), 2011. *Agrobiodiversity -The key to food security and adaptation to climate change*. Available online at http://www.mamud.com/Docs/giz2011-en-agrobiodiv-food-security-climate-change.pdf

Gliessman, S.R., 1985. "Multiple Cropping Systems: A Basis for Developing an Alternative Agriculture." In *Innovative biological technologies for lesser developed countries: workshop proceedings*. Congress of the U.S. Office of Technology Assessment. Washington, DC, pp. 67-83.

Gohar, S., F. van Steenbergen, B. Chaudry, (forthcoming). Half the Water: Groundwater Management in Pakistan.

GOI (Government of India), 2008. *Agricultural Statistics at a Glance*, Ministry of Agriculture, Government of India, New Delhi.

Gonzalez, C., 2011. *Climate Change, Food Security, and Agrobiodiversity: Toward a Just, Resilient, and Sustainable Food System*. Seattle University School of Law Legal Paper Series 11-19. Fordham Environmental Law Review 22. Available online at http://agrobiodiversityplatform.org/climatechange/files/2011/08/CLIMATE-CHANGE-FOOD-SECURITY.pdf

Govaerts, B., N. Verhulst, A. Castellanos-Navarrete, K.D. Sayre, J. Dixon, L. Dendooven, 2009. "Conservation Agriculture and Soil Carbon Sequestration: Between Myth and Farmer Reality". *Critical Reviews in Plant Sciences* 28(3), 97-122.

Gruhn, P., F. Goletti, M. Yudelman, 2000. *Integrated Nutrient Management, Soil Fertility, and Sustainable Agriculture: Current Issues and Future Challenges*. Food, Agriculture, and the Environment Discussion Paper 32. IFPRI, Washington, DC.

GTZ (Deutsche Gesellschaft für Technische Zusammenarbeit), 2006. *Agrobiodiversity and climate change – A complex relationship*. Issue Papers: People, Food and Biodiversity. Available online at http://conservation-development.net/Projekte/Nachhaltigkeit/DVD_11_China/Material/pdf/en-issue-paper-climate_change-2006.pdf

Guo, J.H., X.J. Liu, Y. Zhang, J.L. Shen, W.X. Han, W.F. Zhang, P. Christie, G.W.T. Goulding, P.M. Vitousek, F.S. Zhang, 2010. "Significant Acidification in Major Chinese Croplands". *Science* 327(5968), 1008-1010.

Gupta, R.K., J.K. Ladha, S. Singh, R.G. Singh, M.L. Jat, Y. Saharawat, V.P. Singh, S.S. Singh, et al., 2006. *Production technology for direct-seeded rice*. Technical Bulletin 8. Rice-Wheat Consortium for the Indo-Gangetic Plains, New Delhi, India, pp.16.

Gustavsson, J., C. Cederberg, U. Sonesson, R. van Otterdijk, A. Meybeck, 2011. *Global Food Losses and Food Waste*. Food and Agriculture Organization of the United Nations, Rome, Italy.

Hahlbrock, K., 2009. *Feeding the planet: Environmental Protection through Sustainable Agriculture*. Haus Publishing Ltd., London, UK.

Hanson, B.R., J. Šimunek, J.W. Hopmans, 2006. *Evaluation of urea-ammonium-nitrate fertigation with drip irrigation using numerical modelling*. Agricultural Water Management 86, 102-113.

Hartman, G.L., E.D. West, T.K. Herman, 2011. "Crops that feed the World 2. Soybean-worldwide production, use, and constraints caused by pathogens and pests". *Food Security* 3, 5-17.

Hoek, W. van der, R. Sakthivadivel, M. Renshaw, J.B. Silver, M.H. Birley, F. Konradsen, 2001. *Alternate Wet/Dry Irrigation in Rice Cultivation: A Practical Way to Save Water and Control Malaria and Japanese Encephalitis?* Research Report 47. International Water Management Institute, Colombo, Sri Lanka.

Hoekstra, A.Y., 2013. *The Water Footprint of Modern Consumer Society*. Routledge, New York, NY.

Hoekstra, A.Y., A.K. Chapagain, 2008. Globalisation of water: *Sharing the planet's freshwater resources*. Blackwell Publishing, Oxford, UK.

Hou, Z., P. Li, B. Li, J. Gong, Y. Wang, 2007. "Effects of fertigation scheme on N uptake and N use efficiency in cotton". *Plant and Soil* 290, 115-126.

ICID-CIID (International Commission on Irrigation and Drainage), 2012. "Regionwise Arable and Permanent Cropped Areas of the World". Available at http://icid.org/posters_2012.pdf.

Inter Academy Council, 2004. *Annual Report of the IAC Executive Director for 2004*. Available online at http://www.interacademycouncil.net/23450/27010/27036.aspx.

