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

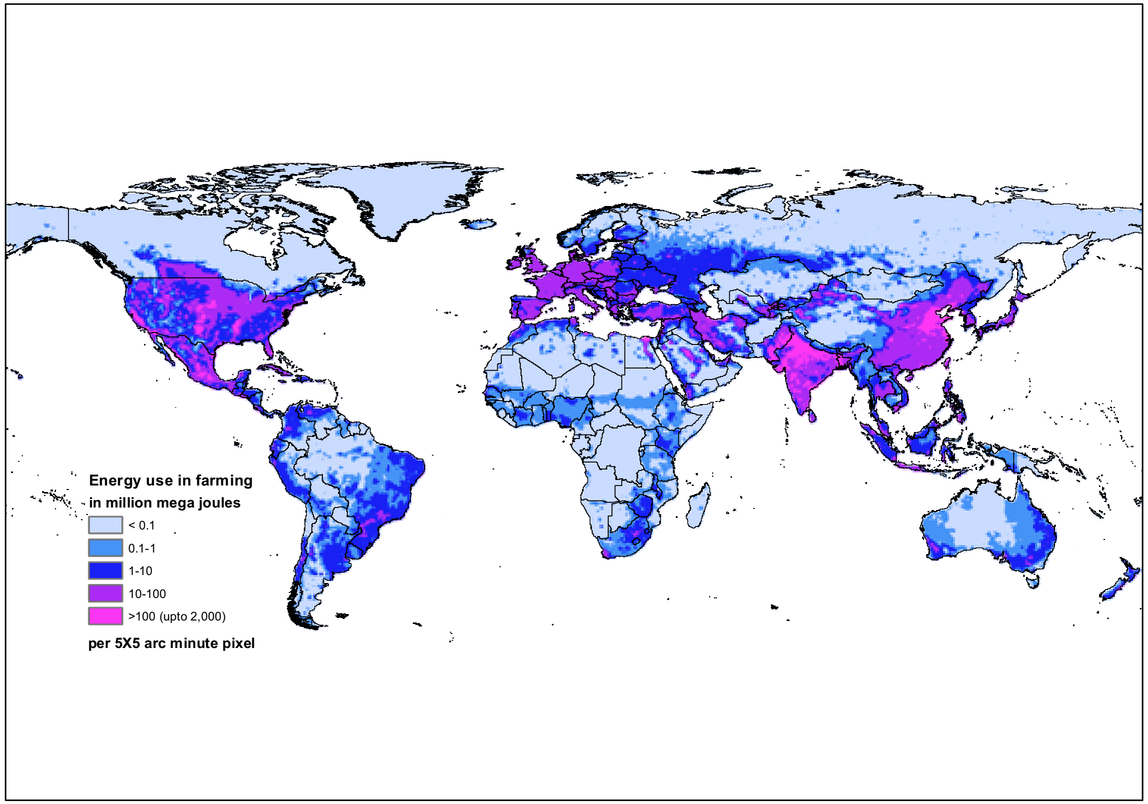
1
INTRODUCTION

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.

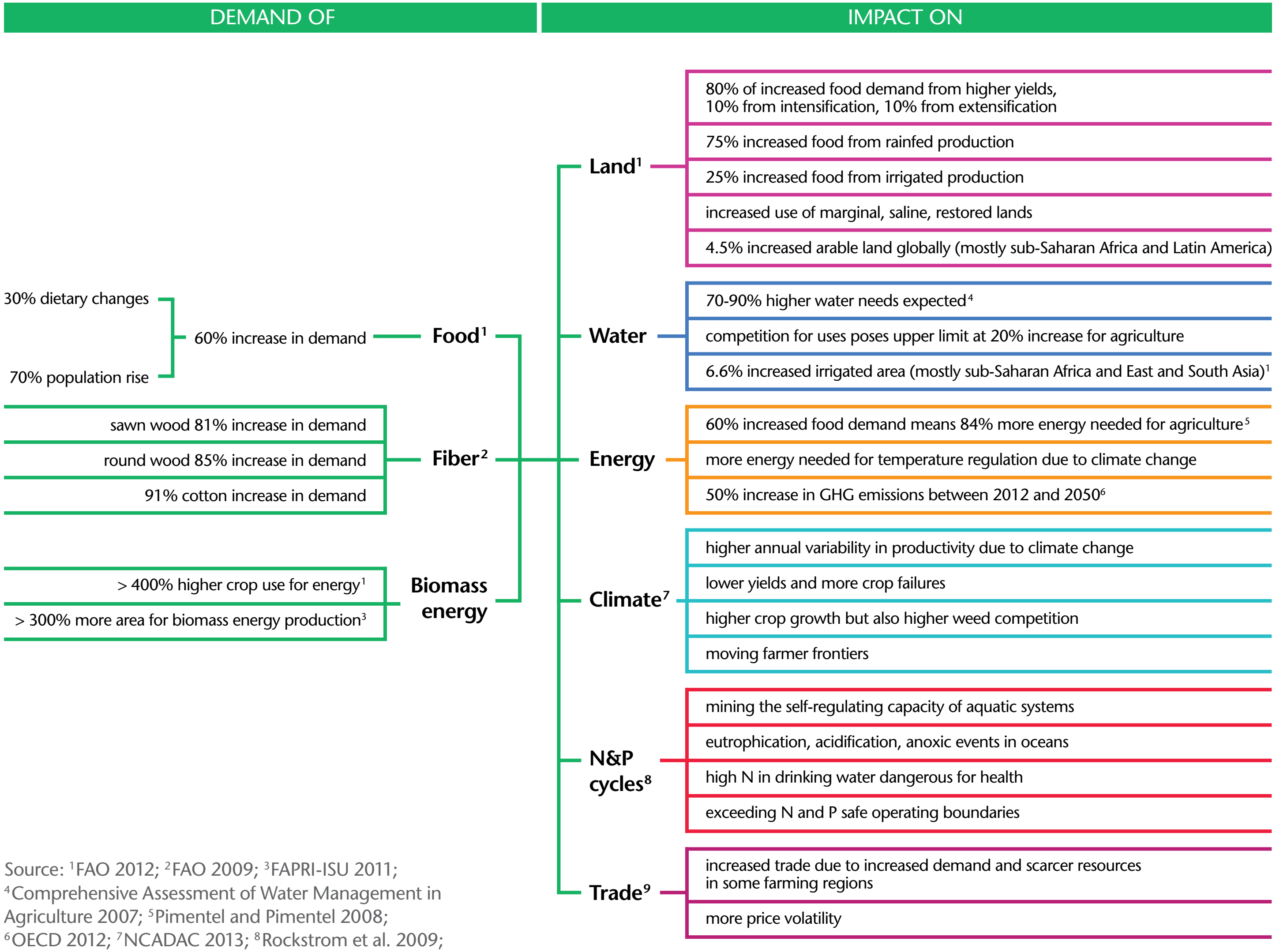
The main challenges are:

- 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% Maize: 30-165% Wheat: 25-35% 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 greenhouse 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 rice9 by 2050. This is far beyond the projected global cereal demand of 3 billion tonnes in 205010 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.

SMART CROP MANAGEMENT

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.)

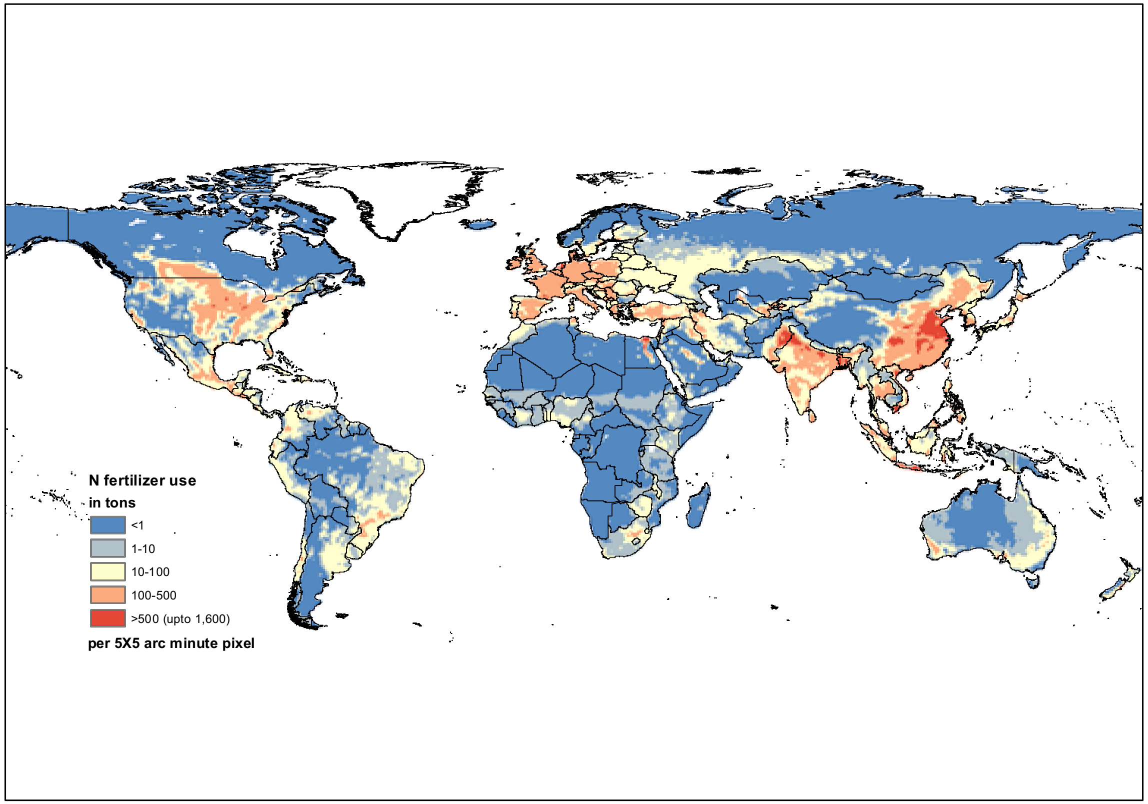
Efficient fertilizer use

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

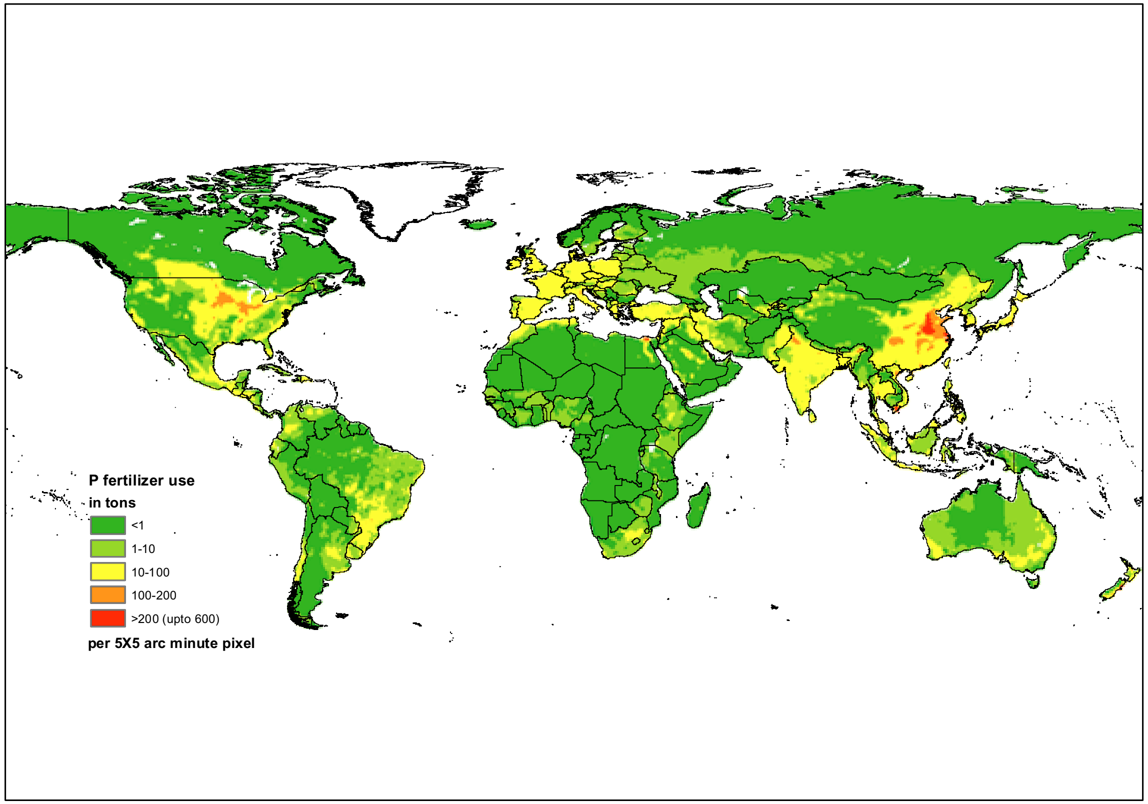


Source: WBCSD Nexus Model, prepared by Resourcematics Ltd., 2013

[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

Figure 3b

Spatial patterns of phosphorous fertilizer use

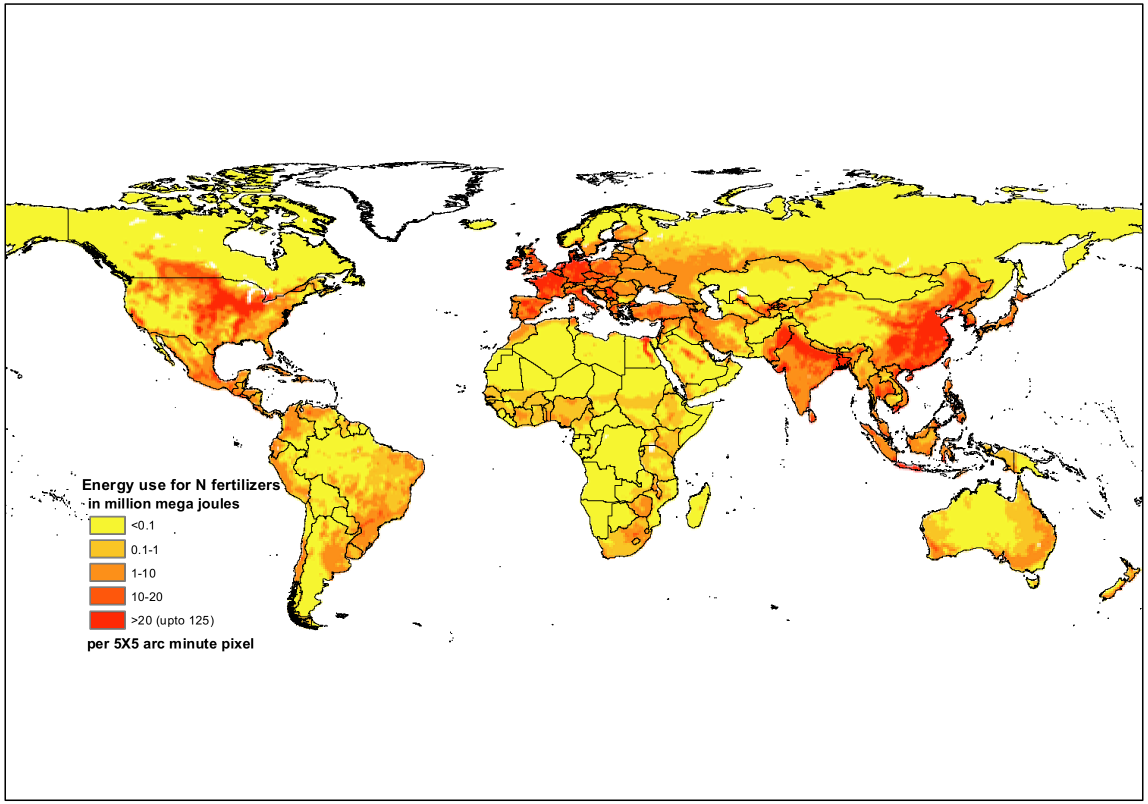


Source: WBCSD Nexus Model, prepared by Resourcematics Ltd., 2013

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

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

SMART CROP MANAGEMENT

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/m3 water; for rice 0.5-2.0 Kcal/m3 water; for corn 1.0-7.0 Kcal/m3 water; for lentils 0.8-3.2 Kcal/m3 water; for groundnut 0.8-3.2 Kcal/m3 water; and for apples 0.52-2.6 Kcal/m3 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

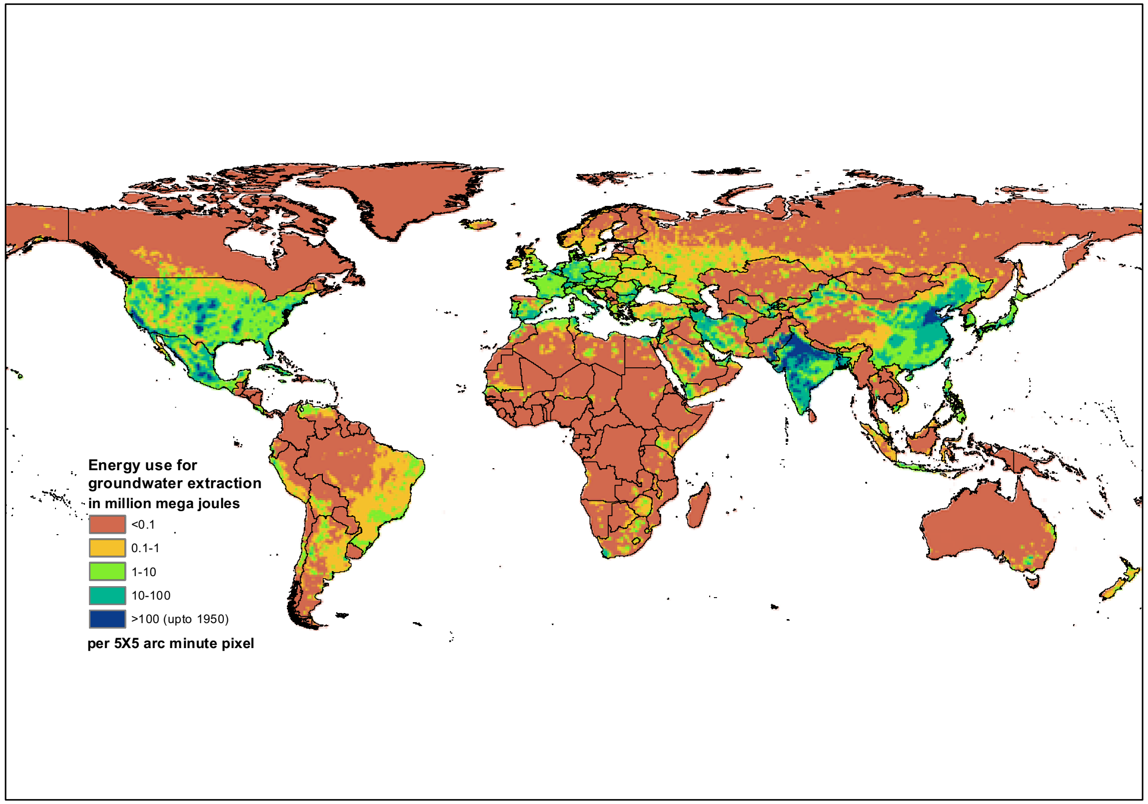
	Spread	Yield	Energy	Water	Climate
Precision irrigation					
Precision systems – i.e,. drip, micro-sprinkler combined with fertigation	Still on less than 2% of irrigated area; groundwater systems (40%), horticulture	10-54% higher in vegetables	29-44% energy savings[i]	30-70% water savings but also less 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

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

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

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 km^3, 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

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

REDUCING FOOD LOSS AND WASTE

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
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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
Ni	nickel
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

7
ANNEXES

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

DESCRIPTION OF NEXUS MODEL METHODOLOGY

Contents

1 Rationale

Businesses have recognized a clear need to develop new solutions to deal with the interconnectedness of water, energy and food, feed and fiber. The challenge is to provide more food, fiber and fuel in a growing and more affluent world and at the same time to be more efficient in the use of water and energy – both vital resources already under strain. Moreover, it is not only necessary to save water and energy but also other resources, such as land and scarce minerals, while mitigating and adapting to climate change.

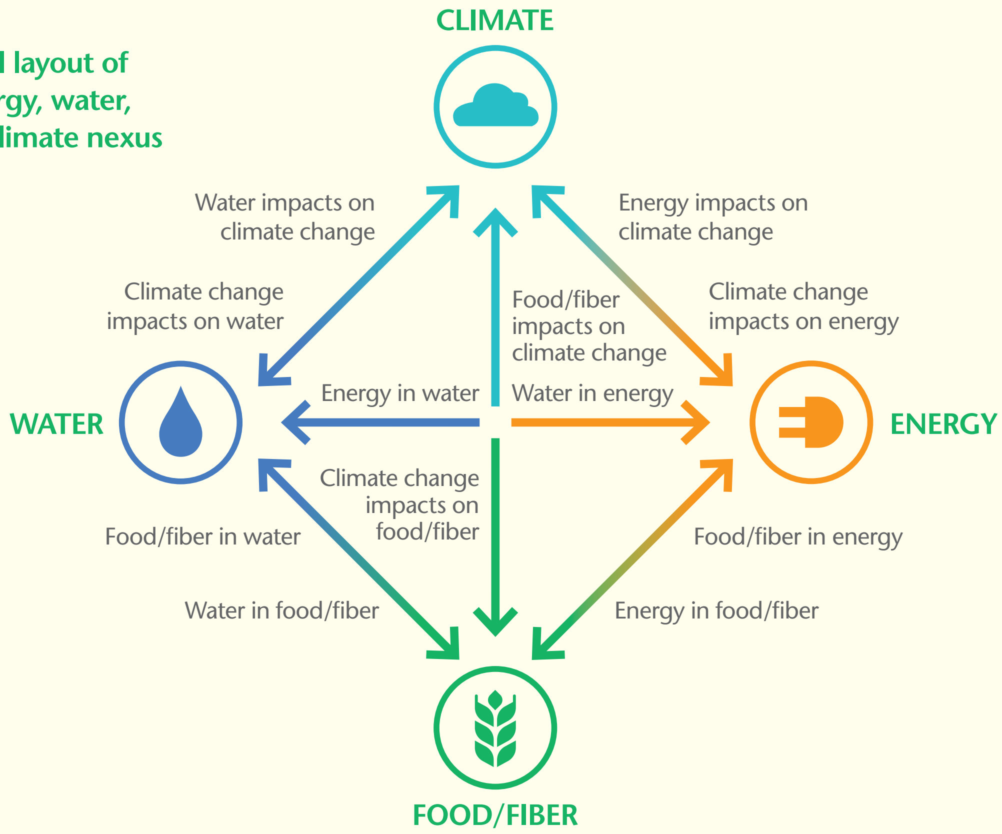
The WBCSD's climate, water, energy and food nexus pathway reflects business actions in the search for co-optimized solutions.

Analytical work has been done to understand the nexus linkages at the national as well as at the regional levels. A systematic approach was required to address such vast and complex topics. The approach adopted here builds upon existing knowledge and science.

This document briefly describes the methodology of the WBCSD's nexus modeling. It also offers some promising directions in terms of a solutions feed, having identified, understood and quantified the interconnectedness of the nexus.

The framework aims to inform national, regional and global policies and regulations while offering businesses an effective tool to assess risks and opportunities. It is important to note that its wider application and usefulness is currently restricted due to the technical and complex data structure of the output. Hence a simpler, intuitive user interface is recommended to amplify the impact of the model.

Figure 1
Conceptual layout of water, energy, water, food and climate nexus



2 Objectives and framework

- Develop long-term insights for short-term responses to the water, energy, food/feed/fiber/fuel and climate change nexus.
- Understand and document the linkages between water, energy, food/feed/fiber/fuel and climate change and develop policy and technology options to address the challenges identified.

The WBCSD kick-started the work on water and energy in October 2007 which led to the publication of *Water, Energy and Climate: A contribution from the business community* in March 2009. In 2012, the WBCSD carried out analytical work to guide businesses in making strategic decisions. The objective of this analysis was to answer the following questions:

- What are the constraints on the availability of water and energy resources as a result of future demand for food/feed/fiber/fuel/biomaterials?
- Which crops and geographies of interest can be considered hotspots today and in 2030, 2050? Why?
- If yield intensification is associated with high water and energy use in crops, then how does this translate into additional water and energy required if the intensities are scaled up to meet demand?