IFA (International Fertilizer Industry Association), n.d. Viewed 30 March 2013. Available at http://www.fertilizer.org/.

IFA (International Fertilizer Industry Association), 2009. *Feeding the Earth: Energy Efficiency And $CO_2$ Emissions In Ammonia Production. 2008-2009 Summary Report*. Available online at www.fertilizer.org/ifacontent/download/26110/374422/ver.

IME (Institution of Mechanical Engineers), 2013. *Global Food: Waste Not, Want Not*. Available online at http://www.imeche.org/knowledge/themes/environment/global-food.

IPCC (Intergovernmental Panel on Climate Change), 2007. *Climate Change 2007*. Synthesis report. IPCC, Geneva.

ITC Limited, 2013. *Case Studies in Sustainable Agricultural Practices*. Unpublished.

Jones, C., G. Basch, A. Baylis, D. Bazzoni, J. Biggs, R. Bradbury, K. Chaney, L. Deeks, et al., 2006. *Conservation Agriculture in Europe: An approach to sustainable crop production by protecting soil and water?* SOWAP, Jealott's Hill International Research Centre, Bracknell, UK.

Jordan, V.W.L., J.A. Hutcheon, G.V. Donaldson, D.P. Farmer, 1997. "Research into and development of integrated farming systems for less-intensive arable crop production: experimental progress (1989–1994) and commercial implementation". *Agriculture, Ecosystems & Environment* 64(2), 141-148.

Jothimani, S., T.M. Thiagrajan, 2005. "Water and Nitrogen Use Efficiency of Rice under System of Rice Intensification". *Water Policy Research Highlight* 24. IWMI-TATA, Colombo, Sri Lanka.

Kasirajan, S., M. Ngouajio, 2012. "Polyethylene and biodegradable mulching for agricultural applications: a review". *Agron Sustain. Dev.* 32, 501-529.

Kelly, V.A., 2006. *Factors Affecting Demand for Fertilizers in sub-Saharan Africa*. Agriculture and Rural Development Discussion Paper 23. The World Bank, Washington, DC.

Khan, M.A., R. Ansari, 2008. "Potential use of halophytes with emphasis on fodder production in coastal areas of Pakistan". In *Biosaline agriculture and high salinity tolerance*, pp. 157-162. Birkhäuser Basel.

Khan, Z., C. Midega, J. Pittchar, J. Pickett, T. Bruce, 2011. "Push-pull technology: a conservation agriculture approach for integrated management of insect pests, weeds and soil health in Africa". *International Journal of Agricultural Sustainability* 9(1), 162-170.

Kaut, A.H.E.E., H.E. Mason, H. Navabi, J.T. O' Donovan, D. Spaner, D., 2008. "Organic and conventional management of mixtures of wheat and spring cereals". *Agron. Sustain. Dev.* 28, 363-371.

Knoop, L., F. Sambalino, F. van Steenbergen, 2012. *Securing Water and Land in the Tana Basin: a resource book for water managers and practitioners*. 3R Water Secretariat, Wageningen, The Netherlands.

Kongshaug, G., 1998. "Energy Consumption and Greenhouse Gas Emissions in Fertilizer Production". IFA Technical Conference, Marrakesh, Morocco, 28 September-1 October 1998. Available online at http://www.fertilizer.org/ifa/HomePage/LIBRARY/Publication-database.html/Energy-Consumption-and-Greenhouse-Gas-Emissions-in-Fertilizer-Production.html.

Kristinsson, J., 2006. "The energy-producing Greenhouse". PLEA2006-The 23rd Conference on Passive and Low Energy Architecture, Geneva, Switzerland, 6-8 September 2006. Available online at http://www.cuepe.ch/html/plea2006/Vol1/PLEA2006_PAPER112.pdf.

Kumar, V., R.R. Bellinder, R.K. Gupta, R.K. Malik, D.C. Brainard, 2008. "Role of herbicide-resistant rice in promoting resource conservation technologies in rice-wheat cropping systems of India: A review". *Crop Protection 27*, 290-301.

Kumar, M.D., O.P. Singh, 2005. "Virtual Water in global food and water policy making: is there a need for rethinking?" *Water Resources Management* 19, 759-789.

Kuzma, J., P. VerHage, 2006. *Nanotechnology in Agriculture and Food Production: Anticipated Applications*. Woodrow Wilson International Centre for Scholars, Project on Emerging Nanotechnologies.

Lamont, W.J., M.D. Orzolek, J.K. Harper, A.R. Jarrett, G.L. Greaser, 2002. "Drip irrigation for vegetable production". Pennsylvania State University, College of Agricultural Sciences. Viewed 30 December 2011. Available at http://extension.psu.edu/business/ag-alternatives/horticulture/horticultural-production-options/drip-irrigation-for-vegetable-production.

Li, C., J. Qiu, S. Frolking, X. Xiao, W. Salas, B- Moore III, S. Boles, Y. Huang, R. Sass, 2002. "Reduced methane emissions from large-scale changes in water management of China's rice paddies during 1980–2000". *Geophysical Research Letters 29*(20), 33-1-33-4.

Li, T., B. Liu, M.H. Spalding, D.P. Weeks, B. Yang, 2012. "High efficiency TALEN-based editing produces disease-resistant rice". *Nature Biotechnology* 30(5), 390-392.

Liao, Y., C. de Fraiture, M. Giordano, 2008. "Global trade and water: Lessons from China and the WTO". *Global Governance* 14(4), 503-521.v

Linder, S.B., 1961. *An Essay on Trade and Transformation*. Almqvist and Wiksell, Stockholm.

Lipinski, B., C. Hanson, R. Waite, T. Searchinger, J. Lomax, L. Kitinoja, 2013. "Creating a Sustainable Food Future, Installment Two - Reducing Food Loss and Waste". *Working paper World Resources Institute* – UNEP.

Lobell, D.B., K.G. Cassman, C.B. Field, 2009. "Crop Yield Gaps: Their Importance, Magnitudes, and Causes". *Environment and Resources* 34, 179-204.

Marshall, A., S. Cowan, S. Edwards, I. Griffiths, C. Howarth, T. Langdon, E. White, 2013. "Crops that feed the world 9: Oats-a cereal crop for human and livestock feed with industrial applications". *Food Security* 5(1), 13-33.

Mazoyer, M., L. Roudart, 1997. *Histoire des agricultures du monde: du néolithique à la crise contemporaine*. Editions du Seuil.

Mensbrugghe, D. van der, I. Osorio-Rodarte, A. Burns, J. Baffes, 2010. "Macroeconomic Environment and Commodity Markets: A Longer-Term Outlook". In Conforti, P. (ed.) *Looking ahead in world food and agriculture: perspective to 2050*. Food and Agriculture Organization of the United Nations, Rome, Italy.

Molden, D., T. Oweis, T., P. Steduto, P. Bindraban, M.A. Hanjra, M.A., J. Kijne, 2010. "Improving agricultural water productivity: between optimism and caution". *Agricultural Water Management* 97(4), 528-535.

Monfreda, C., N. Ramankutty, J.A. Foley, 2008. "Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000". *Global Biogeochemical Cycles* 22 (1), 1944-9224.

Morris, R.A., D.R. Garrity,1993. "Resource capture and utilization in intercropping". *Field Crops Research* 34, 303-317.

Mukhopadhyay, S.K., A. Chattopadhyay, I. Chakraborty, I. Bhattacharya, 2011. "Crops that feed the world 5. Sweetpotato. Sweetpotatoes for income and food security". F*ood Security* 3(3), 283-305.

Nano Green Sciences Inc., (n.d.). "Agriculture". Viewed 27 December 2011 http://www.nanogreensciences.com/agriculture.html.

Narayanamoorthy A., 1996. "Impact of drip irrigation on consumption of water and electricity". *Asian Econ.Rev.* 38(3), 350-364.

Narayanamoorthy, A., 2007. *Micro-Irrigation and Electricity Consumption Linkages in Indian Agriculture: A Field Based Study*. Available online at http://www.iwmi.cgiar.org/EWMA/files/papers/Drip-energy-AN-paper%20(2).pdf.

NCADAC (National Climate Assessment Development Advisory Committee), 2013. *Federal Advisory Committee Draft Climate Assessment Report*. U.S. Global Change Research Program, Washington, DC. Available online at http://ncadac.globalchange.gov/.

National Research Council, 1996. *Lost Crops of Africa. Volume I. Grains*. National Academy Press, Washington, DC.

NCPAH (National Committee on Plasticulture Applications in Horticulture), 2011. *Practical Manual on Plastic Mulching*. Department of Agriculture & Cooperation, Ministry of Agriculture, Government of India, New Delhi. Available online at http://www.ncpahindia.com/nmmi/Plastic_Mulching.pdf.

Nelson, G.C., M.W. Rosegrant, J. Koo, R. Robertson, T. Sulser, T. Zhu, C. Ringler, S. Msangi, et al., 2009. *Climate change: Impact on agriculture and costs of adaptation*. Food Policy Report 19. IFPRI, Washington, DC.

OECD (Organisation for Economic Co-operation and Development), 2012. *Environmental Outlook to 2050*. OECD, Paris.