This publication describes the conceptual framework, scope of work and modeling methodology of the WBCSD's nexus pathway. It focuses specifically on targets for:

1 Water demand for energy (i.e. power and fuel types)

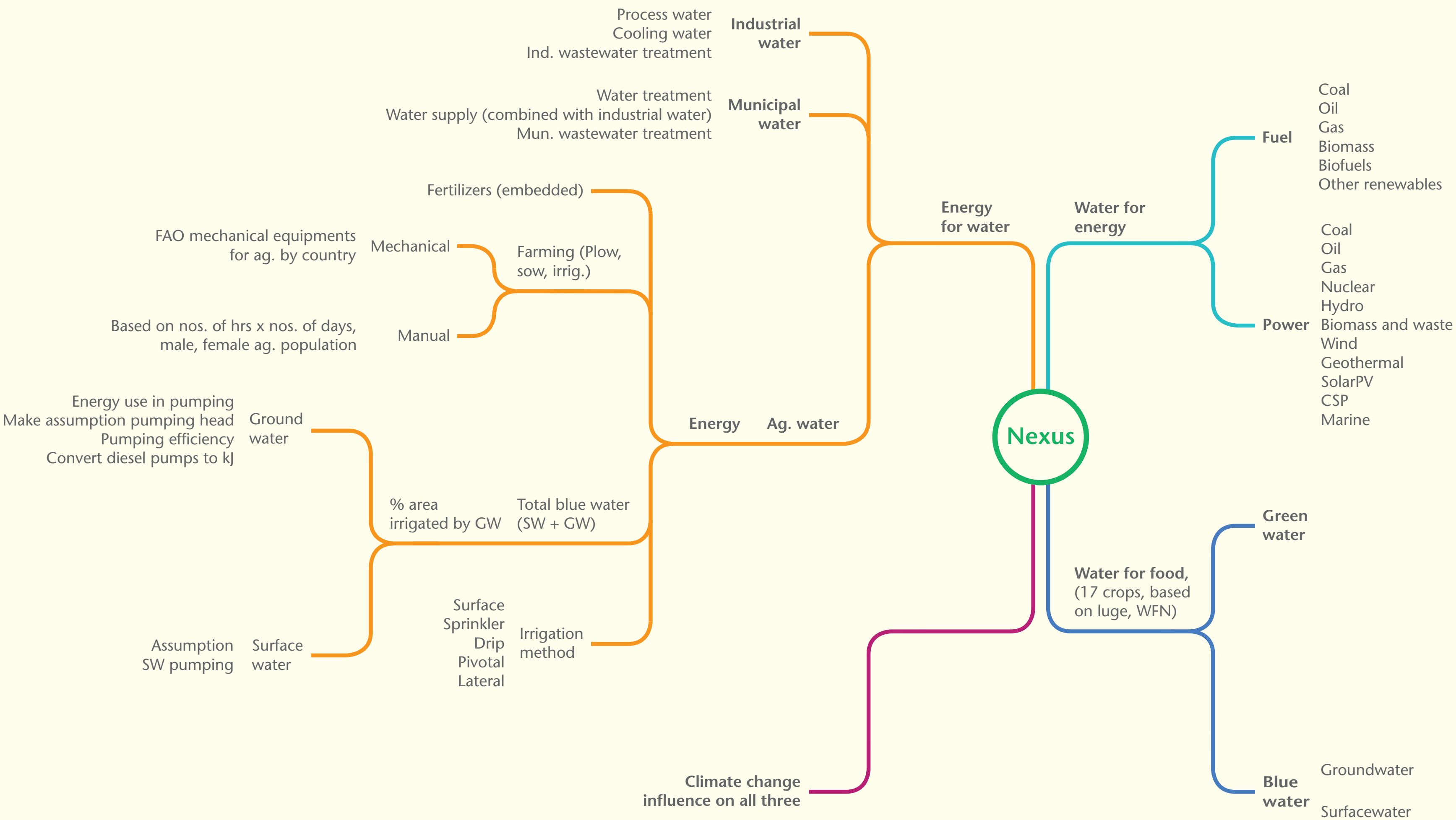
2 Water demand for food, feed, fuel and fiber (i.e., crops)

3 Energy demand for water supply and treatment (only the agriculture sector will be a focus in this phase; municipal and industrial sectors are left for the next phase)

4 Energy demand for food production (i.e., within farms for crop production)

A conceptual plan for the modeling work is illustrated in figure 1. So far, quantitative analysis of water demand for energy (number 1 above) and water demand for food (number 2 above) have been completed. This is illustrated on the right-hand side of figure 1. Current and future work will focus on the left-hand side of the flow diagram. At present, only energy demand for agriculture will be considered; energy demand for industrial water and municipal water has been identified as future work.

Figure 2
Conceptual framework for nexus modeling



3 Scope of work

1 Water demand for energy (i.e. power and fuel types)

a Water demand for energy has been broadly categorized into i) fuel and ii) power.

b Fuel has been further subdivided into coal, oil, gas, biomass, biofuels and other renewables.

c Power has been subdivided into coal, oil, gas, nuclear, hydro, biomass and waste, wind, geo-thermal, solar photovoltaic (PV), concentrated solar power (CSP) and marine.

2 Water demand for food, feed, fuel and fiber (i.e., crops)

a Seventeen crop categories have been identified for the analysis of water (and energy) demand for food crops. These crops are listed in appendix 1.

b The 17 crops identified account for around two-thirds of total agriculture water and roughly the same amount of area harvested globally.

3 Energy demand for water supply to agriculture

a This includes energy demand for only blue water for supply at farm gates, e.g., groundwater pumping and surface water supply.

b Energy demand for green water (i.e., rainwater, soil moisture) is out of the scope of this work.

4 Energy demand for farming (i.e., within farms for crop production)

a Energy demand within farm gates is considered in this analysis. Energy demand for farming includes:

i Farming, e.g., plowing, sowing, harvesting; this is subcategorized into manual and mechanical energy

ii Irrigation methods, e.g., surface/flood, sprinkler, drip, pivotal, lateral

iii As an exception, embedded energy in fertilizers is considered here; this is attributed to the selected crops and locations.

iv Energy for seeds, insecticides and pesticides has been left out due to lack of data and with the assumption that energy demand from these categories will be insignificant; this hypothesis could be checked in the future through a review of literature.

5 Solutions feed

a The solutions feed is the important component of the modeling. Once the problem is quantified, with reference to the water, energy and food nexus, various solution pathways are applied by adjusting and fine-tuning water, energy and food indicators.

b This model focuses on smart varieties of seeds, pressurized irrigation, effective fertilizer application, alternative farming practices and pumping efficiency. A detailed list of various solution pathways is given in appendix 3.

c The economic costs of each solution pathway have been identified as a future scope of work.

6 Climate change

a This is carried out in the final phase of the modeling. Various climate change scenarios are applied to project future energy, water and food supplies. However, climate change impacts that are already known through a review of the literature are applied during projections of water, energy and food supplies.

4 Methodology

1 Water demand for energy (i.e., power and fuel types)

a Detailed methodology and data can be found in Schornagel, J. et al. 2012.

2 Water demand for food, feed, fuel and fiber (i.e., crops)

a Blue water and green water

i Detailed methodology for green and blue water for crop production can be found in "The green, blue and grey water footprint of crops and derived crop products".[1]

ii Spatial resolution of the Water Footprint Network (WFN) output is available in 5-by-5 minutes latitude and longitude (i.e., approximately 9X9 km at the equator).

b Global crop area and yield

i Crop yield and crop area harvested is based on Monfreda et.al. 2008.

ii Spatial resolution of Land Use and the Global Environment (LUGE) output is available in 5-by-5 minutes latitude and longitude (i.e., approximately 9X9 km at the equator).

c Irrigation efficiency

i Data for irrigation efficiency was taken from International Water Management Institute (IWMI). The study is based on Seckler et al. 1998.

d Groundwater use

i Data on global groundwater use was taken from two different sources. Groundwater use for irrigation was taken based on Siebert et al 2010.

ii Spatial allocation of groundwater and area and size of aquifers was based on Gleeson et al. 2012.

e Socioeconomic data on agriculture

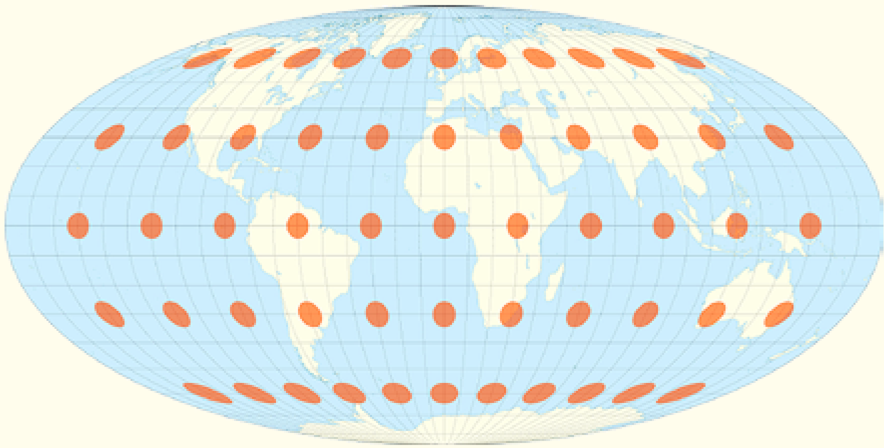
i Data such as population (male and female) engaged in agriculture, share of agriculture in national gross domestic product (GDP) and mechanization in agriculture was based on FAOStat.

f Fertilizer use data

i Spatial allocation of fertilizer use data was taken from Potter et al. 2010.

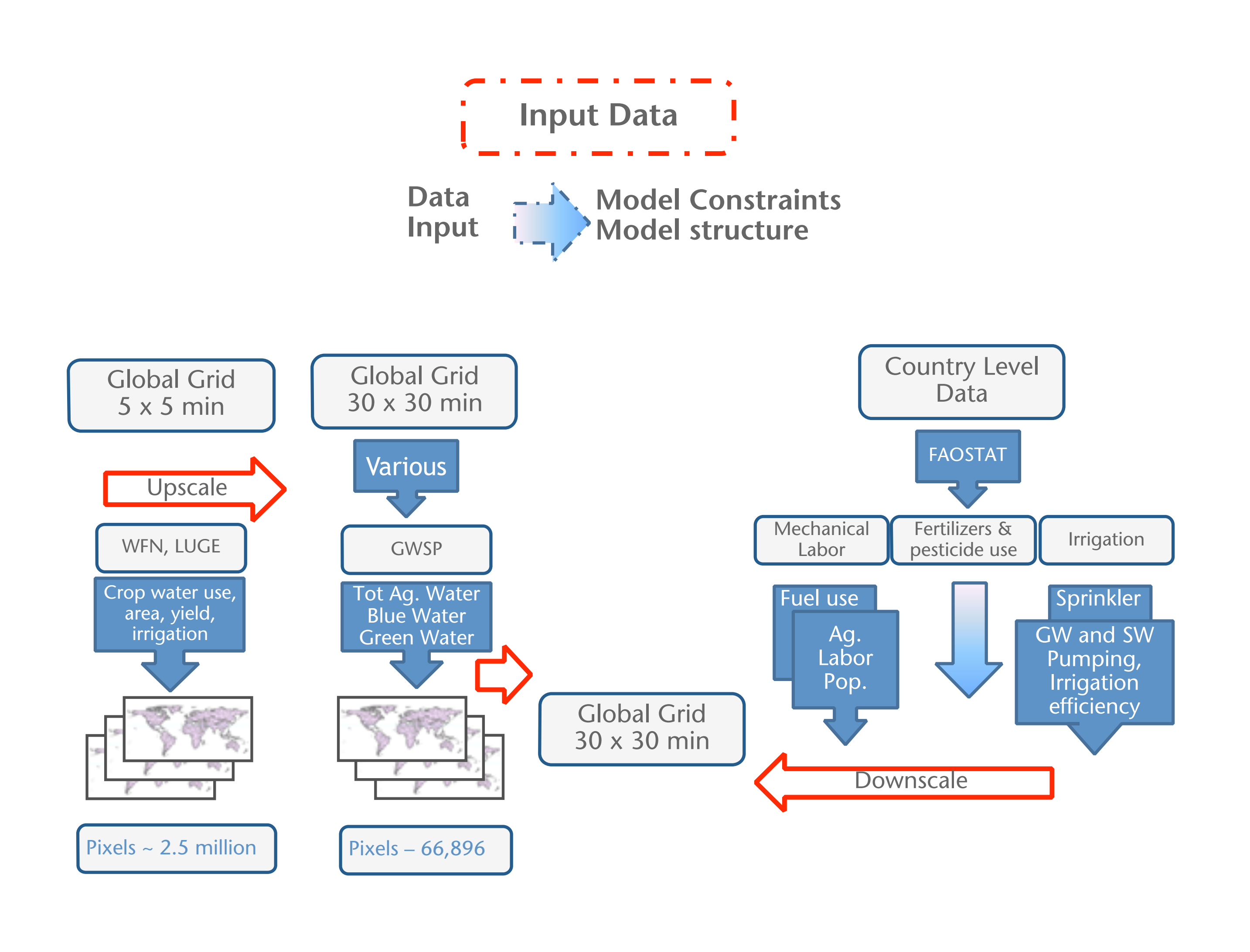
ii Fertilizer use by crop in each individual country was based on FAO 2006.

Figure 3
Geographic projections



[1]Mekonnen and Hoekstra, 2011

Figure 4
Conceptual layout of model



g Spatial resolution, upscaling and downscaling

i The resolution of the WBCSD model was kept at 30-by-30 minutes (i.e., 0.5 X 0.5 degrees; approximately 55 X 55 km at the equator).

ii Data available in finer resolution were upscaled and the coarser resolution data were downscaled. However, it is possible to convert all datasets into 5 X 5 min. resolution, which will require additional computational calculations.

iii Water demand for energy pathways is analyzed at country level. This is considered as a sufficient unit.

iv Data such as total water consumption (blue and green) from the WFN and LUGE were upscaled to 30 X 30 minutes. This was done by taking average or sum as appropriate of each of the 36 5-by-5 arc minute grid cells contained in the 30-by-30 arc.

v For attributes such as water consumption (both green and blue) and total area harvest for a given crop, the sum of all 36 5-by-5 arc minutes grid cells was taken. In the case of crop yields, the average of each 5-by-5 arc minutes falling within 30-by-30 arc minutes cell was taken.

Figure 5
Methodology for upscaling

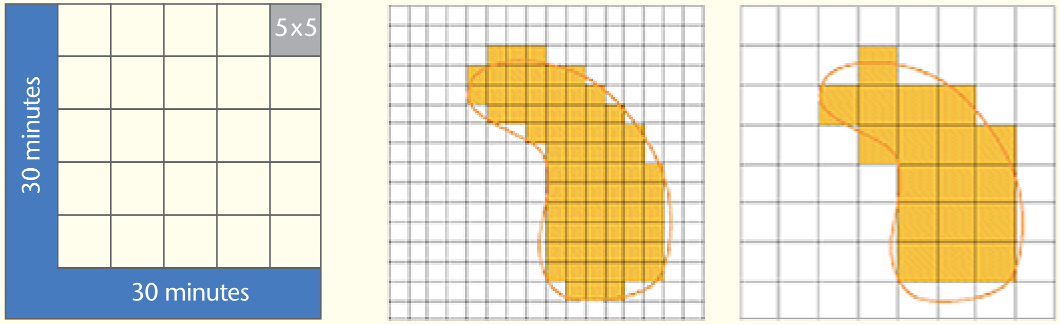
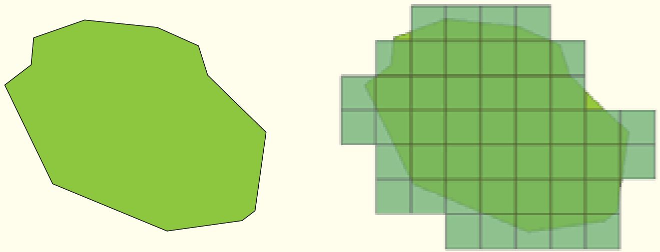


Figure 6
Methodology for downscaling



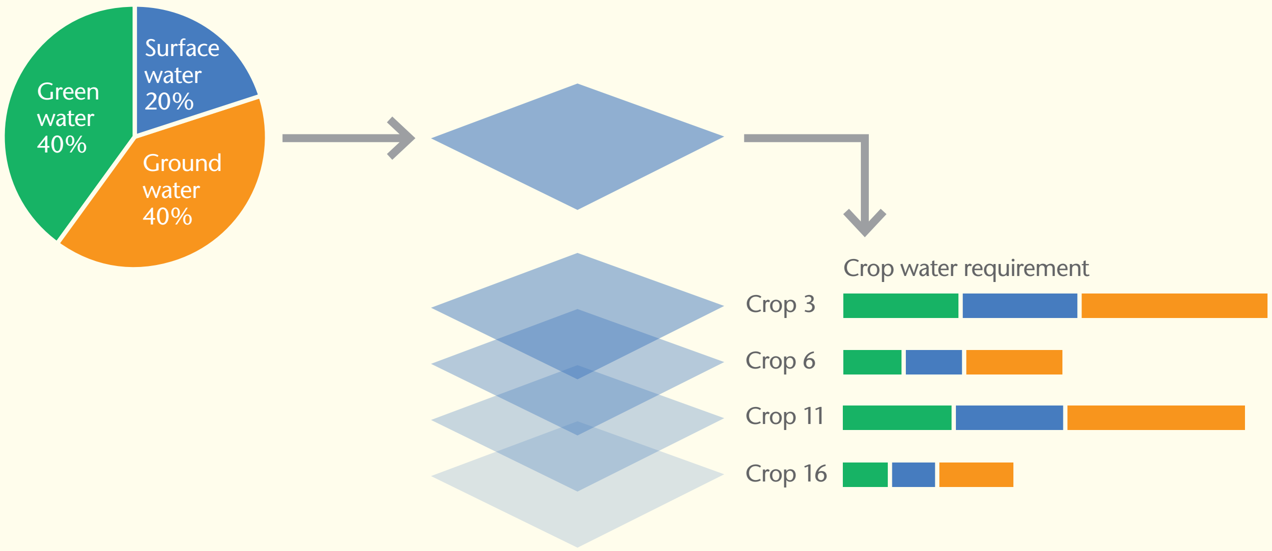
vi The model uses IWMI's irrigation efficiency (2c above). The irrigation efficiency is available at country level; the same irrigation efficiency has been applied to all pixels falling in the respective country polygon. Further, all crops grown in a given pixel were assumed to have the same irrigation efficiency.

vii The assumption has been made that the same proportion of groundwater (or surface water and rainwater) is applied to all crops falling within a given pixel. Figure 7 illustrates a logical method of water accounting for an individual crop. For instance, a given pixel receives groundwater (40%), surface water (20%) and rainwater/green water (40%). This proportion was applied to all crops grown in this pixel.

viii These are significant generalizations, but it is expected that the model will offer flexibility to users to adjust these numbers (refer to model's user interface).

Figure 7

Conceptual diagram – water accounting for blue and green water for individual crop in a pixel



3 Energy demand for water supply to agriculture

a Total groundwater use for a given crop is estimated based on 2d (groundwater use) and 2e (socioeconomic data on agriculture).

b Area and size of groundwater aquifers is based on Gleeson et al. 2012.

c Groundwater is estimated based on levels indicated in a literature review; expert opinion is crucial for this exercise.

d Energy use for pumping groundwater is estimated based on Shah et al. 2009, Rothausen and Conway 2011, and Wang et al. 2007.

e The energy requirement for groundwater pumping is calculated based on,

$$\text{Energy (kWh)} = \frac{9.8\ (\text{m s}^{-2}) \times \text{lift (m)} \times \text{mass (kg)}}{3.6 \times 10^6 \times \text{efficiency (\%)}}$$

f All energy use is converted into kilojoule (kJ).

g If there is demand among businesses for energy use for pumping groundwater in India, China and the U.S. (as they are the largest abstractors) at sub-national level, it can be calculated in detail.

h To estimate energy use for irrigation water application, two matrixes were developed: i) irrigation efficiency by technology (table 1) and ii) area covered under various irrigation methods by country.

i The energy use for irrigation method was taken based on a literature review. Table 2 gives values adopted in the model.

j Each country is allocated a proportion of drip, sprinkler, pivot, surface and other irrigation methods based on a literature review. Appendix 4 gives the values for each country.

k Total energy use for irrigation application is estimated based on the area under various irrigation methods, water efficiency under each method and water used under irrigation methods.

Table 1
Percentage of irrigation efficiency

Irrigation method	Lower	Mean	Upper
Automated irrigation	75%	90%	95%
Sub-surface drip	75%	90%	95%
Drip (micro irrigation)	70%	85%	95%
Lateral (linear)	80%	85%	87%
Pivotal (standard)	75%	80%	90%
Sprinkler	60%	75%	85%
Lateral (movable)	60%	70%	80%
Surface	25%	40%	55%

Source: Howell, 2003

Table 2
Energy use for irrigation application, kWh per cubic meter

Sprinkler irrigation	0.20
Drip irrigation	0.38
Pivot irrigation	1.01

4 Energy use for fertilizer production

a Energy use for fertilizer use is based on Gellings and Parmenter 2004. (Table 3)

b As mentioned in section 2f, spatial allocation of fertilizer use has been adopted from Potter et al. 2010.

c Global average energy use in kJ per kg was applied to LUGE fertilizer use data.

d Energy use for fertilizer is available for production (Prdt_kgpkg), packaging (Pckg_kgpkg), transport (Trnp_kjpkg), application (Apli_kjpkg) and total (Enr_kjpkg).

e The units for all are kJ per hectare.

Table 3
Global average of energy use for fertilizer, kJ/kg

	Nitrogen	Phosphate	Potash
Produce	69,530	7,700	6,400
Transport	4,500	5,700	4,600
Package	2,600	2,600	1,800
Apply	1,600	1,500	1,000
Total	78,230	17,500	13,800

Source: Gellings and Parmenter 2004

5 Energy demand for farming (i.e., within farms for crop production)

a Energy use for mechanical farming is estimated based on FAOStat. The dataset gives mechanical farming equipment used at country level. Expert opinion and literature review are carried out to assess total inputs required for individual crop. Again, normalization and generalization are made across country.

b Energy use for manual farming with the help of human inputs and animal inputs are estimated based on demographic data. The estimate is made based on:

> *Total male and female population engaged in agriculture X total hours spent for various farming activities, e.g., plowing, sowing, harvesting and other items, X total energy (calories) burned per hour of each activity*

c Energy use for various irrigation methods is based on a literature review, commercial equipment brochures and interviews with irrigation equipment suppliers (e.g., Jain Irrigation Systems, International Development Enterprises (iDE), netafim). Distribution of irrigation methods across geographies and crops is based on expert opinion and equipment suppliers' interviews.

d Use of fertilizers across geographies is estimated based on FAOStat (resources) and IFA n.d. Fertilizer use across crop and across country is estimated based on FAO 2006. Energy use for fertilizer production is estimated based on a literature review, e.g., Gellings and Parmenter 2004 and IPCC n.d.

e Minor adjustments and alterations are made as per the requirement and with availability of new data.

6 Solutions feed

a For the time being, only smart variety seeds, pressurized irrigation, effective fertilizer application, alternative farming practices and pumping efficiency are considered for the modeling work.

b The solution feed also reviews literature on future crop production and crop yield projections by geographical area, including the influence of climate change.

c Some of the qualitative data is converted into quantitative data by assigning appropriate values and numbers. This is carried out on case-by-case basis.

d It is understood that since solutions are based on a literature review and case studies, generalization at large scale is not strictly appropriate. However, the aim of the model is to guide business decisions by answering generic "what-if" type questions with reference to comprehensive nexus perspectives.

e Again, the user interface offers flexibility to users to adjust some of the parameters and to make the model more relevant to ground realities.

5 Status of work

1 Water demand for energy

a Water demand for energy is complete and output can be found in Schornagel et al. 2012.

2 Water demand for food crops

a Water demand for 17 food crops (both green and blue) is complete and output is available in GIS format at 30-by-30 arc minutes resolution.

3 Energy demand for agricultural water

a Energy demand for agriculture water supply, mainly groundwater pumping, is available in GIS format at 30-by-30 arc minutes resolution.

b Energy demand for irrigation application for drip, sprinkler and pivot is available at country level in Excel format as well as in GIS format at 30-by-30 arc minutes resolution. However, it should be noted that country level numbers are equally distributed at pixel level. Therefore, it may not be accurate to compare sub-national level variation.

4 Energy demand for fertilizer application

a Energy demand for fertilizer application is available in GIS format at 30-by-30 arc minutes resolution for nitrogen and phosphorus.

5 Energy demand for farming

a Energy demand for farming due to mechanization and manual labor is currently being analyzed.

6 Visualization of solutions feed

a Various means of visualizing the solutions feed are under development.