OECD-FAO (Organisation for Economic Co-operation and Development and Food and Agriculture Organization of the United Nations), 2011. *OECD-FAO Agricultural Outlook 2011-2020*. Organisation for Economic Cooperation and Development, Paris, France/Food and Agriculture Organization of the United Nations, Rome, Italy.

Oerke, E.C., 2006. "Crop losses to pests". *Journal of Agricultural Science* 144, 31-43.

Owen, M.D.K., 2009. "Herbicide-tolerant Genetically Modified Crops: Resistance Management". In Ferry, N., A.M.R. Gatehouse (eds.) *Environmental Impact of Genetically Modified Crops*. CAB International.

Owen, M.D.K., I.A. Zelaya, 2005. "Herbicide-resistant crops and weed resistance to herbicides". *Pest Management Science* 61(3), 301-311.

Pathak, H., A.N. Tewari, S. Sankhyan, D.S. Dubey, U. Mina, V. Singh, N. Jain, A. Bhatia, 2011. "Direct-seeded rice: Potential, performance and problems-A review". *Current Advances in Agricultural Sciences* 3(2), 77-88.

Parthasarathi, T., K. Vanitha, P. Lakshamanakumar, D. Kalaiyarasi, 2012. "Aerobic rice-mitigating water stress for the future climate change". *International Journal of Agronomy and Plant Production* 3(7), 241-254.

PepsiCo, 2010. Sustainable Agriculture Practices. Available online at http://www.pepsico.com/Download/PepsiCo_agri_0531_final.pdf.

Pieri, C., G. Evers, J. Landers, P. O' Connell, E. Terry, 2002. *No-Till Farming for Sustainable Rural Development. Agriculture & Rural Development Working Paper*. The International Bank for Reconstruction and Development, Washington, DC. Available online at http://www.betuco.be/CA/No-tillage%20Farming%20for%20Sustainable%20Development.pdf.

Pimentel, D., M.H. Pimentel, 2008. *Food, Energy, and Society*. 3rd Edition. CRC Press, New York, US.

Pinheiro, B.S., E.M. Castro, C.M. Guimaraes, 2006. "Sustainability and profitability of aerobic rice in Brazil". *Field Crops Research* 97(1), 34-42.

Potter, P., N. Ramankutty, 2010. "Characterizing the Spatial Patterns of Global Fertilizer Application and Manure Production". *Earth Interactions* 14, 1-22.

Prasad, P.V.V., V. Satyanarayana, V.R.K. Murthy, K.J. Boote, 2002. "Maximising yields in rice-groundnut sequence through integrated nutrient management". *Field Crops Research* 75, 9-21.

Pretty, J.N., C. Toulmin, S. Williams, 2011. "Sustainable Intensification in African Agriculture". *International Journal of Agricultural Sustainability* 9, 5-24.

Pretty J., A.D. Noble, D. Bossio, J. Dixon, R.E. Hine, F.W.T. Penning de Vries, J.I.L. Morison, 2006. Resource-conserving agriculture increases yields in developing countries. *Environmental Science and Technology* 3(1), 24-43.

Qaim, M., I. Matuschke, 2005. "Impacts of genetically modified crops in developing countries: a survey". *Quarterly Journal of International Agriculture* 44, 207-227.

Qaim, M., D. Zilberman, 2003. "Yield effects of Genetically Modified Crops in Developing Countries". Science 299, 900-902.

Ratnadass, A., P. Fernandes, J. Avelino, R. Habib, 2012. "Plant species diversity for sustainable management of crop pests and diseases in agro-ecosystems: a review". *Agron. Sustain. Dev.* 32, 273-303.

Radstake, F., F. van Steenbergen, 2013. *Shanxi Farmers Embrace Modern Irrigation Methods to Adapt to Climate Change*. ADB Knowledge Showcases Issue 45.

Ritzema, H.P., T.V. Satyanarayana, S. Raman, J. Boonstra, J., 2008. "Subsurface drainage to combat waterlogging and salinity in irrigated lands in India: lessons learned in farmers' fields". *Agricultural Water Management* 95(3), 179-189.

Rockstrom, J., W. Steffen, K. Noone, A. Persson, F.S. Chapin, III, E. Lambin, T.M. Lenton, M. Scheffer, et al., 2009. "Planetary Boundaries: Exploring the Safe Operating Space for Humanity". E*cology and Humanity* 14(2), 32.

Rozema, J., T. Flowers, 2008. "Crops for a salinized world". *Science* 322(5907), 1478-1480.

Sass, R.L., F.M. Fischer Jr. 1997. "Methane emissions from rice paddies: a process study summary". *Nutrient Cycling in Agroecosystems* 49(1-3), 119-127.

Sahai, S., M. Gautam, U. Sajjad, A. Kumar, J. Hill, 2010. *Impact on Farm Economics of Changing Seed Use – A Study in Jharkhand*. Gene Campaign, New Delhi, India. Available at http://www.genecampaign.org/reports/impact_on_farm_economics-jharkhand.pdf.

Samobor, V., D. Horvat, B. Kesteli, M. Jost, 2008. "Effect of stone meal on control of seed-borne diseases in wheat". *Agronomski Glasnik* 70(6), 563-572. Presented at 2nd Mediterranean Conference on Organic Agriculture-Contribution to Sustainable Ecosystem, Dubrovnik, 2-4 April 2008.

Saunders, C., A. Barber, G Taylor, 2006. *Food Miles-Comparative Energy/Emissions Performance of New Zealand's Agriculture Industry*. Lincoln University. Agribusiness and Economics Research Unit.

Savory, A., J. Butterfield, 1999. *Holistic Management: A New Framework for Decision Making*. Island Press, Washington, DC.

Scharf, P.C., D.K. Shannon, H.L. Palm, K.A. Sudduth, S.T. Drummond, N.R. Kitchen, L.J. Mueller, V.C. Hubbard, L.F. Oliveira, 2011. "Sensor-Based Nitrogen Applications Out-Performed Producer-Chosen Rates for Corn in On-Farm Demonstrations". *Agronomy Journal* 103(6), 1683-1691.

Schuiling, R.D., P. Krijgsman, 2006. "Enhanced Weathering: An Effective and Cheap Tool to Sequester $CO_2$". *Climate Change* 74(1-3), 349-354.

Seck, P.A., A. Diagne, S. Mohanty, M.C. Wopereis, 2012. "Crops that feed the world 7: Rice". *Food Security* 4(1), 7-24.

Shah, T., O.P. Singh, A. Mukherji, 2006. “Some aspects of South Asia’s groundwater irrigation economy: analyses from a survey in India, Pakistan, Nepal Terai and Bangladesh”. *Hydrogeology Journal* 14(3), 286-309.

Shamba Shape Up, (n.d.). A practical, make-over style TV series aimed at East Africa’s rapidly growing rural and peri-urban TV audience. Viewed 15 March 2013 http://www.shambashapeup.com/.

Sheehy, J.E., P.L. Mitchell, B. Hardy (eds.), 2007. *Charting New Pathways to C4 Rice*. International Rice Research Institute, Los Banos, Philippines, 422p.

Sheykhbaglou, R., M. Sedghi, M. Tajbakhshshishivan, R. Seyed Sharifi, 2010.” Effects of nano-iron oxide particles on agronomic traits of soybean”. *Notulae Scientia Biologicae* 2(2), 112-113.

Shiferaw, B., B. M. Prasanna, J. Hellin, M. Bänziger, 2011. “Crops that feed the world 6. Past successes and future challenges to the role played by maize in global food security”. *Food Security* 3(3), 307-327.

Singandhupe, R.B., G.G.S.N. Rao, N.G. Patil, P.S. Brahmanand, 2003. “Fertigation studies and irrigation scheduling in drip irrigation system in tomato crop *(Licopersiconesculentum* L.*)”. European Journal of Agronomy* 19, 327-340.

Singh, I., A.K. Srivastava, P. Chandna, R.K. Gupta, 2006. “Crop sensors for efficient nitrogen management in sugarcane: potential and constraints”. *Sugar Tech.* 8(4), 299-302.

Smedema, L.K., S. Abdel-Dayem, W.J. Ochs, 2000. “Drainage and agricultural development”. *Irrigation and Drainage Systems* 14, 223–235.

Smedema, L.K., W.J. Ochs, 1998. “Needs and prospects for improved drainage in developing countries”. I*rrigation and Drainage Systems* 12, 359–369.

Smil, V., 2001. *Feeding the World: A Challenge for the Twenty-First Century*. MIT Press, Cambridge, Mass.

Smil, V., 2004. “Improving efficiency and reducing waste in our food system”. *Environmental Sciences* 1, 17-26.

Smith, J., 2010. *Agroforestry: Reconciling Production with Protection of the Environment. A Synopsis of Research Literature.* The Organic Research Centre, Elm Farm. Progressive Farming Trust Limited, Berkshire, UK.

Song, F.P., M. Zhang, Y.X. Shi, Y.Y. Hu, 2005. “Releasing characteristics of controlled-release nitrogen-fertilizer and its effects on rice yields”. *Acta Pedologica Sinica* 42(4), 619-627.

Steenbergen, F. van., A. Tuinhof, L. Knoop, 2011. *Transforming Lives Transforming Landscapes. The Business of Sustainable Water Buffer Management*. 3R Water Secretariat, Wageningen, The Netherlands.

Stuart, T., 2009. *Waste: Uncovering the Global Food Scandal*. Penguin Books Ltd, London, UK.