6 User interface – geographic visualization

a The current output (as well as future energy demand for food and agricultural water) needs two additional features to make better informed decisions:

  i A comprehensive picture of water, energy and food: Currently, various maps and spreadsheets of indicators remain independent and do not interact with each other; and

  ii Solution feeds: This will be at least as important as identifying and narrating a problem. Eventually businesses would like to ask "what-if" type questions and see results to make decisions.

b The next phase of the nexus modeling aims to combine the above two – linking all water, energy and food pieces together and providing solution feeds to users. The objective of the user interface is to offer companies a linkages tool to make strategic business decisions.

c The tool will answer "what if" scenarios backed by the spreadsheet numbers in various cross sections with past, current and future trends; it allows users to run queries and get answers.

7 Appendices

Appendix 1
Crop selection**

Crop number	Crop	Category
1	Barley	Food/bioenergy/biofuel
2	Cassava	Food/bioenergy/biofuel
3	Coconut	Food/bioenergy/biofuel
4	Coffee	Food/bioenergy/biofuel
5	Cotton	Fiber
6	Groundnut	Food/bioenergy/biofuel
7	Maize	Food/feed/bioenergy/biofuel
8	Millet	Food/feed/bioenergy/biofuel
9	Palm oil	Food/bioenergy/biofuel
10	Potatoes	Food/bioenergy/biofuel
11	Rapeseed	Food/bioenergy/biofuel
12	Rice	Food/bioenergy/biofuel
13	Sorghum	Food/feed/bioenergy/biofuel
14	Soybean	Food/feed
15	Sugarcane	Food/bioenergy/biofuel
16	Sunflower	Food/bioenergy/biofuel
17	Wheat	Food/bioenergy/biofuel
18	Rest of all	Food/feed/fiber/bioenergy/biofuel

** Note: Commercial plantation crops such as eucalyptus, pine, etc. will be added to this list as the data becomes available.

Appendix 2
Additional data sources and information

Sr.no	Sources and type of data	Output
1	**Collection and analysis of secondary data**	**Global, national**
	1 Data collection and analysis a FAO AQUASTAT b FAOStat (crop production, land resources, consumption, trade, price and food balance data) c Population (UNStat) d GDP (IMF) e Energy data (IEA/US EIA) f Published literature	Analysis and insight used for presentations/papers and to build the model
2	**National administrative boundaries overlay to Global Water System Project (GWSP) point maps**	**National + sub-national**
	2 GWSP data (0.5X0.5 degree) maps, (GWSP_ Withdrawal) a Total agriculture water = Irrigation water (waterwithdrirrigation) + Livestock water (waterwithdrlivestock), km^3 b Blue water (bluewater1_0), km^3 c Green water (Green water consumption on cropland), km^3	Per country water withdrawal, a Agri b Blue c Green
3	**Land use analysis**	**National + sub-national**
	3 GIAM/University of Kassel a Land use map (Kassel) (global land use, LADA Land Use System) b Area and volume of irrigation water, by crops (GIAM)	a Area under irrigation (preferably GW/SW b Arable, pasture, forest land (various classifications) c irrigation water volume, km^3 (joint exercise with IWMI)

Appendix 2 (continued)
Additional data sources and information

Sr.no	Sources and type of data	Output
4	**Data validation/comparison with other sources**	**National data**
	4 Output 2(a) with 3(c) as well as FAO land data, FAO AQUASTAT (ResourceSTAT-Land1.xls) 5 Output 2(b), (c) with Water Footprint Network (WFN) country/point data	adjusted water withdrawal, a Agri b Blue c Green d Irrigation water (GW/SW)
5	**Country level primary and secondary data**	**National**
	6 Fertilizer use a FAO Fertistat +(ResourceSTAT-Fertilizers1) IFA, fertilizer.org 7 Mechanization energy use a FAO (Resources > ResourceSTAT-Machinery 1.xls) b John Deere c Pimental 8 Occupation type a Demographic data (UNStat) b Occupation categories (FAO – Resources > PopSTAT-Annual-Time-Series1.xls)/CIA Factbook) 9 Pesticide consumption a FAO (Resources > ResourceSTAT-Pesticides_ Consumption1) 10 Water management practices a Area under sprinkler/drip irrigation b SW/GW pumping	a Fertilizer use, interpolation energy use b Mechanization, interpolation energy use c Labor inputs, interpolation energy use d Pesticide inputs, interpolation energy use e Irrigation water (GW/SW), interpolation energy use

Appendix 2 (continued)
Additional data sources and information

Sr.no	Sources and type of data	Output
6	**Primary data collection**	**National + sub-national**
	11 Water productivity (m^3/tonne) for all 17 crops	
	12 Energy productivity (GJ/tonne) for all 17 crops (as many as possible)	
7	**Groundwater data analysis**	**Global, national**
	13 GRACE data	
8	**Overlay of Global maps to 0.5X0.5 grid map**	**Global, national + sub-national**
	14 Koppan climate class map	Global, national + sub-national
	15 Geological map http://portal.onegeology.org	
	16 Global NDVI CoV	
	17 Potential rainfed ag. Production (food_I_e00)	
9	**Analysis of 0.5X0.5 grid map**	**National + sub-national**
	18 Mean annual ET 1950-2000	
	19 Mean annual precipitation 1950-2000	
	20 Mean annual runoff 1950-2000	
10	**Advancement of the model**	**National + sub-national**
	21 Incorporate external models/outputs, ex. IMPACT, GIAM, IEA	

Acronyms:
GW: groundwater; SW: surface water; GIAM: Global Irrigated Area Mapping, IWMI's research; NDVI: Normalized Difference Vegetation Index; CoV: Coefficient of Variation; ET: Evapotranspiration; GRACE: Gravity Recovery and Climate Experiment

Appendix 3
Area under irrigation, by method, in hectares

Country	Total irrigation area	Drip irrigation	Sprinkler	Pivot	Other	Surface
Afghanistan	3,759,391.90	75.19	187.97	375.94	1,879.70	3,756,873.11
Albania	341,918.10	34.19	170.96	34.19	170.96	341,507.80
Algeria	811,777.20	8.12	162.36	81.18	405.89	811,119.66
American Samoa	1.00	0.01	0.00	0.00	0.00	0.99
Angola	151,213.10	3.02	7.56	15.12	75.61	151,111.79
Antigua and Barbuda	126.60	0.63	6.33	0.01	0.06	119.56
Argentina	2,264,278.60	679.28	1,132.14	226.43	1,132.14	2,261,108.61
Armenia	314,436.70	125.77	157.22	31.44	157.22	313,965.05
Australia	2,579,697.50	2,063.76	206,375.80	25,796.98	1,289.85	2,344,171.12
Austria	118,238.50	59.12	59.12	11.82	59.12	118,049.32
Azerbaijan	1,527,285.80	305.46	763.64	152.73	763.64	1,525,300.33
Bahamas	1.00	0.00	0.00	0.00	0.00	1.00
Bahrain	5,636.50	28.18	112.73	0.56	2.82	5,492.21
Bangladesh	3,831,726.10	191.59	191.59	191.59	1,915.86	3,829,235.48
Barbados	1,536.60	7.68	76.83	0.15	0.77	1,451.17
Belarus	131,412.90	65.71	65.71	13.14	65.71	131,202.64
Belgium	65,895.70	0.66	32.95	6.59	32.95	65,822.56
Belize	25,329.40	0.25	2.53	2.53	12.66	25,311.42
Benin	32,292.60	161.46	9.69	3.23	16.15	32,102.07
Bermuda	1.00	0.01	0.05	0.00	0.00	0.94
Bhutan	45,184.30	2.26	2.26	4.52	22.59	45,152.67
Bolivia	219,486.50	658.46	109.74	21.95	109.74	218,586.61
Bosnia and Herzegovina	9,446.90	47.23	0.94	0.94	4.72	9,393.05
Botswana	6,824.20	34.12	0.34	0.68	3.41	6,785.64

Source: Based on authors' estimation.

Appendix 3 (continued)
Area under irrigation, by method, in hectares

Country	Total irrigation area	Drip irrigation	Sprinkler	Pivot	Other	Surface
Brazil	3,452,562.50	172,628.13	1,035,768.75	345,256.25	1,726.28	1,897,183.09
Brunei	1,569.00	47.07	47.07	0.16	0.78	1,473.92
Bulgaria	814,614.60	40.73	162.92	81.46	407.31	813,922.18
Burkina Faso	39,477.20	0.39	11.84	3.95	19.74	39,441.28
Burundi	34,114.20	3.41	1.71	3.41	17.06	34,088.61
Cambodia	421,149.40	84.23	21,057.47	42.11	210.57	399,755.01
Cameroon	51,168.90	0.51	2.56	5.12	25.58	51,135.13
Canada	921,246.20	184.25	184.25	92.12	460.62	920,324.95
Cape Verde	3,186.20	95.62	0.32	0.32	1.59	3,088.35
Cayman Islands	1.00	0.00	0.00	0.00	0.00	1.00
Central African Republic	523.80	0.01	0.05	0.05	0.26	523.43
Chad	58,648.50	0.59	2.35	5.86	29.32	58,610.38
Chile	2,181,787.80	21.82	218.18	218.18	1,090.89	2,180,238.73
China	61,731,358.00	740,776.30	1,358,089.88	370,388.15	30,865.68	59,231,238.00
Clipperton Island	1.00	0.00	0.00	0.00	0.00	1.00
Côte d'Ivoire	143,878.30	7.19	71.94	14.39	71.94	143,712.84
Colombia	1,186,669.00	1,186.67	593.33	118.67	593.33	1,184,177.00
Comoros	232.10	0.00	0.02	0.02	0.12	231.94
Congo, Democratic Republic	21,826.20	0.22	2.18	2.18	10.91	21,810.70
Congo, Republic	3,324.40	0.03	0.33	0.33	1.66	3,322.04
Costa Rica	147,694.40	443.08	7.38	14.77	73.85	147,155.32
Croatia	12,971.40	220.51	6.49	1.30	6.49	12,736.62
Cuba	1,116,315.70	11.16	111.63	111.63	558.16	1,115,523.12
Cyprus	51,717.80	517.18	517.18	25.86	25.86	50,631.73

Appendix 3 (continued)
Area under irrigation, by method, in hectares

Country	Total irrigation area	Drip irrigation	Sprinkler	Pivot	Other	Surface
Czech Republic	64,936.00	974.04	32.47	6.49	32.47	63,890.53
Denmark	481,443.00	240.72	24.07	48.14	240.72	480,889.34
Djibouti	2,687.10	0.03	0.27	0.27	1.34	2,685.19
Dominica	1.00	0.00	0.00	0.00	0.00	1.00
Dominican Republic	352,196.30	3.52	35.22	35.22	176.10	351,946.24
Ecuador	1,123,467.90	112.35	561.73	112.35	561.73	1,122,119.74
Egypt	3,731,214.20	373.12	1,865.61	746.24	1,865.61	3,726,363.62
El Salvador	74,137.30	0.74	37.07	7.41	37.07	74,055.01
Equatorial Guinea	1.00	0.00	0.00	0.00	0.00	1.00
Eritrea	39,192.30	0.39	3.92	3.92	19.60	39,164.47
Estonia	1,485.10	44.55	0.74	0.15	0.74	1,438.91
Ethiopia	483,199.50	4.83	43.49	48.32	241.60	482,861.26
Faroe Islands	1.00	0.00	0.00	0.00	0.00	1.00
Fiji	6,196.70	0.06	0.62	0.62	3.10	6,192.30
Finland	115,945.60	57.97	8.12	11.59	57.97	115,809.94
France	2,881,898.60	1,285,326.78	634,017.69	288,189.86	1,440.95	672,923.32
French Guiana	4,862.90	0.05	0.49	0.49	2.43	4,859.45
French Southern Territories	1.00	0.00	0.00	0.00	0.00	1.00
Gabon	9,716.70	0.10	0.97	0.97	4.86	9,709.80
Gambia	5,681.20	0.06	0.57	0.57	2.84	5,677.17
Georgia	416,253.20	124.88	208.13	41.63	208.13	415,670.45
Germany	639,283.90	319.64	639.28	63.93	319.64	637,941.40
Ghana	45,932.50	0.46	9.19	4.59	22.97	45,895.29
Greece	1,555,225.10	15.55	155.52	155.52	777.61	1,554,120.89

Appendix 3 (continued)
Area under irrigation, by method, in hectares

Country	Total irrigation area	Drip irrigation	Sprinkler	Pivot	Other	Surface
Greenland	1.00	0.00	0.00	0.00	0.00	1.00
Grenada	138.90	1.39	17.92	0.01	0.07	119.51
Guadeloupe	2,371.30	0.02	0.24	0.24	1.19	2,369.62
Guam	212.60	0.00	0.02	0.02	0.11	212.45
Guatemala	171,637.20	85.82	34.33	17.16	85.82	171,414.07
Guinea	127,612.50	893.29	63.81	12.76	63.81	126,578.84
Guinea-Bissau	25,451.20	0.25	2.55	2.55	12.73	25,433.13
Guyana	155,548.30	1.56	15.55	15.55	77.77	155,437.86
Haiti	138,489.50	1.38	13.85	13.85	69.24	138,391.17
Honduras	114,916.00	1.15	11.49	11.49	57.46	114,834.41
Hong Kong	4,491.30	0.04	0.45	0.45	2.25	4,488.11
Hungary	364,721.50	182.36	182.36	36.47	182.36	364,137.95
Iceland	1.00	0.00	0.00	0.00	0.00	1.00
India	59,883,315.20	898,249.73	1,497,082.88	299,416.58	29,941.66	57,158,624.36
Indonesia	5,596,812.80	55.97	559.68	559.68	2,798.41	5,592,839.06
Iran	9,223,736.70	156,803.52	922,373.67	92,329.60	4,611.87	8,047,618.03
Iraq	3,849,188.80	769.84	384.92	384.92	1,924.59	3,845,724.53
Ireland	1,185.90	0.01	0.12	0.12	0.59	1,185.06
Israel	181,164.20	54,349.26	45,834.54	9,058.21	90.58	71,831.61
Italy	3,884,478.10	349,603.03	388,447.81	174,801.51	1,942.24	2,969,683.51
Jamaica	38,537.60	3.85	19.27	3.85	19.27	38,491.35
Japan	3,838,295.80	767.66	345.45	383.83	1,919.15	3,834,879.72
Jordan	125,398.90	37.62	62.70	12.54	62.70	125,223.34
Kazakhstan	2,496,172.10	124.81	1,248.09	249.62	1,248.09	2,493,301.50
Kenya	141,178.60	1.41	7,058.93	14.12	70.59	134,033.55

Appendix 3 (continued)
Area under irrigation, by method, in hectares

Country	Total irrigation area	Drip irrigation	Sprinkler	Pivot	Other	Surface
Korea, Democratic People's Republic	1,467,643.60	14.68	146.76	146.76	733.82	1,466,601.57
Korea, Republic of	1,137,796.80	227,559.36	113.78	102.40	568.90	909,452.36
Kosovo	73,192.80	0.73	7.32	7.32	36.60	73,140.83
Kuwait	9,273.70	185.47	1,103.57	0.93	4.64	7,979.09
Kyrgyzstan	1,468,877.40	73.44	73,443.87	146.89	734.44	1,394,478.76
Laos	414,824.80	4.15	41.48	41.48	207.41	414,530.27
Latvia	1,164.40	0.01	0.12	0.12	0.58	1,163.57
Lebanon	162,158.20	32.43	48.65	16.22	81.08	161,979.83
Lesotho	6,199.60	0.06	0.62	0.62	3.10	6,195.20
Liberia	2,984.20	0.03	0.30	0.30	1.49	2,982.08
Libya	666,126.80	6.66	66.61	66.61	333.06	665,653.85
Lithuania	4,649.00	23.25	232.45	0.46	2.32	4,390.52
Luxembourg	624.80	0.01	0.06	0.06	0.31	624.36
Macedonia	172,875.90	1.73	17.29	17.29	86.44	172,753.16
Madagascar	1,335,331.40	13.35	26.71	133.53	667.67	1,334,490.14
Malawi	66,681.20	3.33	3.33	6.67	33.34	66,634.52
Malaysia	499,727.60	249.86	249.86	49.97	249.86	498,928.04
Mali	363,832.60	3.64	36.38	36.38	181.92	363,574.28
Martinique	4,279.80	0.04	0.43	0.43	2.14	4,276.76
Mauritania	61,617.80	0.62	6.16	6.16	30.81	61,574.05
Mauritius	31,285.30	312.85	312.85	15.64	15.64	30,628.31
Mexico	8,229,417.60	123,441.26	2,468,825.28	82,376.47	4,114.71	5,550,659.88
Micronesia	1.00	0.00	0.00	0.00	0.00	1.00
Moldova	347,193.60	173.60	173.60	34.72	173.60	346,638.09

Appendix 3 (continued)
Area under irrigation, by method, in hectares

Country	Total irrigation area	Drip irrigation	Sprinkler	Pivot	Other	Surface
Mongolia	139,314.10	6.97	13.93	13.93	69.66	139,209.61
Montenegro	1,945.70	38.93	0.58	0.19	0.97	1,905.02
Morocco	1,999,691.40	999.85	999.85	199.97	999.85	1,996,491.89
Mozambique	229,613.80	2.30	22.96	22.96	114.81	229,450.77
Myanmar	2,137,711.20	21.38	213.77	213.77	1,068.86	2,136,193.43
Namibia	25,994.40	129.97	129.97	2.60	13.00	25,718.86
Nauru	1.00	0.00	0.00	0.00	0.00	1.00
Nepal	1,111,357.60	11.11	11.11	111.14	555.68	1,110,668.56
Netherlands	431,987.00	215.99	43.20	43.20	215.99	431,468.62
Netherlands Antilles	1.00	0.00	0.00	0.00	0.00	1.00
New Caledonia	1.00	0.00	0.00	0.00	0.00	1.00
New Zealand	591,311.60	118.26	295.66	59.13	295.66	590,542.89
Nicaragua	71,513.20	71.51	7.15	7.15	35.76	71,391.63
Niger	117,195.70	1.17	11.72	11.72	58.60	117,112.49
Nigeria	523,554.80	5.24	52.36	52.36	261.78	523,183.08
Niue	1.00	0.00	0.00	0.00	0.00	1.00
Northern Mariana Islands	43.20	0.00	0.00	0.00	0.02	43.17
Norway	173,833.50	1.74	17.38	17.38	86.92	173,710.08
Oman	131,458.20	65.73	1,314.58	13.15	65.73	129,999.01
Pakistan	14,648,136.30	1,464.81	732.41	1,025.37	7,324.07	14,637,589.64
Palau	1.00	0.00	0.00	0.00	0.00	1.00
Palestine	41,522.40	0.42	4.15	4.15	20.76	41,492.92
Panama	49,335.50	789.37	2.47	4.93	24.67	48,514.06
Papua New Guinea	1.00	0.00	0.00	0.00	0.00	1.00
Paraguay	81,629.30	0.82	8.16	8.16	40.81	81,571.34

Appendix 3 (continued)
Area under irrigation, by method, in hectares

Country	Total irrigation area	Drip irrigation	Sprinkler	Pivot	Other	Surface
Peru	2,113,159.20	2,113.16	1,056.58	211.32	1,056.58	2,108,721.57
Philippines	1,914,811.80	957.41	957.41	191.48	957.41	1,911,748.10
Poland	179,336.60	89.67	1,793.37	17.93	89.67	177,345.96
Portugal	792,127.80	396.06	396.06	79.21	396.06	790,860.40
Puerto Rico	33,669.10	16.83	16.83	16.83	16.83	33,601.76
Qatar	13,663.60	136.64	546.54	6.83	6.83	12,966.76
Reunion	22,372.10	0.22	2.24	2.24	11.19	22,356.22
Romania	2,226,162.00	222.62	1,113.08	222.62	1,113.08	2,223,490.61
Russia	5,686,698.80	2,843.35	1,137,339.76	682,403.86	2,843.35	3,861,268.49
Rwanda	9,937.70	0.10	0.99	0.99	4.97	9,930.64
Saint Helena	1.00	0.00	0.00	0.00	0.00	1.00
Saint Kitts and Nevis	13.10	0.13	0.00	0.00	0.01	12.96
Saint Lucia	327.50	0.00	0.03	0.03	0.16	327.27
Saint Pierre and Miquelon	1.00	0.00	0.00	0.00	0.00	1.00
Saint Vincent and the Grenadines	1.00	0.00	0.00	0.00	0.00	1.00
Samoa	1.00	0.00	0.00	0.00	0.00	1.00
Sao Tome and Principe	8,179.60	0.08	0.82	0.82	4.09	8,173.79
Saudi Arabia	2,153,691.10	1,076.85	258,442.93	215,369.11	1,076.85	1,677,725.37
Senegal	181,313.20	36.26	18.13	18.13	90.66	181,150.02
Serbia	91,223.70	0.91	9.12	9.12	45.61	91,158.93
Sierra Leone	45,869.10	0.46	4.59	4.59	22.93	45,836.53
Slovakia	251,642.70	2.52	25.16	25.16	125.82	251,464.03
Slovenia	21,786.20	10.89	10.89	2.18	10.89	21,751.34

Appendix 3 (continued)
Area under irrigation, by method, in hectares

Country	Total irrigation area	Drip irrigation	Sprinkler	Pivot	Other	Surface
Solomon Islands	1.00	0.00	0.00	0.00	0.00	1.00
Somalia	243,699.20	2.44	24.37	24.37	121.85	243,526.17
South Africa	2,119,881.20	211,988.12	317,982.18	211,988.12	1,059.94	1,376,862.84
Spain	3,713,119.50	816,886.29	297,049.56	148,524.78	1,856.56	2,448,802.31
Sri Lanka	612,935.20	12.26	612.94	61.29	306.47	611,942.25
Sudan	2,182,188.80	21.82	218.22	218.22	1,091.09	2,180,639.45
Suriname	68,211.20	0.68	2.73	6.82	34.11	68,166.86
Svalbard and Jan Mayen	1.00	0.00	0.00	0.00	0.00	1.00
Swaziland	69,611.60	3.48	6.96	6.96	34.81	69,559.39
Sweden	198,496.10	1.98	19.85	19.85	99.25	198,355.17
Switzerland	71,611.80	0.72	7.16	7.16	35.81	71,560.96
Syria	1,525,532.40	152.55	762.77	152.55	762.77	1,523,701.76
Taiwan	594,131.60	5.94	59.41	59.41	297.07	593,709.77
Tajikistan	758,114.70	7.58	75.81	75.81	379.06	757,576.44
Tanzania	319,596.60	3.20	31.96	31.96	159.80	319,369.69
Thailand	5,644,933.20	56.45	564.49	564.49	2,822.47	5,640,925.30
Timor-Leste, East	36,964.20	0.37	3.70	3.70	18.48	36,937.96
Togo	11,738.10	35.21	3.52	1.17	5.87	11,692.32
Tokelau	1.00	0.00	0.00	0.00	0.00	1.00
Tonga	1.00	0.00	0.00	0.00	0.00	1.00
Trinidad and Tobago	5,271.90	1.05	1.05	0.53	2.64	5,266.63
Tunisia	577,411.10	115.48	288.71	57.74	288.71	576,660.47
Turkey	5,813,198.40	2,906.60	4,069.24	2,325.28	2,906.60	5,800,990.68
Turkmenistan	1,945,361.70	972.68	194.54	194.54	972.68	1,943,027.27
Tuvalu	1.00	0.00	0.00	0.00	0.00	1.00

Appendix 3 (continued)

Area under irrigation, by method, in hectares

Country	Total irrigation area	Drip irrigation	Sprinkler	Pivot	Other	Surface
Uganda	21,927.40	0.22	855.17	2.19	10.96	21,058.86
Ukraine	3,336,881.80	333.69	1,334.75	333.69	1,668.44	3,333,211.23
United Arab Emirates	356,153.50	178.08	213.69	178.08	178.08	355,405.58
United Kingdom	234,773.70	164.34	117.39	23.48	117.39	234,351.11
United States	28,927,775.90	867,833.28	4,339,166.39	1,446,388.80	14,463.89	22,259,923.56
United States Minor Outlying Islands	1.00	0.00	0.00	0.00	0.00	1.00
Uruguay	279,511.90	2.80	27.95	27.95	139.76	279,313.45
Uzbekistan	4,161,997.40	416.20	1,248.60	416.20	2,081.00	4,157,835.40
Vanuatu	1.00	0.00	0.00	0.00	0.00	1.00
Venezuela	839,962.80	419.98	671.97	419.98	419.98	838,030.89
Vietnam	3,199,236.80	31.99	1,599.62	1,279.69	1,599.62	3,194,725.88
Virgin Islands, U.S.	1.00	0.00	0.00	0.00	0.00	1.00
Wallis and Futuna	1.00	0.00	0.00	0.00	0.00	1.00
Western Sahara	1.00	0.00	0.00	0.00	0.00	1.00
Yemen	527,744.30	527.74	527.74	52.77	263.87	526,372.16
Zambia	255,319.40	2.55	127.66	25.53	127.66	255,036.00
Zimbabwe	279,553.20	2.80	55.91	27.96	139.78	279,326.76
Total		**5,937,395**	**15,046,334**	**4,407,264**	**157,377**	**289,205,442**

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POSSIBLE BREAKTHROUGHS SMART VARIETIES

Continually increasing physiological yields over the last decades have had much to do with plant breeding and biotechnology, which keep pushing the potential yield frontier forward. The two main directions for breeding are: breeding for maximum yield under controlled circumstances and developing crops that are more resilient to non-optimal conditions. In the face of projected negative climate change impacts on agricultural production, this last aspect is of particular relevance. Finally, while progress has been made in using plant breeding technologies to improve yields of major crops, genetic diversity and locally developed varieties remain of tremendous importance in building resilient cropping systems, sustaining local livelihoods, and providing a range of ecosystem services.