Suranovic, S., 2007. *Economies of Scale and Returns to Scale. International Trade Theory and Policy.*

Syngenta, 2011a. “Conservando la Tierrita program”. *Executive Management Report*, December 2011.

Syngenta, 2011b. *Science Matters. Keeping abreast of Syngenta Research & Development: An integrated approach*.

Syngenta, 2012a. “Food security case studies: Smallholder farmer focus”. *Syngenta Food Security Agenda 2012*.

Syngenta, 2012b. *Science Matters. Keeping up to date with Syngenta Research & Development*.

Syngenta, 2012c. “Rice”. Available online at http://www.syngenta.com/global/corporate/SiteCollectionDocuments/pdf/presentations/investor/rice-crop-update-250912.pdf.

Tabbal, D.F., B.A.M. Bouman, S.I. Bhuiyan, E.B. Sibayan, M.A. Sattar, 2002. “On-farm strategies for reducing water input in irrigated rice; case studies in the Philippines”. *Agricultural Water Management* 56(2), 93-112.

Tilman, D., C. Balzar, J. Hill, B.L. Befort, 2011. “Global food demand and the sustainable intensification of agriculture”. *Proceedings of the National Academy of Sciences of the United States of America* 108(50), 20260-20264.

Tilman, D., K.G. Cassman, P.A. Matson, R. Naylor, S. Polasky, 2002. “Agricultural sustainability and intensive production practices”. *Nature* 418, 671-677.

Trenkel, M.E., 2010. *Slow-and Controlled Release and Stabilized Fertilizers: An option for enhancing Nutrients Use Efficiency in Agriculture*. International Fertilizer Industry Association (IFA), Paris, France.

Tsubo, M., E. Mukhala, H.O. Ogindo, S. Walker, 2003. “Productivity of maize-bean intercropping in a semi-arid region of South Africa”. *Water* SA 29(4), 381-388.

UNEP (United Nations Environment Programme), 1998. Part 1. *The Fertilizer Industry’s Manufacturing Processes and Environmental Issues*. Technical Report 26-Part 1. UNEP, Paris, France/UNIDO, Vienna, Austria/IFA, Paris, France.

US EPA (US Environmental Protection Agency), n.d. “Integrated Pest Management (IPM) Principles”. Viewed 15 March 2013. Available at http://www.epa.gov/opp00001/factsheets/ipm.htm.

US EPA (US Environmental Protection Agency), 2010. *Renewable Fuel Standard Program (RFS2) Regulatory Impact Analysis*. Available online athttp://www.epa.gov/oms/renewablefuels/420r10006.pdf.

Vandersypen, K., K. Bengaly, C.T. Keita, S. Sidibe, D. Raes, J.Y. Jamin, 2006. “Irrigation performance at tertiary level in the rice schemes of the Office du Niger (Mali): adequate water delivery through over-supply”. *Agricultural Water Management* 83, 144–152.

Vandersypen, K., A.C.T. Keita, Y. Coulibaly, D. Raes, J.Y. Jamin, 2007. “Drainage problems in the rice schemes of the Office du Niger (Mali) in relation to water management”. *Agricultural Water Management* 89, 153–160.

Venkatesh, M. S., M. Ali, 2007. “Role of Legumes in Nitrogen Economy of Cereals/Cropping systems- The Indian Scenario”. In Abrol, Y.P., N. Raghuram, M.S. Sachdev (eds.). *Agricultural Nitrogen Use & its Environmental Implications*. International Publishing House Pvt. Ltd., New Delhi, pp. 351-368.

Verma, S., D.A. Kampman, P. van der Zaag, A.Y. Hoekstra, 2009. “Going against the flow: A critical analysis of inter-state virtual water trade and the context of India’s National River Linking Program”. *Physics and Chemistry of the Earth* 34, 261-269.

Vilich-Meller, V., 1992. “Pseudocercosporella herpotrichoides, Fusarium spp. and Rhizoctonia cerealis stem rot in pure stands and interspecific mixtures of cereals”. *Crop Prot.* 11, 45-50.

Waddington, S.R., X. Li, J. Dixon, G. Hyman, C.M. de Vicente, 2010. “Getting the focus right: production constraints for six major food crops in Asian and African farming systems”. *Food Security* 2, 27-48.

Wageningen U.R., 2011. “Biobased product is echt duurzamer”. *Wageningen World* 2, p. 7.

Wang, Z.Y., Y.C. Xu, Z. Li, Y.X. Guo, R. Wassman, H.U. Neue, R.S. Lantin, L.V. Buendia, Y.P. Ding, Z.Z. Wang, 2001. “A four-year record of methane emissions from irrigated rice fields in the Beijing region of China”. *Nutrient Cycling in Agroecosystems* 58, 55-63.

WBCSD (World Business Council for Sustainable Development), 2009. *Tackling climate change on the ground. Corporate case studies on land use and climate change*. WBCSD, Geneva, Switzerland.

WBCSD (World Business Council for Sustainable Development), 2010a. *Biodiversity and ecosystem services: Scaling up business solutions*. WBCSD, Geneva, Switzerland.

WBCSD (World Business Council for Sustainable Development), 2010b. *Vision 2050: The new agenda for business*. WBCSD, Geneva, Switzerland.

WEF (World Economic Forum), 2011. Water Security: *The Water-Food-Energy-Climate nexus: The World Economic Forum Water Initiative*. Island Press, Washington, DC.

Werf, W. van der, K. Keesman, P. Burgess, A. Graves, D. Pilbeam, L.D. Incoll, K. Metselaar, M. Mayus, R. Stappers, H. van den Keulen, J. Palma, C. Dupraz, 2007. “Yield-SAFE: A parameter-sparse, process-based dynamic model for predicting resource capture, growth, and production in agroforestry systems”. *Ecological Engineering* 29(4), 419-433.

Wichelns, D., 2004. “The policy relevance of virtual water can be enhanced by considering comparative advantages”. *Agricultural Water Management* 49, 131-151.

Wichelns, D., 2010. “Virtual water: A helpful perspective, but not a sufficient policy criterion”. *Water Resources Management* 24(10), 2203-2219.

World Bank, 1999. *Inter-Sectoral Water Allocation, Planning and Management*. Allied Publishers Limited, New Delhi.

World Water Assessment Programme, 2009. *Water in a Changing World*. United Nations World Water Development Report (WWDR3).

Zhu, Y., H. Chen, J. Fan, Y. Wang, Y. Li, J. Chen, J.X. Fan, S. Yang, et al., 2000. “Genetic diversity and disease control in rice”. *Nature* 406, 718-722.

# 6
# ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| APS | Alternative Policy Scenario of the International Energy Agency |
| AWDI | alternate wet/dry irrigation |
| B | boron |
| BAT | best available technologies |
| Ca | calcium |
| CA | Comprehensive Assessment of Water Management in Agriculture |
| CalCAN | California Climate & Agricultural Network |
| CBD | Convention on Biological Diversity |
| CCSP | US Climate Change Science Program |
| CGIAR | Consultative Group on International Agricultural Research |
| $CH_4$ | methane |
| CIA | Central Intelligence Agency |
| CIMMYT | International Maize and Wheat Improvement Centre |
| CIT | Center for Irrigation Technology |
| Cl | chlorine |
| CoV | coefficient of variation |
| CRF | controlled release fertilizer |
| CSP | concentrated solar power |
| Cu | copper |
| CUF | common urea fertilizer |
| DAP | diammonium phosphate |
| DPEP | Diesel Pumping Efficiency Program |
| EC | European Commission |
| ET | evapotranspiration |
| EU | European Union |
| EVA | ethylene vinyl acetate |
| FAO | Food and Agriculture Organization of the United Nations |
| FAOStat | Food and Agriculture Organization of the United Nations, Statistics Division |
| FAPRI | Food and Agricultural Policy Research Institute |
| Fe | iron |
| GBC | Global Biofuel Centre |
| GDP | gross domestic product |
| GHG | greenhouse gas |
| GIAM | Global Irrigated Area Mapping |
| GIZ | German Society for International Cooperation (Deutsche Gesellschaft für Internationale Zusammenarbeit) |
| GLADIS | Global Land Degradation Information System |
| $Gm^3$ | billion cubic meters |
| GOI | Government of India |
| GRACE | Gravity Recovery and Climate Experiment |
| GTZ | Deutsche Gesellschaft für Technische Zusammenarbeit |
| GW | ground water |
| GWP | greenhouse warming potential |
| GWSP | Global Water System Project |
| ha | hectare |
| $HCO_3$ | bicarbonate |
| HP | horsepower |
| ICID-CIID | International Commission on Irrigation and Drainage |
| iDE | International Development Enterprises |
| IEA | International Energy Agency |
| IFA | International Fertilizer Industry Association |
| INCID | Indian National Committee on Irrigation and Drainage |
| IME | Institution of Mechanical Engineers |
| INM | integrated nutrient management |
| IPCC | Intergovernmental Panel on Climate Change |
| IPM | integrated pest management |
| IRRI | International Rice Research Institute |
| ISRIC | International Soil Reference and Information Centre |
| ISU | Iowa State University |
| ITPGRFA | International Treaty on Plant Genetic Resources for Food and Agriculture |
| IWM | International Water Management Institute |
| K | potassium |
| $K_2O$ | potassium oxide |
| kJ | kilojoule |
| Kt | kilotonne |
| kWh | kilowatt-hour |
| LADA | Land Degradation Assessment in Drylands |
| LCA | life cycle analysis |
| LDPE | low-density polyethylene |
| LLDPE | linear low-density polyethylene |
| LER | land equivalent ratio |
| LUGE | Land Use and the Global Environment |
| MAS | marker-assisted selection |