Description

In spite of the tremendous increase in potential yields of all major crops achieved during the last decades, mainly as a result of progress in plant breeding for increased harvest indexes,[1] the development of new, higher yielding varieties is slowing down. Given present climate uncertainty (see box 1) and resource-constrained conditions, it would be more interesting to make varieties more resilient to biotic stresses (pests and diseases), which would reduce the use of pesticides, and increase tolerance to abiotic stresses (nutrients, water, temperature, salinity), among others, rather than pushing maximum yields for major crops further. Selecting for these traits will make it easier for smallholder farmers to move closer to current attainable yields.[2]

The development of new varieties can be obtained in the laboratory by conventional breeding or by genetic crop engineering. The latter technology involves incorporating desired exogenous genes from other organisms or plant species into a certain crop. Bacillus thuringiensis (Bt) crops are an example of genetically modified, pest-resistant crops in which genes from the bacterium bacillus thuringiensis, which produces a toxin that is harmful to specific insects, have been incorporated into the crop's genome. A recent breakthrough in pest control is the use of "transcription activator-like effector nucleases (TALENs)". These are artificial restriction enzymes that are specific to any DNA sequence and can thus cut and isolate desired genes that can then be engineered into crops. Thanks to this technology, great progress has been made in the control of very harmful bacterial blight in rice. TALENs technology can potentially be applied to a vast range of crops and traits.[4]

Box 1

Impact of climate change on current cropping systems

According to the Intergovernmental Panel on Climate Change (IPCC), rainfed farming system yields could decrease by as much as 50% in large areas of Africa by 2020 as the climate becomes hotter and drier. By 2080, agricultural output could decline by as much as 28% in Africa, 24% in Latin America and 19% in Asia. Agricultural output in India could decline by as much as 38%, and some African countries could experience declines in excess of 50%. Climate change is also anticipated to severely impact biodiversity by causing the significant extinction of species and the loss of ecosystem services essential to food production.

[1]Molden et al. 2010, [2]CA 2007; Fischer et al. 2010, [3]Gonzalez 2011, [4]Li et al. 2012

Description (continued)

DuPont Pioneer and Syngenta, in collaboration with the International Maize and Wheat Improvement Centre (CIMMYT), have also made strides in marker-assisted breeding for water-limited conditions of corn that can yield 15% more than conventional hybrids in water-stressed conditions and equal or even more under optimal conditions. Marker-assisted selection (MAS) is an indirect selection process where a trait of interest is selected not based on the trait itself, but on a marker linked to it, which can be either morphological, biochemical or based on an DNA/RNA variation.

The key role of the preservation and use of traditional seed varieties in building climate resilient cropping systems have been recognized in international policy arenas since the turn of the millennium. The Food and Agriculture Organization of the United Nations (FAO) declared that 75% of the world's food crop diversity was lost in the 20th century as "farmers abandoned local varieties in favor of genetically uniform high-yielding crops."[5]

FAO has identified the loss of genetic diversity when modern cultivars replace landraces as the greatest loss in global agricultural systems. The small genetic resource base makes cropping systems sensitive to diseases and pests and unable to deal with altering rainfall patterns and temperature due to climate change (see box 1). Examples of actions to countervail these threats include the Convention on Biological Diversity (CBD), the International Treaty on Plant Genetic Resources for Food and Agriculture (ITPGRFA), the United Nations declaration of the year 2010 as the "Year of Biodiversity", and the development of stronger linkages between genetic varieties available in seed banks and cropping systems in the field.

Worldwide there are close to 1,400 gene banks storing approximately 6 million samples of genetic resources for crops.[6] Three-quarters of these samples are stored in Consultative Group on International Agricultural Research (CGIAR) centers.

Also, on the more local level, various organizations aim to further the genetic diversity in cropping systems. For example, NativeSe, a North America-based organization, is training farmers to store, use and multiply genetic crop resources. While industrial agriculture largely uses homogeneous hybrid seeds obtained by controlled pollination between highly inbred lines, in traditional agricultural systems, farmers cross genetically distinct parents, both within and between populations, varieties and species.[7] It has been proved that this practice makes cropping systems more resilient to climate change, making them better able to cope with pests, water shortages and temperature fluctuations.

[5]Gonzalez 2011, [6]InfoResources 2008, [7]NativeSeeds 2012

Geography

Climate change will affect rainfall, salinity levels, temperature, sunshine hours and wind patterns. This will change soil composition and growing conditions worldwide. As a consequence, half of the world's 23 major food crops will lose suitable land in sub-Saharan Africa and the Caribbean by 2055.[8] The selection of the right cultivars helps nations in these regions adapt their cropping systems and create resilient food systems.[9]

Internationally, Peru, Ethiopia, India and China are centers of origin and hotspots of globally important food crops and livestock. Brazil is a center of biodiversity of global importance and also home to important agricultural crops. All five countries, however, face erosion of diversity. For instance, rice varieties in China declined from 46,000 in the 1950s to 1,000 today.[10] The German Society for International Cooperation (GIZ) foresees an important role for these countries and for gene banks to make cropping systems climate proof in the decades to come.

[8]Bioversity International 2010, [9]FAO 2011, [10]GIZ 2011

Energy

- Insecticide resistant crops imply less fuel consumed for pesticide applications.
- New corn hybrids are 11% more nitrogen efficient than old hybrids.[11]
- Water and nitrogen-efficient crops require less fertilizer use and less energy for pumping and fertilizer application.
- Herbicide tolerant rice needs less water for weed control and less energy for pumping.[12]

Water

- Aerobic rice consumes 30-50% less water than inundated rice.[13]
- Drought-tolerant corn uses less water and yields 6-15% more than conventional hybrids under water-stressed conditions.[14]

Local varieties

- Dryland seed varieties often have lower water requirements with similar or higher production than high-yielding varieties. Drylands are important stores of genetic variability for crops that are adapted to harsh, uncertain and low-input environments.[15]
- Plants have shorter growth cycles, longer roots, water stores in roots and trunks, and dormancy during dry seasons.[16]
- The brown tepary bean (Phaseolus acutifolius) is relatively drought resistant as it can access water from large soil volumes thanks to its large taproot and can reduce water losses by folding up its leaves.
- The use of mixed seed reduces crop failure risks when faced with irregular rainfall patterns
- In Guatemala, farmers grow varieties with different growing seasons or sow a mixture of different varieties in the same field such as varieties of beans that tolerate drought along with those that prefer wetter conditions.

[11]Ciampitti and Vyn, 2012, [12]Kumar et al., 2008, [13]Bouman et al., 2002; Pinheiro et al., 2006, [14]WBCSD, 2009, [15]GIZ, 2010, [16]GIZ, 2010

Productivity

Major crops

- Rice varieties developed by the Chinese super-rice breeding program of the International Rice Research Institute (IRRI) are already nearing 12 t/ha – the same also being attained by hybrids grown in eastern China. A 50% increase in rice biomass is deemed possible if the C_3 photosynthetic path is converted to a C_4 photosynthetic path.[17]
- Potential yields for wheat are estimated at 13 t/ha under average conditions and 19 t/ha under optimal conditions – a 50% increase over what is currently possible.[18]
- Syngenta has recently introduced hybrid barley in Europe, alongside a new integrated farming approach. Hybrid barley has shown yields of up to 13.7 t/ha compared to 8-10 t/ha of inbred varieties.[19]
- An analysis by Qaim and Matuschke[20] on the impacts of transgenic cotton in developing countries showed a yield increase of 20% while using 50% less insecticides.
- Cereal yield growth would decrease to 0.7% every year (0.8% in developing countries), and average cereal yield would reach some 4.3 t/ha by 2050, up from 3.2 t/ha at present.[21]
- Research in heterosis (improved or increased function of any biological quality in a hybrid offspring), molecular breeding and genetic engineering suggest that gains from genetic sources could be increased by at least 50%, the rate needed to generate 60% more staples by 2050 without major increases in food prices.[22]

Local varieties

- Understanding the genetic diversity of Cherimoya (*Annona cherimola*) species helped identify "elite" selections to improve production.[23]
  – As a result of improved quality, in Ecuador the market value of cherimoyas rose from US$ 0.07 to US$ 1.00 /kg between 2006 and 2009.
- Ethiopia has a unique genetic diversity of cultivated, semi-wild and wild Arabica varieties with different disease resistance, environmental adaptation and quality features. The genetic diversity of coffee in Ethiopia is of global importance for the breeding of varieties that are adapted to future uncertain environmental conditions and that are disease resistant.[24]
- Due to the excellent drought resistance of the often-overlooked foxtail millet variety, farmers can make a living in the dry areas of northern Karnataka, India.[25]
- The use of intra-specific phenotypic variability of three millet species (finger millet, little millet and Italian millet) adapted to different climatic conditions has enabled villagers of a hilly area of Tamil Nadu, India, to raise their income by 30% while providing a more nutritious food than cereals like wheat and rice.[26]

[17]Sheehy et al. 2007, [18]Reynolds et al. 2011, [19]Syngenta 2012, [20]Qaim and Matuschke 2005, [21]Fisher et al. 2010, [22]Edmeades et al. 2010, [23]Bioversity International 2010, [24]GIZ 2011, [25]GTZ 2006, [26]Gruere et al. 2007,

Costs and benefits

- Higher yields found in hybrid seeds are not always synonymous with higher profits, as highlighted in a study by Gene Campaign in Jharkhand, India.[27]
  - Hybrid rice is more prone to diseases than local varieties and requires higher investment in both fertilizer and pesticide.
  - Hybrid seeds cost US$ 3.85/kg while farmers can reproduce local seeds.

Climate change[28]

- Rice emits large quantities of methane (CH_4) per growing season, mainly due to permanent flooding of paddy fields:
  - Dryland rice (India) is between 30 and 50 kg CH_4/ha
  - Wetland rice (China) is between 200-1100 kg CH_4/ha
- Reducing CH_4 emissions can be achieved by:
  - Growing aerobic rice under upland conditions. Upland rice currently comprises about 12% of world rice area but yields only 4% of global rice production.
  - Using distinct drainage periods in mid-season or alternate wetting and drying of the soil in wetland cultivation.
    - Results in 7-80% less CH_4 emissions; however, nitrous oxide (N_2O) emissions increase.
- Cumulative N_2O emissions from soils during pre-rice fallow and rice and post-rice fallow and wheat range from 6.9 to 13.7 and 2.6 to 3.4 N_2O-N/ha/season respectively.
- In wheat, the major greenhouse gas (GHG) is N_2O emitted in short-term pulses after fertilization, heavy rainfall and irrigation events.[29]

[27]Sahai et al., [28]Based on a 100-year time frame, the greenhouse warming potential (GWP) of CH_4 is 21 times higher whereas the N_2O is 310 times higher than the reference value for CO_2 (IPCC 1996). [29]Wassmann et al. 2004

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POSSIBLE BREAKTHROUGHS
SMART FERTILIZERS

Research and development in smart fertilizers focuses on improving nitrogen use efficiency (NUE). The NUE of urea, the major nitrogen fertilizer, currently only averages 30% to 40% due to its sensitivity to volatilization, denitrification and leaching.

Smart fertilizers that minimize these processes include: i) slow and controlled release fertilizers, ii) nitrification inhibitors, and iii) urease inhibitors. Technological advances in phosphorous fertilization include products that increase phosphorous availability in the soil for better uptake by plants.

Description

A smart nitrogen fertilizer incorporates a mechanism controlling nitrogen release based on crop requirements. This function reduces unproductive losses, such as leaching and atmospheric emissions, while increasing nutrient use efficiency and yields. The major mechanisms used are:

(I) Slow and controlled mechanisms, achieved by:

- Controlled water solubility by semi-permeable coatings, occlusion, protein materials or other chemical forms;[1]
- Slow hydrolysis of water-soluble, low-molecular weight compounds.[2]

(II) Nitrification inhibitors, achieved by:

- Substances that inhibit the biological oxidation of ammonical nitrogen to nitrate nitrogen.[3]

(III) Urease inhibitors:

- Substances that inhibit hydrolytic action on urea by the enzyme urease.[4]

Based on these mechanisms, a wide variety of smart fertilizers has been developed and named after the developer or specific mechanism. Table 1 provides an overview of the variety of smart fertilizers available on the market.

Smart phosphorous fertilizers use specific fungi that stimulate the release of bound phosphorous from the soil for its improved uptake by plants or apply a phosphorous coating with polymers so as to reduce its precipitation or adsorption and improve plant recovery of phosphorous during the following months or years.

Table 1
Marketable smart nitrogen fertilizer products

Release mechanisms	Product
Slow and controlled release	SCU, POCU, PSCU, Meister, Nutricote
Nitrification inhibitor	Nitrapyrin, ATC, CI-1580, DCD, TU, MT, AM, DMPP, ASU, ATS, HPLC, Terrazole, 3-MP, CMP, Neem
Urease inhibitor	PPD/PPDA, hydroquinone (HQ), 2-NPT, ATS, NBPT (Agrotain)

Source: Trenkel, 2010

[1]Trenkel 2010, [2]Ibid. [3]Ibid. [4]Ibid

Geographical usages of smart fertilizer

The use of slow- and controlled-release fertilizers remains limited, amounting to 0.2% of global fertilizer consumption in 2004/05 (786,000 tonnes).[5] Usages of scale are only reported in North America (the United States and Canada), Europe and Asia (China and Japan).[6] The expansion of smart fertilizer usage is mainly constrained by low installed-production capacity of only 7.5 million tonnes. The main production facilities are in Canada (Agrium Inc.) and China (Hanfeng Evergreen Inc.). China is by far the largest producer and consumer of smart fertilizers, amounting to one-third of global smart fertilizer (CRF) production. Conducive policies in China and Japan are stimulating further expansion of smart fertilizer production capacity. China's guiding catalogue of *Industrial Infrastructure Adjustment* (2011 edition) classified CRF as one of the encouraged items, indicating that the development of CRF will speed up during China's 11th five-year plan, from 2011-2015.[7]

Hanfeng Evergreen Inc., China's second largest smart fertilizer producer, is working closely with China's Ministry of Agriculture on a large-scale, soil-based fertilization initiative to increase the use of smart fertilizers in the coming years.[8] Hanfeng is expanding activities to Indonesia, the Philippines and Malaysia to analyze the potential application of smart fertilizers in palm oil production, which in Indonesia alone is expected to increase from 4 million hectares in 2010 to 9 million hectares in 2015.[9]

[5]Trenkel, 2010, [6]Ibid, [7]CCM International, 2011, [8]Hanfeng, n.d., [9]Ibid

Table 2
Yield responses to different smart fertilizer mechanisms

Release rate regulator	Trial setup	Crop	Yield impact	Reference
Slow- and controlled-release fertilizer	CUF (common urea fertilizer) and CRF (controlled release fertilizer)	Rice	General 10-40% higher yield with CRF. 15% higher yield in CRF 2003, with only 1/3 of CUF	Min and Yingying 2005
	Coated urea (ESN) and CUF	Corn	10.9 (CUF) and 11.2 t/ha (ESN)	Killorn et al. 2004.
	CRF and soluble fertilizer	Citrus	Fertilizer application frequency reduced from 15 to 6, maintaining same yields	Zekri 1991 in Trenkel 2010
	CUF and CRF (Meister)	Japanese pear (Hosui)	CUF 230 kg N/ha and 60 kg/tree; CRF 161 kg N/ha en 70 kg/tree	Zekri 1991 in Trenkel 2010
	CUF and CRF	Apple	Increased yield with CRF	Shao et al. 2007 in Trenkel 2010
	Single CRF (Meister) application and split CUF application	Brown rice	CRF (Meister) yield 6.35 t/ha and CUF yield 4.45 t/ha	Ikeda et al. 1998 in Trenkel 2010
	Neem Cake Coated Urea (NCU) and prilled urea	Rice	Higher yields for NCU than CUF	Singh and Sing 1994 in Trenkel 2010
	Urea Supergranules and urea	Rice	Higher yields for NCU and CUF	Geethadevi et al. 1991

Table 2
Yield responses to different smart fertilizer mechanisms (continued)

Release rate regulator	Trial setup	Crop	Yield impact	Reference
Nitrification inhibitors	Urea (treated with DCD + Triazole) and urea alone	Multiple crops	Maize +12%, rice +9%, wheat +12%, potatoes +22% and beets +13%	Wozniak et al. 2010 in Trenkel 2010
	Urea (DCD treated) and urea alone	Multiple crops	Same yields for maize, potatoes, sugar beet and rapeseed with 20-30 kg N/ha less	Sturm et al. 1994 in Trenkel 2010
	Urea (DCD treated) and urea alone	Multiple crops	Wide row crops (maize) and crop preferring ammonium N (potatoes) benefit	Hege and Munzert 1991 in Trenkel 2010
	Urea (DCD treated) and urea alone	Multiple crops	Winter cereals, winter rapeseed and sugar beet no benefit	Hege and Munzert 1991 in Trenkel 2010
	Urea (DCD treated) and urea alone	Grazing systems	Improved pasture yield and quality	Moir et al. 2007 in Trenkel 2010
	ASN + DMPP and CUFRice	Winter wheat	0.6 t/ha yield increase	Pasda et al. 1999 and 2001, in Trenkel 2010
	Urea (DMPP treated) and CUF	Tomato	Increased yield and size of fruits	Banuls et al. 2000 in Trenkel 2010
	Urea (DMPP treated) and CUF	Vegetables	11% increase in yield	Hahndel 2005 in Trenkel 2010

Table 2
Yield responses to different smart fertilizer mechanisms (continued)

Release rate regulator	Trial setup	Crop	Yield impact	Reference
Nitrification inhibitors (continued)	Urease (DMPP treated) and CUF	Winter wheat	7% yield increase	Huther et al. 2000 in Trenkel 2010
	Urea (ASN+DMPP treated) and CUF	Cabbage	Increase of 2-5.5 t/ha and better quality	Xu et al. 2004 in Trenkel 2010
	Urea (DMPP) and CUF	Ryegrass	Higher above-ground dry matter content	Guillaues and Villar 2004 in Trenkel 2010
	Urea (Nitrapyrin; N-Serve) and CUF	Corn	10% yield increase	Iowa State University, in Trenkel 2010
Urease inhibitors	NBPT and urea	Multiple crops	Beneficial high crop yield potential, low soil N and high temperature	Grant et al. 1996, in Trenkel 2010
	NBPT and CUF	Corn	Increase of 0.6-0.8 t/ha	Lamond et al. 1993/1994, in Trenkel 2010
	NBPT and urea	Corn	7% yield increase	IMC-Agrici 1996, in Trenkel 2010

Energy

Smart nitrogen fertilizers reduce energy use by:

Reducing application volume

- Controlled release fertilizers (CRFs) increase NUE, reducing recommended application rates for conventional fertilizer 20-30% (or more) while maintaining the same yield.[10]
- Proportional savings in the consumption of naphtha or natural gas in nitrogen fertilizer production are possible as virtually all nitrogen fertilizers are derived from ammonia, and ammonia production accounts for 87% of the industry's total energy consumption.[11]

Application frequency

- Reduction of fertilizer application frequency, as smart nitrogen fertilizers need to only be applied once (sometimes twice) per cropping season. The reduction of application events reduces fuel use.[12]

Increasing nitrogen use efficiency

- NUE with controlled release urea on paddy fields has been found to be 50-100% higher than conventional urea, meaning fertilizer savings of 30%.[13]

Water

- Advances in biochemical research may produce a "smart fertilizer" that increases the soil's organic content and its ability to retain water.[14]
- The improved fertilizer use efficiency and uptake by plants shown by smart fertilizers means less leaching and water pollution.

[10]Trenkel, 2010, [11]Vyas n.d.; IFA n.d. [12]e.g. Linzmeier et al. 2001 [13]Mao et al. 2005, [14]Jacobs 1999

Productivity

- In-field experiments in China have shown 10-40% increases in rice yields with controlled-release fertilizers compared to those with urea.[15] Even when a third less nitrogen was used, controlled-release fertilizers increased rice yield by 15%.[16]
- Pre-plant inoculation of rice seedling-roots or wheat seeds with phosphorous solubilizing fungus *A. Awamori* led to a yield increase over non-inoculated treatments of 0.09-0.22 t/ha in rice and 0.15-0.45 t/ha in wheat in different years.[17]
- *P. pinophilum* fungi increased the yield of wheat grains by 28.9% and 32.8% in the soil treated with rock phosphate and superphosphate. It also increased the production of faba bean seeds by 14.7% and 29.4% with the same treatments, and the uptake of phosphorous by both plants significantly increased due to inoculation of the soil with the tested fungi.[18]

Climate change

Reducing CO_2 output during production

- Smart fertilizer use requires 20% to 30% less nitrogen fertilizer, reducing CO_2 emissions for production

Reducing nitrous oxide (N_2O) output after application

- Common nitrogen fertilizer loses 1-5% of application as N_2O, a greenhouse gas 300 times stronger than CO_2.[19]
- Over the last 150 years, atmospheric N_2O levels have risen 18%, largely due to nitrogen fertilizer use throughout the world.[20]
- Smart fertilizers have lower N_2O emissions during the growing season than common nitrogen fertilizers.[21]

Costs and benefits

- While the cost effectiveness of applying encapsulated controlled-release fertilizers in high-value crops is proven, there is also scope for their application to low-value crops.[22]
- Total production costs can be reduced by 30 to 50% using smart fertilizers.[23] Shoji and Kanno[24] reported a decrease in farming costs of 65%.[25]
- The controlled supply of nutrients by a single application of a CRF is expected to increase NUE, save labor and/or application costs and improve crop quality and yield.[26]
- Smart fertilizers are especially beneficial where nutrient losses from conventional fertilizers are high, such as on lightly textured soils with excess rainfall and/or irrigation.[27]

[15]Song et al. 2005, [16]Trenkel 2010, [17]Dwivedi et al. 2004, [18]Abdul Wahid and Mehana 2000, [19]Choudhury and Kennedy 2005, [20]Venterea et al. 2008, [21]Ibid, [22]Trenkel 2010, [23]Kitamura and Imai 1995 in Trenkel 2010, [24]Shoji and Kanno 1994, [25]Ibid, [26]Shaviv 2000, [27]Trenkel 2010

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POSSIBLE BREAKTHROUGHS
ROCKDUST AND BIO-FERTILIZERS

Rock dust is pulverized stone, often produced as a by-product of the mining industry. It has no large-scale application and consequently is stockpiled at mining sites. This dust is, however, able to deliver some crop nutrients, like potassium, magnesium and calcium. This allows farmers nearby these mining sites to substantially reduce fertilizer input costs and increase yields.

Description

Rock dust (or stone meal) gains momentum due its beneficial spin-offs compared to conventional marketed fertilizer. As a multifunctional fertilizer, it is able to supply, in addition to the macro-nutrients (N, P and K) required for optimal crop growth, a range of other micro-nutrients (e.g. S, Ca, Mg, B, Cl, Cu, Fe, Mn, Mo, Ni, Zn), while it also improves the physical, chemical and biological quality of the soil.[1] At the field level, these effects materialize in multiple profits for users, including an improved workability of the heavy clayey soils,[2] improved water retention and water holding capacity of the soil (sandy and clay soil),[3] increased (quality of) yields of the cultivated crops, and higher farm benefit due to decreased application and purchase cost relative to conventional fertilizers. At the local and national level, the use of local available rock dust creates employment opportunities, increasing GDP while reducing import costs.

This shift in focus leads to less greenhouse gas emissions through lower demand for conventional fertilizer. Further climate change mitigation mechanisms reside in its capacity to directly sequester carbon and indirectly stimulate tree growth, thus leaving them to act as carbon sinks.