| | |
|---|---|
| Mg | magnesium |
| MIS | micro-irrigation system |
| MJ | megajoule |
| Mn | manganese |
| Mo | molybdenum |
| MWh | megawatt-hour |
| N | nitrogen |
| n.d. | no date |
| $N_2O$ | nitrous oxide |
| NCADAC | National Climate Assessment Development Advisory Committee |
| NCPAH | National Committee on Plasticulture Applications in Horticulture |
| NDVI | Normalized Difference Vegetation Index |
| NGO | non-governmental organization |
| $NH_3$ | ammonia |
| Ninickel | |
| NOx | nitrates |
| NRAA | National Rainfed Area Authority |
| NUE | nitrogen use efficiency |
| $O_3$ | ozone |
| OECD | Organisation for Economic Co-operation and Development |
| OPPE | overall pumping plant efficiency |
| P | phosphorous |
| $P_2O_5$ | phosphorous pentoxide |
| PBL | Planbureau voor de Leefomgeving |
| PE | polyethylene |
| PHA | polyhydroxyalkanoate |
| PICS | Purdue Improved Cowpea Storage |
| PLA | polymerized lactic acid |
| PLENE | Syngenta's integrated solution that combines plant genetics, chemistry and new mechanization technology |
| PM10 | particulate matter smaller than 10 micrometers (µg) |
| PV | photovoltaic |
| PVC | polyvinyl chloride |
| S | sulfur |
| SEED | Small Engines for Economic Development |
| SFI | Syngenta Foundation India |
| SOLAW | The State of the World's Land and Water Resources for Food and Agriculture |
| SRI | System of Rice Intensification |
| SW | surface water |
| t | tonne (metric) |
| TALENs | transcription activator-like effector nucleases |
| $tCO_2e$ | tonnes of carbon dioxide equivalent |
| TDH | total dynamic head |
| UNDESA | United Nations Department of Economic and Social Affairs |
| UNEP | United Nations Environment Programme |
| US EPA | US Environmental Protection Agency |
| US | United States |
| USDA | United States Department of Agriculture |
| USGCRP | United States Global Change Research Program |
| WBCSD | World Business Council for Sustainable Development |
| WEF | World Economic Forum |
| WFN | Water Footprint Network |
| WHO | World Health Organization |
| Zn | zinc |

## About the WBCSD

The World Business Council for Sustainable Development is a CEO-led organization of forward thinking companies that galvanizes the global business community to create a sustainable future for business, society and the environment. Together with its members, the Council applies its respected thought leadership and effective advocacy to generate constructive solutions and take shared action. Leveraging its strong relationships with stakeholders as the leading advocate for business, the Council helps drive debate and policy change in favor of sustainable development solutions.

The WBCSD provides a forum for its 200 member companies – which represent all business sectors, all continents and combined revenue of more than US$7 trillion – to share best practices on sustainable development issues and to develop innovative tools that change the status quo. The Council also benefits from a network of 60 national and regional business councils and partner organizations, a majority of which are based in developing countries.

## Acknowledgments

**Written by Cecilia Borgia, Jaap Evers, Matthijs Kool and Frank van Steenbergen, MetaMeta**
MetaMeta provides research and consultancy services in water governance, and offers specialized communication products geared to the international resource management & development sectors. MetaMeta has also developed innovative new models for managing and monitoring complex programmes.

Nexus Model methodology prepared by Ankit Patel, Resourcematics Ltd.

Sincere gratitude and thanks to the WBCSD member companies and external experts who provided input and guidance throughout the process, in particular member companies that have provided case studies.

**Water Cluster leadership group (as of May 2014)**
Co-chairs: Borealis and EDF. Members: BASF, Bayer, Deloitte, DSM, DuPont, GDF Suez, Greif, Kimberly-Clark, Monsanto, Nestlé, PepsiCo, PwC, SABMiller, Schneider Electric, Shell, Suncor Energy, Unilever, Veolia.

**This piece of work was led by WBCSD water team**
Violaine Berger, Joppe Cramwinckel, Tatiana Fedotova, Julie Oesterlé.

business solutions for a sustainable world

World Business Council for Sustainable Development
Maison de la Paix, Chemin Eugène-Rigot 2, Case postale 246, 1211 Geneve 21, Switzerland, info@wbcsd.org, Tel. +41 (0)228393100