Global occurrence of rock dust usages

The origin of rock dust use dates back to more than three millennia ago, with South and Central America often cited as the regions of origin.[4] This concerns especially Brazil, the region where tera preta soils are found, and Zacatecas, Mexico.[5] In the latter state, the government is investigating the suitability of different rocks to restore grasslands.[6] In Colombia, a movement is rising that supports the use of stone meal among small-scale coffee farmers in order to save their scarce financial resources.[7] Other similar efforts have taken place in Panama and Costa Rica.

In Panama, experiments with basalt powder have shown significant increases in tree growth. In Costa Rica, yields of jatropha have increased with rock dust applications.[8] Tanzania, too, has successfully tested the application of 30,000 tonnes of locally available rock phosphate on agriculture in 2008.[9] Mali and Burkina Faso mines are smaller but still yield considerable amounts of rock dust that can be applied to local cropping systems. Chemical fertilizers are relatively expensive in many African countries due to the absence of local manufacturers. In Asia, the large-scale use of rock dust is taking place in Sri Lanka, where 45,000 tonnes/year are consumed by tea, coconut and rubber plantations; Indonesia and Malaysia import more than 2 million tonnes of phosphate rock per year for use in palm oil plantations; New Zealand imports 130 tonnes/year for application on vast pastures.

[1]Straaten 2006, [2]Ene and Okagbue 2009, [3]Dumitru et al. 2001, [4]e.g. Leonardos et al. 2000, [5]Ibid, [6]Rubio et al. 2009, [7]Remineralize n.d., [8]Ibid, [9]Straaten 2006

In Europe, rock dust is applied at a large scale in forest soils (e.g. Black Forest, Baden-Württemberg and Odenwald) in order to increase the pH of acidified soils.[10] It is estimated that for complete recovery, 600,000 hectares of forest in Baden-Württemberg need annual applications of 45 kg of dolomite for the coming twenty years.[11] Further applications of rock dust in Europe concern the addition of lime to acid-inclined soils, like peat soils in the North of the Netherlands. Similar practices with crushed shells are reported in Japan and along the West Coast of the United States, where shells are also added in forests. Examples of the use of rock dust for other purposes are of smaller scale but numerous. For instance, an Austrian study indicated that one-fourth of small-scale farmers and home gardeners in Tirol used alternative soil additives such as lime, stone meal or turban.[12] Numerous individual initiatives have been reported in Spain,[13] the UK (e.g. SEER Centre) and Portugal.

In Portugal, a feasibility study was conducted by Fonseca et al.[14] to assess the usability of dam sediments for the fertilization of food crops. Results of plot experiments proved the fertilizing effect of dam sediments, as yields increased. Based on these results, the authors recommend that dam owners initiate economic feasibility studies for the use of sediments in nearby agricultural sites.

Rock dust as fertilizer

Despite numerous positive references to the benefits of rock dust, the effect on yield still remains a controversial issue in the literature. Results of experiments with rock dust on crops range from no effect at all to yield increases of 50% (compared to plots where no fertilization at all was applied). These differences are related to the vast array of potential combinations of rock types, soil types and crop types. A further issue of discussion is the identification of the mechanisms responsible for the yield increase, as these are not always clearly mentioned in research reports.

Looking at the mineral composition of rocks, they are able to supply potassium, magnesium, calcium and a range of micronutrients like iron, copper and manganese.[15] Rock types able to supply these and other beneficial nutrients include basalt, biotite, spilite, andesite, phonolite, anortosite, syenite, marl, limestone, serpentinite and micaschist.[16] An early study by Arndt and McIntyre,[17] in which they studied the impact of rock and super phosphate application on sorghum cultivated on clay loamy soil in Australia, shows that both fertilizer sources increased sorghum yield, with the yield response to rock fertilizer being somewhat slower compared to the readily available superphosphate. More recent research includes Goreau's five-year experiment[18] in which basalt powder accelerated tree growth and biomass on impoverished tropical soils in Panama. A more elaborated list of the impact of rock dust on yields is provided in table 1.

[10]Sucker et al., 2009, [11]Ibid, [12]Vogl and Vogl-Lukasser, 2003, [13]One of two countries within EU that have outlined guidelines for organic agriculture at the national and district level.
[14]Fonseca et al. 2003, [15]Nitrogen is not supplied by rocks, phosphorous can only be applied if there is enough water for it to be soluble, which is seldom the case.
[16]Leonardos et al., 2000, [17]Arndt and McIntyre 1963, [18]Goreau 2011

Table 1

Improved yields after rock dust application for various crops

Crop	Rock type	Application rate (t/ha)	Yield response	Source
Lettuce/wheat	W.M.F. fertilizer (rocks-microbes mixtures)	n/a	9.8% average higher yields	Western Mineral Fertilisers 2009
Birdwood grass and legume	Rock phosphate	5-10	Increased yield from 2.4 to 13.1 and 3.1 to 14.7 t/ha	Norman 1965
Clover	Granite powder	20g/kg soil	Increased resp. from 1,482, 2,280, 3,798 to 3,900, 3,682, 6,746 mg/pot	Coreonos et al. 1996
Clover	Basalt dust	0-40	Increased yield	Dumitru et al. 1999
Lettuce	Basalt dust and compost	n/a	Similar yield to completed organic fertilizer	Manning and Vetterlein 2004
Lupine	Granite	n/a	Increased yield with 1/20 of conventional fertilizer cost	Oldfied 1996
Maize	Rock dust	n/a	10% higher yield and 20-50% higher germination rate	Remineralize n.d.
Okra	Compost, feldspar and rock phosphate	N, K and P: 45, 143, 143 K_2O units/ha)	Rock fertilizer 6.9-7.9 t/ha; control and NPK resp. 3.6 and 6.7 t/ha	Abdel-Mouty and El-Greadl 2008
Olive and orchards	Basalt crusher dust	n/a	Increased tree growth and health	Manning and Vetterlein 2004
Onions	Feldspar (Ksp.)	114, 228 and 342 K2O units/ha	Feldspar yields resp. 20.3, 22.5 and 27.8 t/ha Chemical yields resp. 18.5, 27.8 and 34.2 t/ha	Ali and Taalab 2008
Radish	Basalt rock	0-20 t/ha	Up to 50% increase in dry weight	Dumitru et al. 1999

Table 1

Improved yields after rock dust application for various crops (continued)

Crop	Rock type	Application rate (t/ha)	Yield response	Source
Rice	Phlogopite mica, feldspar	Resp. 0.2, 0.5 t/ha	Resp. 93.3 and 69.8 g/pot vs. 41.1 control pot	Weerasuriya et al. 1993
Ryegrass	Granite powder	20g/kg soil	Increased resp. from 2099, 3,749, 3,641 to 3,234, 4,894, 3,990 mg/pot	Coreonos et al. 1996
Sorghum	Rock phosphate	5, 10 and 25 t/ha	0.9, 1.3 and 1.4 t/ha vs. 0.7 t/ha control plot	Arndt and McIntyre 1963
Sugar cane	Basaltic rock	10-90 t/ha	Increased yield following years	D'Hotman de Villiers 1961
Tomatoes	Feldspar powder and compost (+bacteria)	0, 120, 240 and 360 kg K/ha	Yields 27.1, 42.3, 51.7, 58.8 t/ha vs. only compost yields of resp. 27.2, 30.9, 34.2 and 32.3 t/ha	Badr 2006
Tomatoes	Basalt	0-40 t/ha	Increased yield	Dumitru et al. 1999
Trees (not specified)	Granite	15-20 t/ha	Five times faster growth	Oldfield 1996
Tree growth	Basalt powder	n/a	Length 14m vs. 6 local soil; biomass 47 kg/tree vs. 6 kg/tree local soil	Goreau et al. 2011
Wheat	Stone meal, with lupine as green manure	7 years, 440 kg/ha	15% higher yield than conventional fertilizer, resp. 9,076 vs. 7,891 t/ha	Jost and Samobor 2008
Wheat	Rock dust	2 years, 250 kg/ha (lupine as green manure)	Wheat yield of 2.2 t/ha without pesticide and conventional fertilizer application	Oldfield 1996
Wheat	Volcano dust	After eruption	Increased yield	Fyfe et al. 2006

Energy

- Production of conventional fertilizer requires 51-68 MJ/kg nitrogen (N); 6.82 MJ/kg phosphorous pentoxide (P_2O_5) and 2.88 MJ/kg potassium oxide (K_2O).[19]
- Packaging and transport of conventional fertilizer is about 6-8 MJ/kg.[20]
- Application of fertilizer (conventional and rock dust) equals 51.62 MJ/kg.[21]
- Rock dust is locally available as a by-product of mines and quarry sites. Therefore it does not consume energy for its production.
- Rock dust need only be applied once every several years, while conventional fertilizer requires application at least once a season.

Water

- Recent research in Germany does not provide evidence that stone meal improves the water retention capacity of the soil.[22]
- Yet Dumitru et al.[23] found increased soil water retention capacity with the application of basalt rock.

[19]Bhat et al. 1994, [20]Mudahar and Hignett 1987, [21]Lobb 1989, [22]Pers. Comm. Bergsma 2011, [23]Dumitru et al. 2001

Productivity

- Soil quality increases as rock dust micronutrients stimulate biota, biomass and organic matter content. This increases soil water retention and storage capacity.
- Soil's nutrient delivery capacity is enhanced:
  - Basalt dust applications of 10 t/ha on clayey soils reduced phosphorous application requirements by 170 kg/ha super phosphate (US$ 38/ha).[24]

Climate change[25]

- Weathering of rock actually results in carbon sequestration. This process can be described by the following general equation:
  fresh silicate rock + H_2O + CO_2 → soil + cations + HCO_3 (bicarbonate).
- Serpentine and olivine are able to dispose of 0.5 and 0.67 t CO_2 per tonne weathered rock respectively.
- All the CO_2 that is produced by burning 1 liter of oil can be sequestered by less than 1 liter of olivine.

Costs and benefits

- Farmers are able to save up to 95% of the cost of conventional fertilizer.[26]
  - Rock dust can be purchased at a low price; crushed dunite (olivine), for example, costs in the order of a few tens of US dollars per tonne in the Rotterdam harbor.[27]
  - Prices for conventional fertilizers are high, in the order of US$ 420/tonne for urea, US$ 250/tonne for liquid nitrogen, US$ 450/tonne for diammonium phosphate (DAP), and US$ 500/tonne for potash.
- The mining industry is open-minded for rock dust solutions, as it is currently only stockpiled.

[24]Gillmann et al. 2002, [25]Schuiling and Krijgsman 2006, [26]Oldfield 1996, [27]Schuiling and Krijgsman 2006

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POSSIBLE BREAKTHROUGHS NANOTECH PESTICIDES

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. Nanotechnology provides promising responses to these multiple challenges. Due to the higher efficacy of nano-active ingredients, it allows for the reduction of pesticide volumes, thus lowering costs while increasing yields.

Description

"Nanotechnology generally refers to a range of techniques for directly manipulating materials, organisms and systems at a scale of 100 nanometers or less – one nanometer being one-billionth of a meter."[1] "This capability gives us the ability to build materials and devices or shapes and products on that scale."[2] "One of the first nano-industrial applications is the development of nano-chemical pesticides – or nano-pesticides – which are pesticides that contain nano-scale chemical toxins."[3] Characteristics of this new pesticide are: i) increased toxicity, stability or diminished solubility in water as compared to bulk molecules of the same chemical toxins and ii) controlled release of pesticides due to the nanoencapsulation of pesticides.[4] Kuzma and Verhage[5] describe, for instance, a smart pesticide that only releases its pesticide when inhaled by insects. "The higher efficiency avoids the problematic chemical additives that are leading to product bans in a growing number of major markets and results in improved crop yield and reduced environmental impact."[6] However, it is also important to note that the impacts of nanoparticles on the environment and human health are still largely unknown and unpredictable.[7]

[1] Scrinis and Lyons 2010. [2] Sainsce 2009. [3] Kuzma and Verhage 2006. [4] Ibid. [5] Ibid. [6] NanoAll n.d. [7] ETC 2006

Geography

Despite global pesticide use of 2.5 million tonnes per year, production losses as a consequence of plant pests remain in the order of 20-40%.[8] In addition, conventional pesticides are often synonymously mentioned with environmental degradation due to their toxicity, non-biodegradable nature, lack of scientific formulations, leaching and loss during application. The combination of low efficiency and negative side effects of conventional pesticides makes innovative nanopesticides necessary to control pests on the one hand and minimize negative consequences on the other. Nano-based pesticides are promising in this respect as they address both issues. Leading agrochemical companies developing nano-based pesticides are BASF, Bayer Crop Science, Monsanto and Syngenta. However, the marketing of smart pesticides is currently constricted, especially through environmental groups/risk assessors opposing their introduction or potential risks associated with nano-scale materials. Some of the nanopesticides issued on the market recently are mentioned in table 1.

Table 1
Nano-based products on the market[9]

Company	Product	Mechanism
Syngenta	PRIMO MAxx and Karate ZEON	Inhibit neural system
Nano Green	Nano Green	Attacks respiratory apparatus
Agro Nanotechnology Corp.	Nano-Gro	Mimics stress conditions, increasing crop activity and yield

[8]FAO 2011, [9]A detailed overview of other nano-products on the market is provided at http://www.nanotechproject.org/

Energy

- Nanopesticides are applied at smaller volumes and less frequently than conventional pesticides, also resulting in less fuel used for tractor operations.[10]

Water

- As smart pesticides are more effective, they require smaller application volumes than conventional pesticides – less and more precise pesticide use means less non-point water contamination.

Pesticide efficiency and crop productivity

- Nanotechnology promises higher yields and lower input costs by streamlining agricultural management and thereby reducing waste and labor costs.[11]
- Nano-Gro pesticide increased average crop yield by 20% and for some crops even more: sunflower by 50%; rice by 35% and cucumber by 25%.[12]
- Nano Green pesticide increased rice yields by 25%.[13]
- Soybean yields increased 48% with nano-iron oxide particles.[14]

[10] Nano Green Sciences Inc. n.d. [11] Anane-Fenin 2008, [12] Agro Nanotechnology Corporation n.d. [13] Nano Green Sciences Inc. n.d. [14] Sheykhbaglou et al. 2010

Climate change

- Climate change means more pests in certain regions, increasing the need for pesticides.
  - A 1% increase in rainfall raises pesticide treatment costs for corn by 0.45%.[15]
  - A 1% increase in temperature increases pesticide treatment costs for potatoes by 1.41%.[16]

Costs and benefits

- The increased toxicity of nanopesticides and the ability to more precisely control the quantities and conditions under which pesticides are released could result in a reduction of the volume of active compound applied in specific situations, thereby reducing input costs and environmental pollution.[17]
- In the near future, nanostructure catalysts will be available that will increase the efficiency of pesticides and herbicides, allowing lower doses to be used. The higher efficiency of nanostructured pesticides is based on the higher reactive surface area compared to conventional pesticides. Lower doses decrease application costs.[18]

[15]Chen and McCarl 2000, [16]Ibid, [17]Kuzma and Verhage 2006 in Scrinis and Lyons 2010, [18]Joseph and Morrison 2006

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POSSIBLE BREAKTHROUGHS

MIXED FARMING SYSTEMS

Most research and agricultural development has focused on increasing yields and improving farming technologies for a reduced number of crops, preferably grown in monocultural systems. The benefits and potential of multiple cropping and agroforestry systems – not only for the provision of ecosystem services, such as increased biodiversity, but more importantly in terms of pest control, improved resource-use efficiency and resilience to resource-limited environments – have been largely overlooked. Moreover, faced with increasing demands for food, by intensifying crop production into time and space, multiple cropping systems are a means to maximize land productivity per unit area.[1]

[1]Gliessman 1985

Description

Multiple cropping systems imply within-field crop diversification, either in time (i.e., rotations) or in space (e.g., intercropping), with the objective of optimizing ecological interactions between crops that trigger positive synergies. In agroforestry, trees are included in the cropping system or combined with livestock production. These systems lead 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 relevant in light of the vulnerability of major monocultured crops to pests and diseases.[2] As not all mixtures provide suppressive capacity against specific pathogen populations, a deep understanding of both ecological interactions in variety combinations and pest pathogenesis is needed. Most leguminous crops have the capacity to develop symbiotic nodules with soil bacteria (e.g. *Rhizobium*) that convert inert atmospheric nitrogen into ammonia (NH_3). Biological nitrogen fixation by leguminous crops becomes particularly interesting – not only are legumes nitrogen self-sufficient, but they also transfer fixed nitrogen to consociated crops via their root system, reducing the amount of nitrogenous fertilization needed by the consociated staple crop. The contribution of biological nitrogen fixation to food production is certainly important, although there are controversies as to the potential shares. Some argue that biological nitrogen fixation could feed the current global population,[3] others counter that only half of the required food could be produced by naturally fixed nitrogen on current cropland.[4]

In conclusion, intercropping can significantly increase nutrient and water-use efficiency, which reduces the use of fertilizers and irrigation. Curbing the use of pesticides also reduces environmental pollution and health hazards. Agroforestry systems present many of the advantages of multiple cropping systems. Benefits are tangible in the provision of ecosystem services, such as biodiversity conservation, water and soil quality enhancement, and, not least, carbon storage. In terms of production, they support a variety of complementary products encompassing food, feed, fuel wood, timber and energy.

[2]Waddington et al. 2010; Hartman et al. 2011; Ratnadass et al. 2012, [3]Bagdley et al. 2007; Goulding et al. 2009, [4]Erisman and Sutton 2008; Smil 2001

Geography

The benefits of multiple cropping systems are not new to traditional farming in Mesoamerica. These systems also still constitute the major farming and food provision system in sub-Saharan Africa, for a number of reasons, most importantly because they are better adapted to local environmental conditions and the general low fertility of tropical soils. For instance, cereal-legume intercropping is a well-established production system throughout tropical developing countries.[5] As the best lands with good soil, easy water control, and that are easy to mechanize are already cultivated, multiple cropping represents a potentially effective means to make marginal lands increasingly productive.[6] In general, tropical environments lend themselves better to multiple cropping due to greater rainfall, longer growing periods, and a warmer climate. Yet even in environments with limited or variable resource availability (nutrients, water), multiple cropping can make a more efficient use of the resource endowment.

Future perspectives

For the private sector, exploiting the potential of multiple cropping opens up new business opportunities, particularly in sub-Saharan Africa and China, where one-third of the total cultivated area and half of total yields come from multiple cropping systems. At the Centre for Crop Systems Analysis at Wageningen University, researchers emphasize the relevance of multiple cropping systems for the development of high-quality plant production in sustainable agro-ecosystems. According to Dr. Niels Anten and Dr. Tjeerd-Jan Stomph, efforts will have to be directed towards breeding for combinability (e.g., synchronizing crop cycles to have similar critical growth stages, finding cultivars/species that best exploit synergistic benefits) and developing smart technologies and machinery that can handle multiple crops, such as robotic machines.

A basic principle of multiple cropping is that of "complementary crops" and timing, so as to avoid competition for space, light, nutrients and water, or inhibition by toxic compounds produced by the previous crop. This requires greater understanding of the biological and agronomic factors behind certain crop responses. The fact that decision-makers still think poorly of multiple cropping limits the research funding available to make these systems viable alternatives.

[5]Ofori and Stern 1987, [6]Gliessman 1985

Energy

- Improving pest control through biological interactions between multiple crops reduces pesticide use and thus limits the use of tractors, which ultimately reduces energy inputs into the system.
- In India, nitrogen savings of 35-44 kg/ha were registered when a leguminous crop preceded rice or wheat, while intercropping of soybean with maize could save up to 40-60 kg nitrogen (N)/ha.[7]

Water, nutrient, and light use efficiency

Crops with different nutritional requirements, timing of peak needs, and diverse and deeper root structures are grown on the same land simultaneously[8] thus optimizing nutrient and water use.

- Water-use efficiency in intercropping is often 18% higher and can be as much as 99% higher than in sole crops.[9]
- Studies have shown higher water-use efficiency in maize-bean intercropping in Africa as a result of the live mulching activity of beans.[10]
- Faba beans also enhance phosphorus uptake by maize.[11]
- By optimizing plant architecture and different light requirements, multiple cropping systems ensure best use of available light and increase photosynthetic potential.[12]

[7]Venkatesh and Ali 2007, [8]Gliessman 1985, [9]Morris and Garrity 1993, [10]Tsubo et al. 2003, [11]Zhang and Li 2003, [12]Gliessman 1985

Productivity

Yield advantages and improved soil fertility

- Several studies show higher yields per unit area (expressed in relative yield total or land equivalent ratio) than in monocultured systems under the same management level. In corn-bean-squash mixtures in Mexico, corn yields were substantially higher than in monoculture.[13]
- Biological nitrogen fixation, green manure and organic matter reincorporated into the soil lead to increased soil fertility, humidity conservation and microbiological stimulation. These all ensure long-term productivity.[14]
- Maize-bean intercropping has proven more productive than sole maize in various regions of Africa.[15] The fertilization benefits for the cereal crop when associated with a nitrogen-fixing leguminous crop can be ascribed to nitrogen excretion[16] and nodule decomposition[17] of the latter crop during the growing period.
- There is also evidence that competition between cereals and leguminous crops stimulates atmospheric nitrogen absorption and fixation by the leguminous crop.[18] Morgado and Willey[19] found highest efficiency of maize-bean intercropping when applying nitrogen at 50 kg/ha, which led to higher maize cob yields than in maize sole cropping.

Improved pest control

- Mutual pest control exercised by symbiotic relations between crops leads to higher yields and less harvest losses.
- Intraspecific diversity of rice (*Oryza sativa*) has been tested on large-scale fields in Yunnan, China, whereby two different rice varieties – one disease-susceptible (glutinous variety) and one disease-resistant (non-glutinous variety) – were grown in the same field. In addition, the different heights of these two varieties allowed for better aeration, creating less conducive conditions for rice blast, the major rice disease. Yields of glutinous rice were 89% greater

  and pest incidence 94% lower than in monocultured systems. Yields of hybrid (non-glutinous) rice were nearly equal to those of monocultures.[20]
- Other successful implementations of within-field genetic diversity are found in the U.S. where wheat mixtures are grown under highly mechanized conditions. Similarly to mixtures of different cultivars of wheat, interspecific mixtures of wheat and barley have shown greater disease reduction than by the application of fungicides.[21]
- Other examples are those of vegetable mixtures (e.g. carrot-onion, leek-celery) that limit attacks and damage by pests.[22]

[13]Ibid. [14]Ibid. [15]Tsubo et al. 2003, [16]Eaglesham et al. 1981, [17]Saito 1982; Bonetti 1991, [18]Fan et al. 2006, [19]Morgado and Willey 2003, [20]Zhu et al. 2000, [21]Vilich-Meller 1992; Kaut et al. 2008, [22]Uvah and Coaker 1984

Costs and benefits

- Less dependence on external inputs (fertilizers and pesticides) and lower costs.
- Yet, in some circumstances, the complexity of activities required makes these systems economically unviable.
- By making best use of space and labor, multiple cropping systems can offer greater profit per unit area to smallholders while providing for a more nutritious diet.[23]
- Diverse food outputs are obtained through multiple cropping, thus providing greater choice.
- Multiple cropping also provides market benefits as growing a variety of crops helps farmers protect themselves against market fluctuations and low prices in one crop.

Climate change

Biological diversity is crucial for smallholder farmers to create resilience to climate change as it creates capacity to absorb shocks and adapt to changing sets of circumstances.[24]

[23]Gliessman 1985, [24]FAO-OECD 2012

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POSSIBLE BREAKTHROUGHS PRECISION IRRIGATION

Water application at field level can be done either by pressurized (e.g. sprinklers, drip, micro-sprinklers) or gravity (e.g. furrow, basins) systems. Around 98% of the world's irrigated area is served by the latter, despite the fact that the investment costs of both systems balance each other out after a decade. There is further scope to promote sprinkler and drip systems as they reduce farming costs and energy requirements while improving yield.

Description

Pressurized irrigation systems such as sprinkler and drip irrigation allow for better management of crop water requirements. These techniques reduce the travelling time of water between the source and the crop roots. Water conveyed in pipes minimizes evaporation losses, while applying low volumes of water directly to the crop also reduces leaching losses and maximizes irrigation uniformity. Together, these benefits result in lower water use (and costs), reduced labor requirements, lower pumping costs, and higher yields. Although initial investment costs are higher than surface water conveyance systems, in the long term both systems balance each other out.[1]

Geography

The total land area irrigated globally is estimated to be between 278 million hectares[2] and 467 million hectares.[3] Between 1.2% and 2.1% (6 million hectares) of this area is equipped with drip and sprinkler irrigation systems.[4] Most of the irrigated area is in Asia; India and Pakistan alone irrigate over 112 million hectares.[5] Gravity-led irrigation systems are still dominant, covering 95% of total irrigated area.[6] The Asian Development Bank is encouraging small farmers in China to use micro-irrigation.[7] Given dramatically decreasing groundwater tables and the still very limited application of water-saving irrigation technologies, there are great gains to be made here.

The lower efficiency of gravity-led systems compared to pressurized water distribution systems requires larger volumes of water to meet crop water requirements. Given that irrigation is largely supported by groundwater, especially in Asia, water saving technologies could significantly reduce energy use and costs in the agricultural sector.[8] Shah et al.[9] mention that India, Pakistan, Bangladesh and Nepal pump around 210 km^3 of groundwater every year through 20-21 million pumps, of which 13 million are electric and 8 million diesel. Altogether, these pumps use energy equivalent to 100 billion kWh/year, costing farmers US$ 12 billion per year. In this way groundwater irrigation contributes to more than one-quarter of India's total energy demand.[10]

[1]For example, SWMRG 2005, [2]Siebert et al. 2005, [3]IWMI 2007, [4]Reinders 2006, [5]Ibid, [6]Brown and Halweil 1998: specifically referring to China, [7]Radstake and van Steenbergen 2013, [8]Shah et al. 2003, Narayanamoorthy 2007, [9]Shah et al. 2003, [10]Ibid

Table 1

Impacts of changing from surface to drip irrigation systems in India

Crop	Increase in yield (%)	Reduction water application (%)
Bananas	52	45
Cabbage	2-54	40-60
Cotton	10-35	15-60
Grapes	23	48
Okra	72	40
Potatoes	46	0
Sugarcane	6-33	44-60
Sweet potatoes	39	60
Tomatoes	5-50	27-39

Source: CA, 2007

Energy

- Higher water-use efficiency shown by pressurized systems allows for the reduction of total energy use where water is pumped from ground or surface water in both application systems. Farmers in Maharashtra (India) using drip irrigation save 29-44% electricity over farmers using flood irrigation.[11]
- In China, drip and micro-sprinklers could reduce energy consumption by 40%[12] and fertilizer consumption by 35-40% through more efficient application and use.
- Generally, sprinkler systems require higher energy inputs than drip irrigation systems (in the range of one-quarter more). Savings can be achieved by:
  - Using low-pressure drip and sprinkler systems. In the US this can save up to 1925 kWh (US$ 137.5) per hectare per year.[13]
  - Fine tuning pumps and sprinkler and drip systems reduced energy costs by 15% for 60% of farmers in Nebraska.[14]

Water

- Drip irrigation reduces water use by 30-70% compared to surface irrigation.[15]
  - Water application efficiency under surface irrigation ranges from 50-95%.[16] However, common efficiency is 40-60% due to poor management.
  - Sprinkler and drip application efficiency is in the range of 65-85% and 70-95% respectively,[17] the latter having less evaporative losses.[18]
- 40-60% water savings have been registered in China with drip combined with plastic-mulching.[19]
- Improving water-use efficiency at basin level needs further and more complex considerations than water application efficiency at field level because of "scale effects". At basin scale, "wet" rather than "dry" water savings have to be achieved. Wet water saving refers to the reduction of non-beneficial drainage water.[20]

Productivity

- Change from surface water to drip irrigation has increased yields of a wide range of crops in India (see table 1).
- Crop water requirements are better managed using drip and sprinkler irrigation rather than surface irrigation methods. This usually results in higher yields:
  - Pepper yields have increased on average by 30% using drip irrigation, as compared to sprinkler furrow irrigation.[21]
  - Tomato yields have increased 1 to 2 t/ha compared to furrow irrigation and 1.3 to 2.2 t/ha compared to sprinkler irrigation.[22]
- Corn yields in the US using drip-irrigation resulted in 11.5 t/ha; with furrow irrigation they yielded 9.9 t/ha and with sprinkler irrigation 10.3 t/ha.[23]
- Yields have increased 10-40% with drip irrigation combined with plastic mulching in horticultural systems in China.[24]

[11]Narayanamoorthy 2007, [12]Radstake and van Steenbergen 2013, [13]Extension 2011, [14]USDA 2011, [15]Lamont et al. 2002; Narayanamoorthy 2007; Wemyss 2010, [16]Rogers et al. 1997, [17]Ibid. [18]Styles and Burt 1999, [19]Radstake and van Steenbergen 2013, [20]Seckler 1997, [21]Styles and Burt 1999, [22]Hanson et al. 2000, [23]Humphreys et al. 2005, [24]Radstake and van Steenbergen 2013

Climate change

- Groundwater pumping for irrigation in India accounts for an estimated 16-25 million metric tonnes yearly of carbon emissions, 4-6% of India's total. Using water-saving technologies like drip irrigation saves energy use and reduces carbon emissions substantially.[25]

Costs and benefits

- Sprinkler and drip irrigation, because of their high capital investment per hectare, are mostly used for high-value cash crops, such as vegetables and fruit trees.[26]
  - Drip irrigation costs for growing tomatoes (system costs, installation costs, energy costs, maintenance costs) were US$ 568/ha/year higher compared to furrow irrigation.[27]
- Drip and sprinkler irrigation methods, however, reduce overall crop production costs, as less human labor is required to guide water, as is the case in gravity-based conveyance systems.[28] Referring to an Indian National Committee on Irrigation and Drainage (INCID) study in 1994, Narayanamoorthy[29] mentions that: "benefit cost ratios for different crops suggest that investment in drip irrigation is economically viable..." The benefit-cost ratios mentioned for high value crops like grapes are high (13.35), while cost benefit ratios for more local crops, like coconuts, are lower.[30]
- The potential of large-scale irrigation systems in Asia can only be unlocked by introducing innovative practices. Mukherjee et al.[31] argue that integrating modern design principles (e.g. pressurized water delivery systems and advanced field levelling techniques) in these traditional systems is sometimes a cheaper alternative than rehabilitation on its own.

[25]Shah 2009, [26]FAO 1988, [27]Hanson et al. 2000, [28]Narayanamoorthy 2007, [29]Ibid. [30]Ibid. [31]Mukherjee et al. 2009

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POSSIBLE BREAKTHROUGHS CONJUNCTIVE WATER USE AND DRAINAGE

Conjunctive water use refers to the simultaneous use of surface water and groundwater to meet crop demand.[1] Besides meeting quantitative water needs, conjunctive use also blends water from various resources to arrive at preferred water quality. Conjunctive use as a management strategy typically allows organizations to address the energy-water nexus in the agricultural sector while raising productivity. Moreover, water logging is estimated to affect 24% of the global irrigated area.[2] This is the result of inadequate irrigation management and insufficient investment in drainage. Conjunctive water use could effectively lower groundwater tables and reduce water logging.

[1]World Bank 2006, [2]FAO 2011b

Description

Conjunctive water use is distinguished by cyclic and mixed (or blended) conjunctive use. Cyclic conjunctive use is the successive application of water from different sources. The cycle can take place within the same cropping season, in between seasons and within the scheme itself. In mixed/blended conjunctive water use, water from various sources is mixed in the canal. A much-debated topic in scientific papers is what type of conjunctive use actually reduces the accumulation of salts in the soil profile and limits yield reduction. Conjunctive water management can be applicable in areas with problems of high salinity or high alkalinity. Highly saline waters are mostly encountered in arid parts (annual rainfall 300-350 mm), whereas groundwater showing a high incidence (30-50%) of residual alkalinity exists in semi-arid parts (annual rainfall 500-700 mm).[3] See table 1 for an overview of the causes of salinity/alkalinity, the applicable conjunctive use methods and the research focus areas.

Table 1
Saline and alkaline soils/water (causes, conjunctive use methods and research focus areas)

Constraint	Cause	Conjunctive use method	Applies to
Saline soil	Poor drainage, constrained freshwater sources, human activities, such as land clearing and aquaculture	Leaching of salts during monsoon or rainy season with subsurface drainage, pre-sowing irrigation with good quality water	Northern and southern coastal provinces of India, Egypt, Bangladesh, Pakistan, China, Iran
Alkaline soil	Natural presence of soil minerals producing sodium carbonate and sodium bicarbonate, poor drainage	Minimizing the precipitation of calcium or maximizing the dissolution of precipitated calcium, using subsurface drainage	China, northern part of India, Central Europe
Saline water	High salinity surface or groundwater caused by salt accumulation and seepage through saline soils, re-use of high salinity drainage water	An efficient substitution of low-salinity water by blending fresh surface water with salty groundwater	Northern and southern coastal provinces of India, Egypt, Bangladesh, Pakistan, China, Iran
Alkaline water	Application of soft water in irrigation (surface or groundwater) containing a relatively high proportion of sodium bicarbonates, industrial polluted waters	Blending and cyclic use of alkali and good quality waters	China, northern part of India, Central Europe

[3]Minhas et al. 2007

Geography

Conjunctive use practices are dominantly found in large-scale irrigation in South Asia, Iran, Pakistan, and the northern and southern coastal provinces of India, Bangladesh and China. A large-scale survey in India, Pakistan, Nepal-Terai and Bangladesh conducted by the International Water Management Institute (IWMI)[4] shows that, for the region as a whole, 55% of the irrigated area is exclusively irrigated by groundwater and 22% is under conjunctive use of ground and surface water.[5] See table 2 for an overview.

Iran

In central Iran, semi-arid regions with low precipitation and high potential of evapotranspiration are abundant. Rapid population growth, increased irrigation and industrial development during the past decades have put increasing pressure on water resources.[6] Upstream of Nekouabad and in the Borkhar area north of Esfahan city, surface water canals have been implemented. These areas were originally developed using only groundwater. However, this was insufficient to meet the demands of the total potentially irrigable area. The irrigation area has now been designed to operate under conjunctive use systems.[7]

Pakistan

In Pakistan, groundwater for irrigation is used both in isolation and in conjunction with canal water. Conjunctive use of surface and groundwater is more common due to two main reasons: 1) to increase the supply of irrigation water and 2) to improve groundwater quality through dilution. However, farmers are not fully aware of mixing ratios, resultant salinities and their long-term consequences on crops and soils.[8] Drainage in Pakistan is done by both surface and tube well (vertical) drainage. Kazmi et al.[9] show that in the Lagar area, within the general picture of conjunctive use of canal water and groundwater, there is a clear spatial pattern between upstream and downstream areas, with upstream areas depending much less on groundwater than downstream areas. This has to do mainly with differential access to canal and tube well water, resulting in different farmer responses in terms of irrigation strategies.

[4]IWMI 2002 in World Bank 2006, [5]Shah et al. 2006, [6]Safavi et al. 2002, [7]Salemi et al. 2000, [8]Qureshi et al. 2004, [9]Kazmi et al. 2012

Bangladesh

In Bangladesh in 1999, of the 3.99 million hectares of irrigated area, approximately 70% of irrigation was dependent on groundwater.[10] However, the advantages of exploiting groundwater irrigation sources are under serious threat due to arsenic contamination. Recent evidence shows that the groundwater sources of 61 out of 64 districts are contaminated with arsenic.[11]

China

In arid and semi-arid areas of northern China, water logging, salinity and alkalinization are considered serious constraints to agricultural development in irrigated land. Saline/alkaline cultivated land in China covers 7.73 million hectares (5.51 million hectares of which have been improved). It was estimated in 1996 that 24.58 million hectares were subject to water logging, of which 20.28 million hectares were equipped with drainage.[12]

India

In India, it is estimated that nearly 8.4 million hectares are affected by soil salinity and alkalinity, of which about 5.5 million hectares are also waterlogged.[13] Due to intensive groundwater use for irrigation in Uttar Pradesh, 50% of the land area now has water tables that are critically low. Impacts are irrigation tube-well dewatering, yield reduction and pump failure. At the same time, canal leakage and flood irrigation in the head water zones have resulted in around 20% of the land area threatened by rising and shallow water tables, with water logged soils and salinization leading to crop losses and even land abandonment.[14]

[10]Mainuddin 2004, [11]Ibid. [12]FAO 2011a, [13]Ritzema et al. 2008, [14]Foster et al. 2010

Table 2

Profile of irrigation by groundwater and surface water sources

Region (1)	Total cultivated land (ha) (2)	% rainfed (3)	Area irrigated as % to cultivated land[i] (4)	% of cultivated area under respective sources of irrigation			
				Pure canal irrigation (5)	Pure groundwater irrigation (6)	Conjunctive use of ground and surface water (7)	Other sources (8)
Northwestern India	27,778	8.1	91.9	2.9	82.8	5.6	0
Eastern India	10,719	55.6	44.4	3.3	24.1	11.0	5.9
Central Indian tribal belt	11,762	58.3	42.3	0.7	26.4	13.3	1.3
Central and Western India	57,913	71.4	28.6	0.6	24.8	2.0	1.2
Interior peninsula India	31,859	77.2	22.8	2.4	13.2	1.8	5.4
Coastal peninsular India	10,503	45.7	59.0	15.8	19.6	14.7	4.3
India	**150,534**	**57.0**	**43.4**	**2.7**	**32.8**	**5.0**	**2.4**
Pakistan Punjab	63,149	56.9	50.5	16.0	5.0	21.9	0
Pakistan Sindh	4,056	52.5	43.1	19.9	7.3	20.3	0
Pakistan NWFP	7,885	49.5	50.4	28.5	6.8	4.7	0
Pakistan	**75,091**	**55.9**	**44.2**	**17.5**	**5.3**	**20.0**	**1.4**
Northwestern Bangladesh	1,544	18.4	81.6	0	79.2	0	1.3
Rest of Bangladesh	4,350	43.9	56.1	0.2	25.8	6.2	23.8
Bangladesh	**5,904**	**37.2**	**62.8**	**0.2**	**39.9**	**4.6**	**17.9**
Nepal Terai	4,452	42.1	62.1	28.3	31.8	0.3	0
Region aggregate	**236,070**	**55.8**	**44.5**	**7.8**	**24.2**	**9.7**	**2.0**
Source contribution to total irrigated area (%)				17.8	54.8	22.0	4.5

Source: Primary survey conducted by IWMI in 2002. [i]The questionnaire asked sample farmers to separately provide figures for their farm areas under rainfed farming and under different sources of irrigation. Columns 3 and 4 are computed based on these; as a result the sum of the % of rainfed and irrigated area does not always add up to 100%. Source: Shah et al. 2006.

Energy

- Groundwater irrigation consumes a large amount of energy:
  - Groundwater irrigation accounts for one-quarter to one-third of national energy demand in India.[15]
  - India, Pakistan, Bangladesh and Nepal pump around 210 km^3 of groundwater every year using some 21 million pumps (13 million electric and 8 million diesel). Total electricity use is 100 billion kWh/year, a market equivalent of US$ 12 billion.[16]
- Falling groundwater tables, due to unsustainable groundwater withdrawal, further increases the energy demand of the agricultural sector:
  - In 2007, tube wells in Punjab consumed 28% of total electricity consumption in the entire state. If groundwater levels continue to fall, tube wells will consume twice as much energy by 2023.[17]
- By compounding groundwater with surface water, energy use in agriculture can be reduced.
  - In the Madhya Ganga Canal Project in Uttar Pradesh, India, conjunctive water use has saved 75.6 million kWh annually (INR 180 million annual cost savings).[18]

[15]Shah et al. 2003, [16]Ibid, [17]NRAA 2009, [18]IWMI 2002 in World Bank 2006

Water

- Conjunctive water use allows for the storing of excess surface water during normal and high rainfall years and the pumping of large volumes of water during drought years.[19]
- Conjunctive water use has reduced conveyance loses in canals by 50%, raised groundwater levels by six meters over a decade and increased the irrigated area 30-fold.[20]
- Conjunctive water management strategies help reduce evaporation losses from reservoirs, as their storage can be drawn down more quickly if groundwater can be relied on to meet water needs later in the year.[21]
- Planned conjunctive use is a smarter and more sophisticated groundwater overdraft water management technique and is being used more and more frequently.[22]
- In arid and semi-arid regions, subsurface drainage systems effectively prevent water logging and root zone salinity in irrigated lands.[23]
- In Egypt, areas with saline soils decreased from 80% (before drainage) to 30% (after drainage) in saline areas and from 40% (before) to 5% (after) in non-saline areas.[24]
- Average groundwater tables decreased from 0.6 m surface before drainage to about 0.9 m surface four years after the installation of subsurface drainage. Most groundwater levels are now under control.[25]

[19]Dudley and Fulton 2006, [20]International Water Management Institute (IWMI) 2002 in World Bank 2006, [21]World Bank 2006, [22]Gleick et al. 2011, [23]Ritzema and Schultz 2010, [24]Ali et al. 2001, [25]Ibid

Productivity

- Conjunctive water management increased farm income by about INR 1,000 and 5,000 per hectare compared to only using canal and tube well water, respectively.[26]
- Paddy yields using the conjunctive irrigation method (3.4, 3.1 and 2.7 t/ha) were on average half a tonne higher than paddy yields solely irrigated with the tank system (2.9, 2.4 and 2.2 t/ha).[27]
- Mixing salt and freshwater:
  - "The profit decreased from 12,000 to 7000 INR/ha when the canal water supply decreased from 15 to 10 cm with a groundwater (EC = 6 dS m_1) use of 15 cm."[28]
- In Uttar Pradesh, India, average cropping intensity can be increased from less than 150% to more than 220% with planned conjunctive use.[29]
- Crop yields increased on average 54% for sugarcane, 64% for cotton, 69% for rice and 136% for wheat. This was mainly because in drained fields groundwater tables and soil salinity levels were 25% and 50% lower than in non-drained fields, respectively.[30]

[26]Jehangir et al. 2003, [27]Sekar 2008, [28]Tyagi 2003, [29]Foster and Garduno 2011 [30]Ritzema et al. 2008

Climate change

- The importance of managing ground and surface water conjunctively increases with water scarcity and with inter- and intra-temporal fluctuations in precipitation, the latter due to climate change.[31]
- Controlled drainage will allow farmers to optimize their on-farm water management based on the specific conditions and their own preferences. Furthermore, it enables farmers to respond to changes in land use and/or the effects of climate change.[32]

Costs and benefits

- Conjunctive water use in the Madhya Ganga Canal Project in Uttar Pradesh, India, increased farmers' income by 26%.[33]
- Farmers in Gujarat, India were attracted to buying land with subsurface drainage at prices five times higher than the pre-drainage period, i.e., for €7,500 to €12,000/ha compared to pre-drainage land values of €1,500 to €2,500/ha.[34]
- Better management of surface and groundwater during the 1996-2004 drought in the Yaqui Valley (Mexico) could have significantly reduced the impact of the drought without affecting profits in wet years.[35]

[31]Gemma and Tsur 2007, [32]Ritzema and Schultz 2010, [33]International Water Management Institute (IWMI) 2002 in World Bank 2006, z`[34]Ritzema et al. 2008, [35]Schoups et al. 2006

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POSSIBLE BREAKTHROUGHS WATER-SAVING RICE SYSTEMS

Rice is the largest single freshwater user, accounting for a quarter to a third of total freshwater withdrawals.[1] More than 90% of total rice is produced and consumed in Asia. Rice feeds billions of people and will continue to play an increasingly relevant role in sustaining food security and livelihoods in various regions of the world. This is especially true in sub-Saharan Africa where rice demand and production is expected to grow most – a 130% increase relative to 2010.[2] Irrigated systems predominate in Asia, rainfed rice in Africa.[3] Increasing water scarcity in rice growing areas, low nitrogen use efficiency, high energy inputs for water pumping, and rising concerns for the huge amounts of methane emissions (8.7-28% of total anthropogenic methane emissions) from paddy fields, call for a shift in practices towards water-saving technologies, a search for new varieties and, possibly, even for more fundamental rethinking of rice systems.

[1]CA, 2007 [2]Seck et al. 2012, [3]Seck et al. 2012

Description

Some 25 million hectares of rainfed rice suffer frequent droughts, and 15-20 million hectares of irrigated rice are projected to suffer some degree of water scarcity over the next 25 years.[4] This, and the high cost of pumping, demands sustainable solutions for the improvement of water productivity. Water consumed by farmers during the growing period is much higher than actual crop water requirements,[5] and continuous submergence is not a prerequisite for high yields.[6] The reasons for inundating paddies include better weed control, easier soil labor, temperature regulation and water storage during monsoons.

In many circumstances, however, water consumption can be reduced. Alternate wet/dry irrigation (AWDI) and direct seeding are among the most promising methods at hand to reduce water consumption in rice systems. Whereas in traditional lowland rice systems fields are kept permanently inundated throughout the growing cycle, in alternate wet/dry irrigation, irrigation water depth and intervals are manipulated to allow the field to dry intermittently.[7] This allows for important water savings without significant yield reductions. Also, better soil aeration stimulates root growth, leading to higher yields and water-use efficiency.[8] Chapagain and Riseman[9] also found a low incidence of pests and diseases under alternate dry and wet irrigation and explained this as a consequence of less favorable environmental conditions and disruption of the pest and disease life cycles.

In many rice systems, land preparation is the practice that consumes the largest amount of water, and particularly so when the establishment of the crop is done by transplanting. Before transplanting the young seedlings, paddy fields are first saturated with water, then plowed and puddled. Farmers often delay plowing and puddling while waiting for the seedlings to be nurtured in the seedbed. This implies large water losses through seepage, percolation and evaporation.

[4]CA 2007, [5]van der Hoek et al. 2001, [6]Guerra et al. 1998, [7]Chapagain and Riseman 2011, [8]Shuichi and Uphoff 2007, [9]Chapagain and Riseman 2011

Description (continued)

Direct seeding, especially dry direct seeding, is a method to minimize land preparation duration and thus irrigation water inputs.[10] In dry seeding, dry seeds are sown onto the dry or wetted soil, often coinciding with the first rains. In this case, by ensuring early crop establishment, and as it does not require pre-saturation irrigation, this method can reduce water inputs consistently.[11] Moreover, direct seeded rice develops deeper roots and needs less frequent irrigation.

Nitrogen-use efficiency is also a major concern, with an average of 65% of nitrogen lost to the environment.[12] Rice production, particularly permanently inundated paddy fields, also contributes to climate change through methane and nitrous oxide emissions.[13] Methane emissions per growing season can range 30-50 kg CH_4/ha in dryland rice and 200-1100 kg CH_4/ha in wetland rice.[14] Constraints to direct-seeded rice are higher weed infestation and weeds that are difficult to control. This requires improved information on chemical and biological (rotations, consociations) weed control methods. More research is needed to improve the productivity of direct-seeded rice through the development of higher yielding varieties suitable for different agro-ecological zones, improved nutrient and water management as well as improved weed control.

Researchers are trying to develop varieties with improved tolerance to water stress without compromising high yields under optimal water supplies (see box 1). Varieties have been developed that are more tolerant to water-limited conditions, such as aerobic rice used in upland systems. However, at present, their yields are not nearly comparable to those of lowland rice. Additional research, especially into root morphology and root biology, and the underlying genetic differences, is needed to understand drought tolerance mechanisms and rice response to water.

[10]Cabangon et al. 2002, [11]Ibid, [12]Pathak et al. 2011, [13]Ibid, [14]Wassmann et al. 2004

Geography

Direct seeding, once a traditional practice in India, is currently back in vogue as a promising water and laborsaving technique.[15] PepsiCo also endorsed the technique through a number of initiatives with farmers in India covering about 10,000 acres. The company also introduced for the first time in India, a special tractor with a direct-seeding machine that is adjustable according to seed variety, planting depth and plant-to-plant spacing. Currently, direct seeding in India is applied to 29 million hectares, approximately 21% of the total rice cultivation area.[16] It is also extensively practiced in the U.S. and Australia.[17]

AWDI is particularly advantageous in areas with sandy soils. Nevertheless, where water supplies are really restricted or more costly, for instance if capital-intensive irrigation systems have been used, it is more economically viable to grow other crops than rice under non-flooded conditions.[18] In China, where almost all rice is irrigated, this is common practice in lowland rice systems.[19]

Globally, there are about 150 million hectares of rice cultivation, 50% of which are in irrigated lowlands. This gives an order of magnitude for the potential spread and impacts of water saving technologies for rice.

[15]Gupta et al. 2006, [16]Pandey and Velasco 2002, [17]Pathak et al. 2011, [18]van der Hoek et al. 2001, [19]Li and Barker 2004

Box 1

Growing rice like wheat

In 2012, Plant Research International at Wageningen UR, the International Rice Research Institute (IRRI), Bangalore University (India), and Yangzhou University (China) launched a joint program with the objective of fundamentally transforming rice into a crop with water requirements similar to those of wheat. Prem Bindraban, of Plant Research International, believes that as most arguments for growing rice in inundated conditions are agronomic rather than physiological, there should be a way to identify the mechanisms that prevent rice from being grown like wheat. The benefits are manifold and encompass socioeconomic and environmental aspects: less labor requirements, less methane emissions, lower costs, adaptability to water scarce conditions, increased crop diversification and improved profitability.

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 phonological and physiological features. Rice is very sensitive to spells of drought, and crops will fail as soon as the muddy soil starts to crack. This could be attributed, among others, to root morphology and the capacity of roots to take up water under limited conditions. Sub-Saharan Africa, with scarcer water and lighter soils, could benefit most from the results of this research, as it is precisely here where most of the expansion in rice demand and production is expected to happen.

The water "saved" if rice were to be grown like wheat could be used for other, more valuable crops or uses. Altogether these transformations create opportunities for new business and investments.

Energy

- Alternate wet/dry irrigation can achieve 26% higher nitrogen-use efficiency,[20] which ultimately means a reduction in fertilizer use.
- Up to 60% energy (diesel) savings with direct seeding, as it does not require nursery raising and puddling of fields and requires less water application.[21]

Water

Varietal improvement

- Aerobic rice systems, pioneered in Brazil and China, are higher yielding than traditional upland varieties. But the development of higher-yielding aerobic varieties is still in its infancy.[22]
- Experiments with aerobic rice in China showed 30-50% less water use and 20-30% lower yields with maximum yields of 5.5 t/ha.[23]
- At Wageningen University, efforts are directed at transforming rice into a crop like wheat, consuming 1,000 l/kg compared to actual 2-5,000 l/kg (see box 1).

Water-saving technologies

- Alternate wet/dry irrigation can save up to 15-20% water without reducing yields.[24]
- Water savings of 29% with alternate wet/dry irrigation over conventional irrigation were found in Japan without significant yield reductions (7.2 vs 7.8 t/ha).[25]
- Direct seeding is making advances relative to transplanting[26] and has proven effective in reducing water consumption by making better use of rainfall and reducing irrigation needs.[27]
- Direct seeding can achieve 19-60% water savings.[28]
- An initiative launched by PepsiCo on direct seeding of rice in India demonstrated 30% water savings compared to traditional puddling.
- Direct seeding in lowland rice presents multiple advantages, such as better drought tolerance, better use of early rainfall and improved nitrogen use efficiency.
- Resource-use efficiency increases the possibility of growing a second or even a third crop.[29]

[20]Jothimani and Thiagrajan 2005, [21]Pathak et al. 2011, [22]CA 2007, [23]Wang et al. 2000, [24]Tabbal et al. 2002, Belder et al. 2004, [25]van der Hoek et al. 2001, [26]CA 2007, [27]Cabangon et al. 2002, [28]Pathak et al. 2011, [29]CA 2007

Productivity

- With alternate wet/dry irrigation, 5-15% higher yields could be achieved.[30]
- Inadequate weed control in direct-seeded rice can lead to yield decreases. For instance, 20% yield decreases were found in India compared to transplanted rice, often because of inadequate weed control.[31]
- Yet when are weeds appropriately controlled, yields are comparable to those of transplanted rice.[32]
- Dryland rice currently comprises approximately 12% of the world's rice area, but yields account for only 4% of global rice production.[33] Improved aerobic varieties in upland rice systems in Brazil have shown 6 t/ha.[34]
- In environments prone to droughts, salinity and floods, the combined effect of improved varieties and better management practices increases yields by 50-100%.[35]

Climate change

Reducing methane (CH_4) emissions

- Growing "aerobic rice" under upland conditions and adding aluminum sulfate.
  - Reduces CH_4 emissions, reduction of nitrates (NO_3) remains unsure.[36]
- Using distinct drainage periods in mid-season or alternate wetting and drying of the soil in wetland cultivation.
  - Reductions of 7-80% have been measured, however, nitrous oxide (N_2O) emissions increase.[37]
  - Reductions of 30-50%.[38]
- Direct-seeded rice.
  - Reduction of 18% compared to transplanted rice.[39]
  - Up to 50% reduction when combined with mid-season drainage.[40]

Impacts of climate change on rice

- Increased yields and water productivity due to higher CO_2 concentrations might be offset by higher temperature-induced sterility.
- To optimize potential contributions of increased CO_2 on yields, there is a need to tap into genotypic variation in sensitivity to increased temperatures, breeding for varieties that are less sensitive.

[30]Jothimani and Thiagrajan 2005, [31]Johnson et al. 2003, [32]Tabbal et al. 2002, [33]Wassman et al. 2004, [34]Pinheiro et al. 2006, [35]CA 2007, [36]Wassmann et al. 2004, [37]Wassmann et al. 2004, [38]Lu et al., 2000; Wang et al. 2000, [39]Corton et al. 2000, [40]Wassman et al. 2004

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POSSIBLE BREAKTHROUGHS
CONSERVATION AGRICULTURE

Conservation agriculture is a set of principles,[1] whose adoption depends on time and space considerations. There are three fundamental principles in conservation agriculture:

> Reduced tillage (i.e. minimum or no-tillage). This 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.

> Diversified crop rotations. This reduces pest pressure and keeps the soil nutrient balance stable. Incorporating nitrogen-fixing legumes in the rotation reduces the need for external fertilizer inputs.

> Keeping a permanent vegetative cover on the bare land. This 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.

[1]Jones et al. 2006

Description

Key benefits of conservation agriculture:

- Reduced tillage keeps biotic community intact, improving biotic activity in the soil. In the long term this improves soil texture and structure, resulting in improved infiltration and soil water retention capacity.
- Crop diversification through rotations reduces pest pressure and keeps soil nutrient balance stable. Incorporating nitrogen-fixing legumes in the rotation reduces nitrogen fertilizer applications. A 10-year study of 18 medium and large farms in two regions of Paraguay shows that fertilizer and herbicide input dropped by 30-50% under conservation agriculture.
- Maintaining an organic matter mulch cover on the soil surface during both growing seasons creates a micro-climate with:

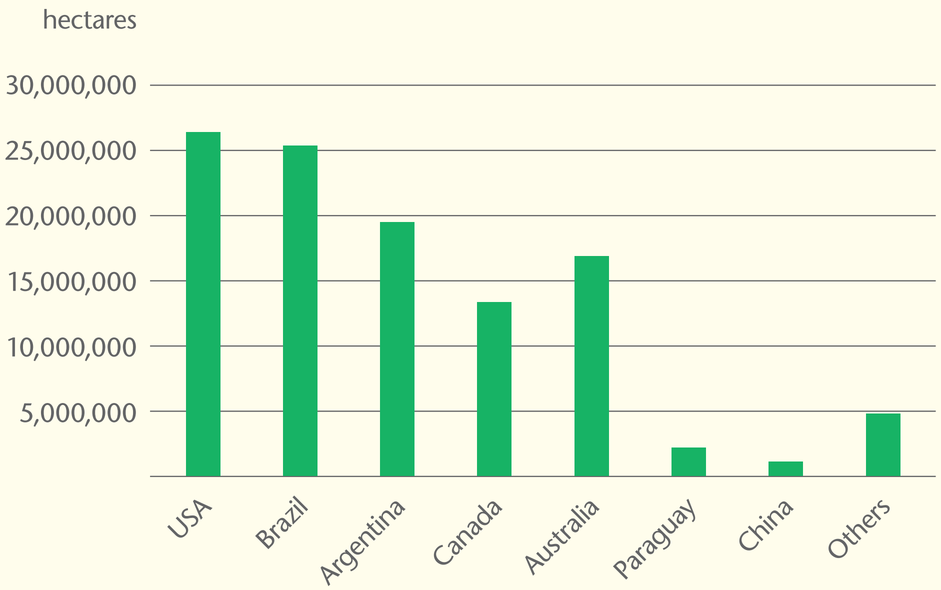
  i) Increased temperature, allowing earlier maturing of crops and reducing frost events;

  ii) Reduced evaporation losses;

  iii) Reduced soil erosion. A 17-year average study in Brazil showed that the adoption of a no-tillage system decreased soil erosion in maize and soybean systems from 3.4-8.0 to 0.4 t/ha.[2]

Key numbers of the potential impact of no tillage systems on smart resource use are summarized in figure 1 below.

Figure 1
Global coverage of no-tillage systems



Source: Derpsch et al. 2010

[2]Derpsch et al. 2010

Geography

Areas under no-tillage have expanded globally at an annual rate of 6%. From an area of 2.8 million hectares in 1973-74, the area has grown to 72 million hectares in 2003 and to more than 110 million hectares in 2009.[3] Almost 50% of this growth has taken place in South America, with Argentina and Brazil making up a large share. The global area under no- or reduced tillage is given in figure 1.[4] The uptake of conservation agriculture in Europe, Asia, and particularly in sub-Saharan Africa is modest compared to the rest of the world.

Constraints to the adoption of conservation agriculture by farmers in sub-Saharan Africa[5] 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.[6] A range of small-scale cultivation techniques, such as seed drills and weeders, are now on the market, removing some of the bottlenecks.

[3]FAO AQUASTAT 2009 in Derpsch et al. 2010, [4]Derpsch et al. 2010, [5]Giller et al. 2011, [6]Giller et al. 2009

Energy

- Energy benefits are gained through reduced needs for mechanized labor, less fuel consumption and less agrochemicals use
  - – Fuel savings of 27% in no-tillage soy-maize systems in Brazil;[7]
  - – 30-50% less herbicide and fertilizer use;[8]
  - – In South America, 70% energy savings with no-till over conventional;[9]
  - – Studied conservation tillage systems in Europe needed 137 kWh/ha on average compared to 213 kWh/ha for conventional tillage.[10]
- Better water management through pivot irrigation systems coupled with no-till has reduced energy in irrigation.

Water

- No-tillage systems and cover crops increase soil organic matter content and soil water retention capacity
  - – Run-off losses in a no tillage system in South America reduced water use from 990 m^3/ha/year to 170 m^3/ha/year;[11]
  - – Runoff reductions of 40-70% possible.[12]

Productivity

- Crop intensity is 33-100% higher in no-tillage compared to conventional systems.[13]
- Soybean production increased 10% in no-tillage over conventional systems.[14]
- Maize and soybean production increased 27% and 30 % respectively in Brazilian no-tillage over conventional systems.[15]
- Maize and soybean production in no-tillage systems is 88% and 56% higher respectively than in conventional systems.[16]
- 15% lower yields observed in maize and spring barley[17] shows context-specific implementation and effects of conservation agriculture.

[7]Pieri et al. 2002, [8]Derpsch et al. 2010, [9]Ibid, [10]Jones et al. 2006, [11]Derpsch et al. 2010, [12]Jordan and Hutcheon 1997, [13]Beck et al. 1998, [14]Clay 2004, [15]Pieri et al. 2002, [16]Derpsch et al., 2010, [17]Jones et al. 2006

Climate change

- In southern Africa, no-tillage systems sequestered 11 t/ha/year of CO_2[18]
- In Brazil no tillage systems of maize-lablab and maize-castor bean increased soil carbon contents by 47% and 116% respectively.[19]
- Yet the carbon sequestration potential of conservation agriculture has to be studied and thoroughly proven.[20]
- A study by Ogle et al.[21] suggests that observed decreasing soil carbon contents under no-tillage practices depend on decreased carbon inputs resulting from decreasing yields in humid-cold regions.
- There are also claims that no-till has greater adaptation potential than mitigation: no-till carbon sequestration is difficult to quantify and to include in the carbon market as huge areas would be needed for beneficial remuneration.[22] Direct incentives for agriculture's mitigation activities seem a better option. The government or other responsible authority would have to set rules for eligible practices and payment amounts.[23]

Costs and benefits

- Farm operation costs go down as the need for inputs decreases. Higher yields also mean greater resource-use efficiency and larger profits.
  - In Nebraska, USA, the use of pivot irrigation in combination with no-tillage has brought irrigation energy savings of US$ 35-58/ha.[24]
  - In large mechanized soy and maize farms in Brazil, total weed control costs decreased from US$ 208 to US$ 184/ha.[25]
- A 9-year study of small farms in Paraguay with a manual labor force reported a reduction in labor costs of 12% per farm and an increase of net farm income of up to 77%/farm/year.[26]
- Cost reductions of 40-50% with no-tillage.[27]

[18]Derpsch et al. 2010, [19]Ibid, [20]Baker et al. 2007; Govaerts et al. 2009, [21]Ogle et al. 2012, [22]Gattinger et al. 2011, [23]Horowitz and Gottlieb 2010, [24]Pryor,2009, [25]Clay 2004, [26]Pieri et al. 2002, [27]Jones et al. 2006

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POSSIBLE BREAKTHROUGHS
BIODEGRADABLE PLASTIC MULCHES

Mulching is common practice in agriculture aimed at reducing water loss through evaporation, controlling weed growth and increasing soil temperature. The development of bio-based and biodegradable variants of mulches adds to the above-mentioned benefits as it reduces disposal costs for farmers.

Description

Plastic mulching is a technique by which plastic sheets are applied as a skin over the soil surface. This second layer creates a microclimate that allows for better control of crop growth factors, such as water, temperature and nutrients. It is especially applied in the horticultural sector to optimize production and the quality of vegetables and fruits. The vast variety of plastics allows the grower to select the right plastic according to the specific crop conditions. The performance of the plastic mulch in controlling the range of crop growth factors is determined by its material, thickness and color. Common materials used for the production of petrol-based sheets are linear low-density polyethylene (LLDPE), low-density polyethylene (LDPE), ethylene vinyl acetate (EVA) and polyvinyl chloride (PVC). The material used for bio-based mulch is polymerized lactic acid (PLA). The sheets have a typical thickness of 10 to 50 microns and a width of (up to) three meters.[1] The colors used the most are transparent, white, black and green, each having different features that impact crop growth factors. Box I provides a short overview of the performance of the different sheet colors.

Box 1

Specific uses of different types of plastic sheets

Transparent (clear) sheets

- Encourage early season plant growth and cropping as sunlight shines through the sheets and increases the temperature between the sheet and topsoil. Dickerson[2] mentions increases of 4.4-7.8° C and 3.3-7.8° C at 5 and 10 cm soil depth respectively.

Black sheets

- Used to control weed growth as sunlight is unable to penetrate the sheet; thus photosynthesis, required for plant and weed growth, does not occur, which ultimately reduces weeding costs.

White, silver and aluminum

- Used to redirect sunlight that has penetrated the leaf canopy toward the leaves, allowing greater photosynthesis and yields. Simultaneously, it cools down the soil, allowing crop cultivation during high temperatures.[3]

[1]Dow Chemical Company n.d. [2]Dickerson 2002, [3]Lamont 2005; Dickerson 2002

Geography

The adoption of plastic mulching has seen exponential growth. While in 1991 the agricultural area covered amounted to 1.8 million hectares, in 1999 it grew to 12 million hectares, a six-fold increase.[4] This growth is almost completely attributed to the increasing adoption of plastic mulching in China, which expanded by 8 million hectares between 1991 and 2006.[5] In China, farmers, especially those in the drought prone provinces in the northwest, such as Xinjiang and Yunnan, are familiar with this technique as it prevents unproductive evapotranspiration of water.[6] "The mulching extends the growing season and contributes to higher yields and quality compared to open-field cultivation".[7] In some areas, entire valleys glisten as they are partly wrapped up in plastic mulch.

Table 1
Area covered by plastic mulching in 2006

Estimates (ha)	Greenhouse (glass)	Greenhouse (plastic) and large tunnels	Small plastic tunnels	Plastic mulching
Asia	2,476	926,000	665,000	10,000,000
Europe	28,922	171,500	92,000	400,000
Africa/ Middle East	6,682	50,600	112,000	80,000
North America	1,350	11,050	20,000	260,000
Central and South America		9,510	11,000	6,000
World total	**39,430**	**1,168,660**	**900,000**	**10,746,000**

Source: Rabobank 2006

[4]Brown 2004, [5]Brown 2004; Rabobank 2006, [6]Li et al. 2003 [7]Rabobank 2006

Impact on yields

Plastic mulches exercise multiple functions that ultimately lead to higher yields. They improve water and nutrient use by the crops, regulate soil temperature, control weed growth, reduce soil compaction by equipment and people, reduce erosive forces, reduce diseases from splash and reduce rot through contact between plant and soil.[8] Table 2 provides an overview of reported yield increases using the mulch technique.

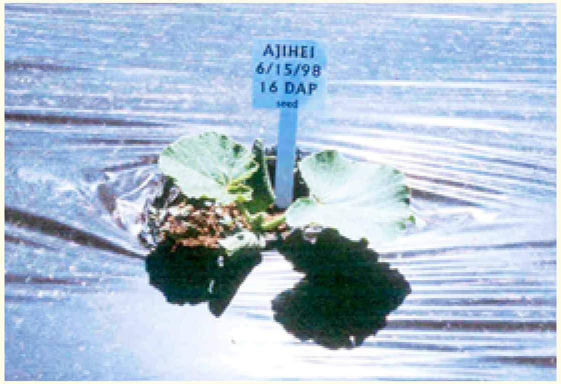

Figure 1
Kabocha squash plant in black plastic mulch 16 days after seeding[9]

Table 2
Yield response to mulching technique

Crop	Region	Yield increase (%)	Reference
Tomato	India	45-50	NCPAH 2011
Tomato	U.S. (North Carolina)	300	Sanders 2001
Pepper (Chile)	India	50-60	NCPAH 2011
Pepper (Chile)	U.S. (North Carolina)	400	Sanders 2001
Pepper (Chile)	Chile	63	Ashrafuzzaman et al. 2010
Potato	India	35-40	NCPAH 2011
White Yam	Nigeria	10-36	Osiru and Hahn 1994

[8]Osiru and Hahn 1994; Sanders 2001; Ashrafuzzaman et al. 2011; NCPAH 2011, [9]Alam and Zimmerman 2002

Energy

- The production of bio-based plastics (such as polymerized lactic acid – PLA) requires between 1 and 5 GJ/t, while petroleum-based plastics (such as low-density polyethylene – LDPE) require more than 75 GJ/t.[10]
- Biodegradable plastic mulch does not have to be removed and transported to a disposal site because the sheets decompose, saving farmers the additional use of machines and fuel.

Water

- Plastic mulch prevents unproductive evapotranspiration of water. Instead, water is kept within the reach of the crop roots.
- Drip irrigation, widely used in combination with plastic mulch, allows for water savings – up to 50% compared to furrow or overhead sprinklers.[11]
- Biodegradable mulches have the same impact on soil moisture content at 15 cm and 46 cm depths compared to black plastic mulch.

Health

- Plastic mulches are oil based and the inner side is often impregnated with fertilizers, pesticides and insecticides.[12] High disposal costs cause farmers to dump sheets uncontrolled into the environment. Besides the fact that it is unaesthetic, the inert substances are able to enter the environmental cycle.
- Biodegradable mulch, composed of biological starting materials, such as starch, decomposes by abiotic and microbial processes into carbon dioxide, methane, water, inorganic compounds and microbial biomass.[13]

[10]Bos et al. 2011, [11]Feibert et al. 1992; Kovach et al. 1999, [12]Kapanen et al. 2008, [13]Song et al. 2009

Climate change

- Production of bio-based plastics sequestrates carbon, ranging from 0.5 t CO_2 per tonne of corn/wheat and 1.8 t CO_2 per tonne of sugarcane.[14]
- Polyethylene (PE) is the most used plastic globally, totaling 80 million tonnes produced per year. It is, however, based on fossil fuels. PE can be also produced from ethanol.[15]
- Bioplastic (PLA) production based on sugar beets reduces fossil fuel use by 65% compared to LDPE plastic mulches.[16]

Costs and benefits

The price of plastic mulch is high at approximately US$ 0.14 per square meter or US$ 700 per hectare; removal and disposal costs are about US$ 250 per hectare.[17]

Bio-based and biodegradable mulches, such as PLA and polyhydroxyalkanoate (PHA) are able to compete with the petrol-based ones and have good potential as agricultural mulches.[18]

- PLA mulch production is increasing and costs are more competitive with PE mulch (currently only approximately 15% higher).[19]
- Global PLA production capacity is 140,000 tonnes/year, at an average cost of US$ 2.1-3.4 per kg.[20]
- PHA is produced by bacteria and is three times more expensive than PLA.

[14]Bos et al. 2011, [15]Ibid, [16]Wageningen UR 2011, [17]Schonbeck 1995, Olsen and Gounder 2001, [18]Vroman and Tighzert 2009, [19]Cup Depot n.d., [20]Bos and Bolck 2008

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POSSIBLE BREAKTHROUGHS
RETROFITTING IRRIGATION PUMPS

Pumping irrigation is a major source of energy consumption in agriculture. In California, where agriculture uses 80% of the state water supply, 90% of all electricity used on farms is consumed for pumping groundwater for irrigation. Examples from Asia show that the energy consumed in irrigated rice production can be twice as high as in rainfed rice, and groundwater irrigation can be 25% more energy intensive than surface-water irrigation, owing to the force that is required to lift water.[1] In India, government policies have supported groundwater use by supplying cheap diesel or free electricity to farmers to enhance food security. Yet negative externalities associated with over-pumping have often been ignored: irrigation has increased yields but contributed to around 3.7% (58.7 million tonnes CO_2-equivalent) to the country's total greenhouse gas (GHG) emissions in 2000.[2] Groundwater pumping with electricity and diesel accounts for an estimated 16-25 million tonnes of carbon emissions, 4-6 % of India's total.[3] Most of these pumps do not work efficiently. According to Shah,[4] Indian electric irrigation pumps probably operate at 40% efficiency. Studies have shown that electricity savings up to 30% are possible[5] – largely by using improved foot valves, by checking valves and by matching the pump and prime mover better.[6]

[1]Rothausen and Conway 2011, [2]Nelson et al. 2009, [3]Shah 2009, [4]Ibid, [5]Bom 2002, [6]Ibid

ANNEX L

Geography

Europe and the U.S.

Policies have been implemented to regulate emissions of diesel engines. For instance in the U.S., the Diesel Emission Reduction Act, executed by the EPA,[7] funds federal or state loan programs to either rebuild diesel-powered engines or install emissions reduction systems. These funds also cover the retrofitting of irrigation pump engine technology. Where possible, diesel pumps have been replaced by electric pumps. However, according to the University of Nebraska, which created the Nebraska Pumping Plant Performance Criteria, (criteria for pump efficiency) more efficient irrigation pumping plants still could save 25-30% of energy on average by properly matching and adjusting the pump and motor to current operating conditions. In Nebraska alone, improvements in pumping plant performance will reduce energy costs by up to US$ 40 million per year.[8]

West Africa

There are several types of motorized pump sets available in West Africa that burn fossil fuels, mostly gasoline or diesel, but sometimes kerosene. Information about the pump sets is fragmented and incomplete and often poorly matched to their applications. The purchase price in West Africa of a Japanese-made gasoline motorized pump set of about 1.5 to 4 kW design output is usually in the range US$ 300-600, and a diesel pump is around US$ 990. Indian-made pump sets tend to cost around US$ 180, while those made in China are considerably cheaper at around US$ 110. These pump sets are often used in applications for which they are seriously overpowered, resulting in unnecessarily high running costs.[9]

[7]US EPA 2007, [8]Kranz 2010, [9]Snell 2004

India

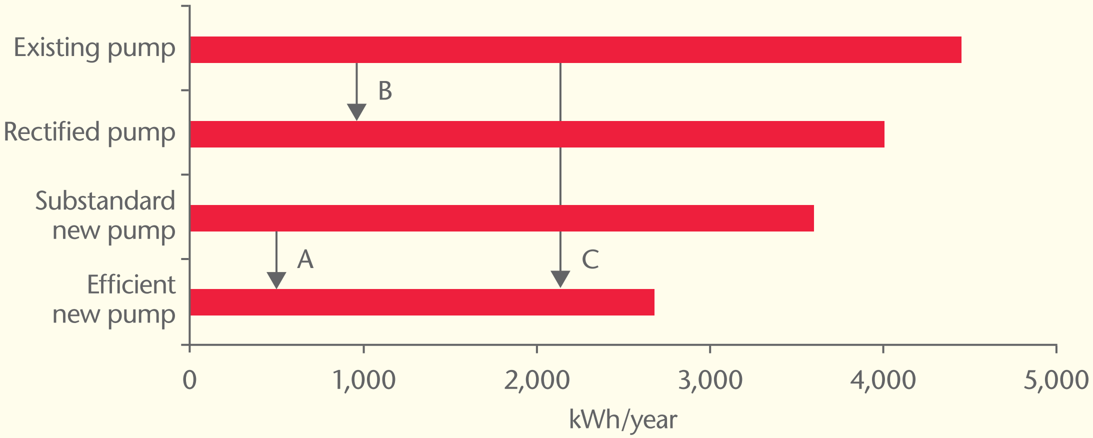
There are millions of diesel pumps operating in South Asia, with India alone accounting for an estimated 6-7 million units.[10] The rising cost of diesel has increased the cost of well irrigation for owners by 32% in south Bihar and 18% in eastern Uttar Pradesh over the 16-year period from 1990-2006.[11] However, there is still discussion about how much this rapid rise in diesel affects farmers. The problem with electric pumps, however, is that power supply to agriculture is highly unreliable, with frequent power cuts and low voltages. The poor quality of supply leads to transformer and motor burnouts. Very often, farmers have to undertake service connection and transformer repair and maintenance work. Thus, even though the tariff is low, the farmer pays a high price for the power by having to replace motors very often and not having power supply when needed.[12] Thus, farmers have little incentive to use electricity efficiently. Nearly 500,000 pumps are added each year to the stock of functioning agricultural pumps, and most of these are not efficient.[13]

China

China is the world's largest emitter of greenhouse gases, and the agricultural sector in China is responsible for 17-20% of annual emissions and 62% of total freshwater use. Groundwater pumping for irrigation alone accounts for roughly 3% of the total emissions from agriculture in China.[14]

Figure 1

Annual electricity consumption (kWh/yr) by selected energy efficiency measures for agriculture water pumping



Note:
A – electricity savings for new pump purchase;
B – electricity savings for pump rectification; C – electricity savings for pump replacement.

Source: Garg et al. 2011

[10]Bom 2002, [11]Kumar 2010, [12]Ramachandra-Murthy and Ramalinga Raji 2009, [13]Sant and Dixit 1996, [14]Wang et al. 2012

Figure 2
Summary of results from 11 diesel-powered pumping plant retrofits

	Before retrofit	After retrofit	Percent improvement
OPE*	14%	23%	64%
Water flow – GPM*	742	1,025	38%
Brake HP Input	80	86	
Engine RPM*	1,734	1,696	
Input HP-hours/acre-foot water pumped	2,237	1,319	-41% (a decrease in energy use)

*RPM = revolutions per minute; OPE = overall pumping plant efficiency, measured in the field and averaged; GPM = water flow from the pump in gallons per minute, measured in the field and averaged.

Source: Canessa et al. 2011

Figure 3
Electric-powered pump retrofit statistics for 41 pumps ranging from 75 to 300 horsepower

1	2	3	4	5	6	7	8	9	10
Condition	OPE (%)	Post-motor OPE (%)	GPM	Total dynamic head (ft)	Input horse-power	kWh/acre-foot	Annual acre-feet pumped	Annual hours operation	Annual kWh
Before retrofit	38	42	893	274	163	738	400	2,433	295,372
After retrofit	65	72	1,372	316	168	498	400	1,584	199,148
Estimated or measured	Meas	Est	Meas	Meas	Est	Est	Est	Est	Est

Source: Canessa et al. 2006

Energy

- Improved energy efficiency of pumps by 10-15% by i) replacing the existing undersized pipes with the appropriate size and new, rigid, low-friction pipes and
ii) replacing high-friction foot valves with low-friction and low head foot valves.[15]
- Rectification can decrease electricity consumption by 444 kilowatt-hours (kWh)/year (see figure 1).
- A study in California by Urrestarazu and Burt[16] where 15,000 electric irrigation pumps were tested, showed energy savings of more than 100,000 megawatt-hours (MWh)/year for well pumps, with a per-pump average of 50 MWh/year. For non-well pumps, total potential savings were 16,500 MWh/year and the average per pump was 34 MWh/year. During their life, pumps can lose their initial efficiency through pump wear, changes in groundwater conditions and changes in the irrigation system. Different groupings of pumps were made according to the annual energy consumed and total dynamic head (TDH) and discharge ranges. Averages for all the variables were calculated for each group. Pumps with an overall pumping plant efficiency (OPPE) below the group average are considered to have the potential for improvement. The energy saved by these pumps is estimated as the difference between actual energy consumption and the average of the top 25% of the pump efficiency within that group.
- A study by the Centre for Irrigation Technology at California State University, Fresno[17] testing the efficiency of 11 diesel pumps before and after a retrofit showed 41% energy savings. Retrofitting involved repair or replacement of either the pump bowl or impeller or both (see figure 2).
- Another study undertaken by the Centre for Irrigation Technology at California State University, Fresno[18] tracked 41 electric powered pumps ranging from 75 to 300 horsepower (HP) both before and after a retrofit. Retrofitting resulted in a decrease of 33% in kilowatt-hours (kWh)/acre-foot, a 35% decrease in annual hours of operation and a 33% decrease in kilowatt-hours required per year (see figure 3).

[15]Garg et al. 2011, [16]Urrestarazu and Burt 2012, [17]Canessa 2011, [18]Canessa et al. 2006

Water

- Improved 2.5 horsepower (HP) motor pumps could yield as much water as the traditional 5 HP pumps with half the fuel consumption.[19]

Costs and benefits

- In a study assessing the efficiency of 15,000 electric pumps, savings of US$ 7,400/year/well pump and US$ 5,000/year/non-well pump could be obtained when pump performance was improved to meet the average of the 25% best-performing pumps. Savings depend on the results of the improvement and the price of energy.[20]
- Based on the results of improved overall water-lifting efficiency in Asia, Van't Hof[21] estimated that irrigation pumping costs for rice production in Mali could be cut by 60% per unit area per season. Specific costs included: fuel, interest (10%), repair and maintenance (10% of initial system cost) and depreciation (desk study).
- The technical adaptation of 11 Petter 5 HP/1500 RPM pumps resulted in 45-60% less fuel use for shallow pump sets in India. This was obtained by removing the foot valve or check valve, reducing the engine speed and increasing the cooling water temperature. For deep pump sets, the average fuel efficiency could be improved by 35%. This means a potential 15% savings on high-speed diesel imports on a national level.[22]
- Chinese 4 HP diesel pumps with heads of up to 6 meters and costing US$ 400 can irrigate 5 hectares consuming 0.45 liters of fuel per hour. Chinese 1.5 HP petrol pumps costing US$ 75 pump 3 liters per second and consume less than 0.3 liters of gasoline per hour.

[19]Bom 2002, [20]Urrestarazu and Burt 2012, [21]Van't Hof 1998, [22]Bom 2002

Productivity

- Pumps are the weakest element in many irrigation systems in developing countries. Their maintenance state, upon which irrigation efficiency and reliability depend, directly affects yields. Because spare parts are often not directly available on local markets, if the pump breaks, this may result in prolonged water shortages at crucial crop development stages, seriously affecting production and income.

Climate change

- Canessa et al.[23] promoters of the Diesel Pumping Efficiency Program (DPEP), estimated that each pump retrofit would result in 3.57 tonnes less nitrogen oxide (NOx) emissions and 0.20 tonnes less PM10.
- Systems have been developed that allow traditional diesel pumps to run with biodiesel. According to the U.S. Environmental Protection Agency's (EPA) 2010 *Renewable Fuel Standards Program Regulatory Impact Analysis* report, the use of soybean biodiesel could result in 57% lower GHG emissions compared to petroleum diesel, while biodiesel produced from waste grease results in an 86% reduction.
- The latest engines used in agricultural pumping devices are TIER 4 engines. TIER 4 refers to a generation of federal air emissions standards established by the U.S. EPA that apply to new diesel engines used in off-road equipment. Essentially it requires manufacturers to reduce the level of particulate matter and NOx to a level that is 50-96% lower than existing diesel engines. It is important to note that TIER 4 emissions requirements apply to new products only and do not apply retroactively to any existing machines or equipment.

[23] Canessa et al. 2006

Table 1
Some of the organizations active in the field of retrofitting diesel/electric pumps

Organization	Region	Mission	More information
Hipponet	Niger, Mali, Chad, Senegal	Hippo's goal is to help turn low-lift pump irrigation into an affordable, sustainable solution for family farms along Sahelian rivers in West and Central Africa.	www.hipponet.nl
Practica Foundation	India, Bangladesh, Bolivia	Fuel-efficient motor pumps for irrigation and motorized deep-well pumps	http://www.practica.org
Ide International	Bangladesh, Zambia	Fuel-efficient diesel pumps	http://www.ideorg.org
Small Engines for Economic Development (SEED)	India, Bangladesh and Ethiopia	Micro-engine technologies for irrigation	http://smallengines.weebly.com/index.html
Center for Irrigation Technology (CIT)	California	The Advanced Pumping Efficiency Program is executed by the CIT, which delivers pump efficiency tests and retrofits diesel and electric pumps	http://www.pumpefficiency.org

Table 2
Some of the companies manufacturing diesel/electric pumps

Companies	Region	More information
Wuxi	China, Australia	www.wxpump.com.cn/web/en
BSA	India	www.bsatiger.com
Lister-Petter	All over the world	www.lister-petter.com
Hatz	All over the world	www.hatz-diesel.com
Don Hardy	USA	www.donhardyengines.com

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POSSIBLE BREAKTHROUGHS
MAKING USE OF TRADE

Factors that may influence global food markets are the evolution of the structure of the private sector, the uncertainties associated with competition for energy (especially through oil prices and biofuel demand) and water and the effects of climate change.[1] Both water and energy are key inputs into any economy. So countries without these basic resources will depend on other countries that do have them. North Africa and the Middle East, but also countries like Mexico and Japan, are heavily dependent on the import of water-intensive commodities.[2] The export of a product from a water-efficient region (relatively low virtual water content of the product) to a water-inefficient region (relatively high virtual water content of the product) saves water globally. This is the physical point of view. Whether trade of products from water-efficient to water-inefficient countries is beneficial from an economic point of view depends on a few additional factors. These include the character of the water savings (blue or green water savings) and the differences in productivity with respect to other relevant input factors, such as land and labor, technology, the costs of engaging in trade, national food policies and international trade agreements.[3]

[1]Godfray 2010, [2]Hoekstra and Chapagain 2008, [3]Ibid.

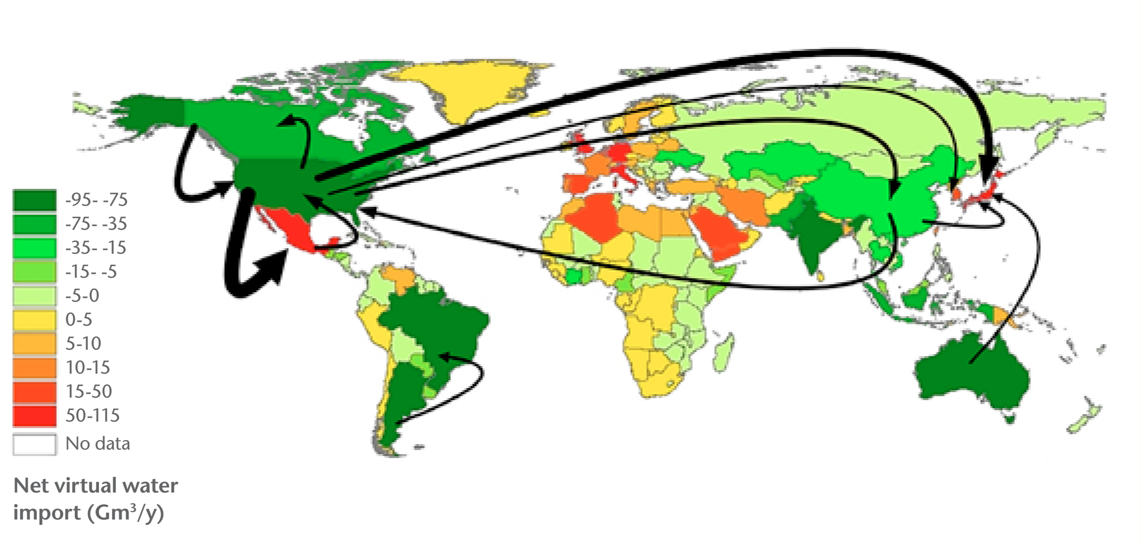
Geography

The increase in trade appears not to be pulled by efficiency gains but more pushed by land and water scarcity. The international trade of water-intensive products (e.g., agricultural commodities) or virtual water trade has been suggested as a way to save water globally.[4] However, a number of economists have expressed reservations regarding whether virtual water trade is a legitimate economic concept and whether it accords with longstanding knowledge about the international economy and comparative advantage.[5] Ansink[6] argues that relative water abundance does not make a good predictor of trade flows in water-intensive products. That is why it is important to take into account results from these two different viewpoints on food trade: virtual water trade (water footprint) and food trade according to comparative advantage.

Virtual water trade and water footprint

The biggest net exporters of virtual water are found in North and South America (the United States, Canada, Brazil, Argentina), Southern Asia (India, Pakistan, Indonesia, Thailand) and Australia. The biggest net virtual water importers are North Africa and the Middle East, Mexico, Europe, Japan and South Korea. Figure 1 shows the virtual water balance per country and the largest international gross virtual water flows. Countries shown in green have a negative balance, meaning net virtual water exports. The countries shown in yellow to red have net virtual water imports.[7]

Figure 1
Virtual water balance per country and direction of gross virtual water flows related to trade in agricultural and industrial products over the period 1996–2005



Note: Only the biggest gross flows (>15 Gm³/year) are shown.

[4]Dalin et al. 2012, [5]Reimer 2012, [6]Ansink (2010), [7]Hoekstra and Mekonnen 2012

Food trade according to comparative advantage

Over the period 1990-2001, only 7% of world agricultural exports were from developing countries. Despite the growth of intra-developing country agricultural trade, agricultural exports only accounted for about 20% of world exports in 2006/07. Developing countries still export a greater amount to industrialized countries than to other developing countries. Despite these changes in the shares, nearly half of world agricultural trade still takes place between industrial countries.[8]

The outlook is that developing countries will become significant net importers, with a trade deficit of almost US$ 35 billion by 2030. This is because of the current rapid growth in imports of temperate-zone commodities by developing countries.[9]

Bruinsma[10] argues that a main driver of shifts in trade patterns at the detriment of developing countries was the difficulty competing with subsidized surpluses of temperate-zone commodities from Organisation for Economic Co-operation and Development (OECD) countries. Then the overall economic development contributed to higher imports of temperate-zone commodities.

The increased trade flow may affect commodity prices. The high prices in 2008 and 2011 coincided with high fuel prices, reduced grain stock and increased demand on the world market because of the emergence of bioethanol and the adverse natural and political conditions affecting food supplies. Global stocks versus use in 2010 stood at 20% of global use, a drastic reduction from 40% in 1986.

C&A and the Water Footprint Network

C&A has developed methods to invest in more sustainable use of water. A study in cooperation with the Water Footprint Network (WFN), of which C&A is a sponsoring partner, concluded that C&A's increasing commitment to the sourcing of organic cotton fiber had led to an improvement in the grey water footprint in organically farmed areas in relation to areas where the cultivation of cotton still takes place in more conventional ways. From a quantitative perspective, and in partnership with Cotton Connect, C&A invested financially in supporting various ways to enable marginal farmers to purchase drip irrigation equipment and therefore, to substantially reduce their water use while increasing yields at the same time.

For more information about the water footprint go to www.waterfootprint.org

[8]Aksoy and Ng 2010, [9]Bruinsma 2003, [10]Ibid.

Energy

- Non-CO_2 emissions will mostly shift to China due to comparative advantages in livestock production and rising livestock demand in the region.[11]
- Deforestation, mainly in Latin America, leads to significant amounts of additional carbon emissions due to trade liberalization.[12]
- Under the International Energy Agency (IEA) Alternative Policy Scenario (APS), the global biofuel water footprint will increase more than ten-fold in the period 2005-2030. The U.S., China and Brazil together will contribute half of the global biofuel water footprint.[13, 14]
- Brazil, the world's pioneer in the production of ethanol, remains the largest exporter with 5.1 billion liters exported in 2008 to more than 40 countries.[15]
- Gerben Leenes et al.[16] show that the water footprint of energy from biomass is 70 to 400 times larger than that of a mix of energy from non-renewable sources.

Water

- The volume of virtual water that is traded globally is 68,125 m^3 per year, which accounts for approximately 10% of the global freshwater used in agriculture or 8% of total global water use.[17]
- Global water savings are modest. Global water use in the period 1997-2001 for the production of agricultural products for export equaled 1,250 billion cubic meters (Gm^3)/year. If the importing countries had produced the imported products domestically, they would have required a total of 1,600 Gm^3/year to do so, which means savings of just 5%.[18]
- The largest savings are from international trade of crop products, mainly cereals (222 Gm^3/year) and oil crops (68 Gm^3/year).[19]
- It is estimated that Egypt saved 5.8 billion m^3 of water from national allocation in 2000 through maize imports, i.e., about 10% of its annual allocation. Additionally, a global saving of 2.7 billion m^3 of real water was generated thanks to the differential of productivity between maize-exporting countries and Egypt.[20]
- Fraiture et al.[21] point out that without trade, global crop water use in cereal production would have been higher by 6% and irrigation depletion by 11%.

[11]Schmitz et al. 2012, [12]Ibid, [13]Gerbens-Leenes et al. 2012, [14]Food-fuel competition is likely to continue in the future. Any analysis must address the eventuality of such competition intensifying, with adverse effects on the food security of some countries and population segments. If this happens, the purchasing power of those demanding more energy could easily overwhelm that of the poor demanding food. See Alexandratos 21995. [15]Kutas 2010, [16]Gerben Leenes et al. (2008), [17]Hoekstra and Chapagain 2008, [18]Chapagain et al. 2006, [19]ibid, [20]Renault 2003, [21]Fraiture et al. 2004

Costs and benefits

Trading strategies based on the virtual water perspective are not consistent with the economic concept of comparative advantage. Optimal trading strategies can be determined only by considering the opportunity costs of production within countries, evaluating comparative advantages and considering other social, economic and environmental dimensions of public policy objectives.[22]

Productivity

- International trade is currently estimated to account for 16-25% of all food crop production.[23]
- Projections are that by 2025, water-scarcity induced cereals trade will increase by 60%.[24]
- Arable land will expand by 70 million ha (less than 5%), an expansion of about 120 million ha (12%) in developing countries being offset by a decline of 50 million ha (8%) in developed countries.[25]
- Developing countries' share in world agricultural exports increased from 32% in 1990/91 to only 42% in 2006/07. Most of this gain came from the expansion of exports to other developing countries (about 12%).[26]
- For low-income countries, other developing countries accounted for 51% of their exports and 69% of imports in 2006/07, up from 27% and 57% respectively in 1990/91.[27]

Climate change

- Climate change and increasing demand for water resources will have an impact on growing conditions, significantly affecting food production in the future. Integrated assessment models have shown that climate change effects on temperature and rainfall will have positive yield effects in cooler climates and negative effects on cereal yields in low-latitude regions, where most developing countries are located.[28]
- To overcome agricultural productivity losses associated with climate change, a well-functioning international trade flow system that is responsive to price signals will be needed to balance production and consumption between and within nations. Increased agricultural output in a region where agricultural production improves can then be used to compensate potential losses in other regions.[29]

[22]Wichelns 2010, [23]Bruinsma 2010, [24]De Fraiture et al. 2004, [25]Bruinsma 2010, [26]Aksoy and Ng 2010, [27]Ibid, [28]Easterling et al. 2007, [29]Juliá and Duchin 2007

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POSSIBLE BREAKTHROUGHS

REDUCING FOOD WASTE

Overall, about one-third of global food production is lost or wasted.[1] Food is lost and wasted throughout the food supply chain, on both the production and consumption sides. In developed countries, food is wasted to a significant extent at retailer and consumer ends, while in developing countries food is lost mostly during the production, storage and transportation stages of the supply chain.[2] Food loss and waste not only mean wasting valuable nutrition, but also wasting valuable land, water and energy. About 30% of global energy consumption is used for the production, processing, and distribution of food, while the food sector contributes more than 20% to total greenhouse gas (GHG) emissions.[3] A significant reduction in food losses and waste will have significant influence on availability of valuable energy and water resources. However, energy inputs are difficult to quantify, as different food products require different amounts. The same holds for water losses, because different food products need different amounts of water for production, processing and transportation.

[1]Gustavsson et al. 2011, [2]Ibid, [3]FAO 2011

Geography

High-income countries

Food losses in industrialized countries are as high as in developing countries, but in developing countries more than 40% of the food losses occur post-harvest and during processing, while in industrialized countries, more than 40% of the food losses occur at retail and consumer levels. This has much to do with supermarket philosophy, cosmetic criteria leading to trimming and discarding perfectly edible food, and poor understanding by consumers of the meaning of the "use-by" date. Solutions to these unnecessary wastes include having supermarkets substitute "use-by" with "best before" dates, adjust aesthetic criteria for food selection, and avoid 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 balanced consumption and more balanced diets.

Techniques for monitoring the quality of perishables from right after they are harvested until they reach the store are in the making (see box 1).

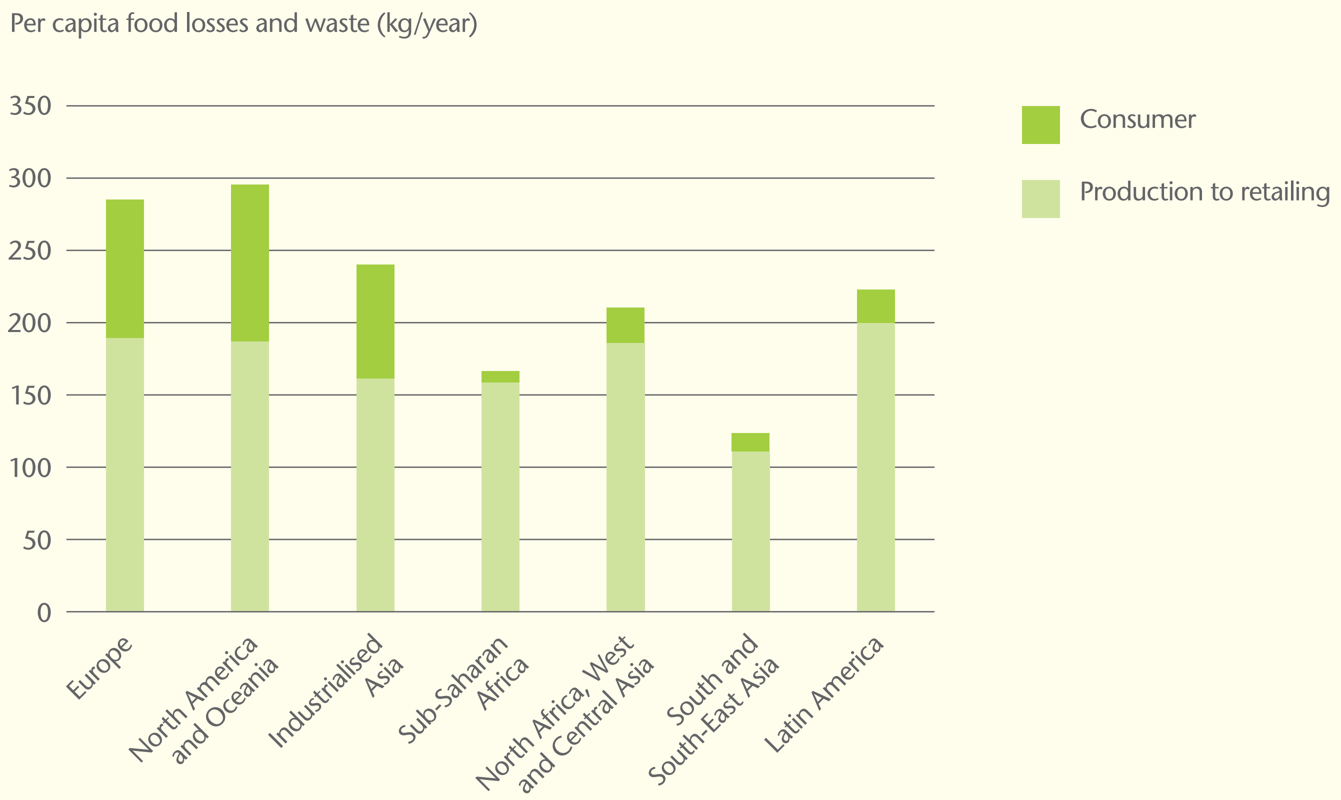
Low-income countries

Food losses in developing countries are often related to deficient infrastructure and facilities for harvest, storage, processing and transport. Already in the field, as much as 50% of the production can get lost because of harvest failures due to lack of labor or machinery and/or inadequate protection against adverse weather conditions and pests (e.g. rodents, birds). Measures to reduce field wastage therefore include: increased protection against pests and climate vagaries; the availability of mechanized harvesting systems or sufficient labor; the use of appropriate boxes or baskets so as to reduce handling of crops while facilitating transport through to consumers.

Secondly, properly designed or maintained storage and processing facilities will lead to less food losses. Moreover, more equal agreements between producers and buyers, such as supply contracts, would create incentives for producers to invest in the crop and reduce over-production as a form of insurance. Available markets and infrastructure to get harvested crops to markets are also crucial factors that have to be considered. Figure 1 gives an overview of the per capita food losses and waste, at consumption and pre-consumption stages, in different regions.[4]

[4]Gustavsson et al. 2011

Figure 1
Per capita food losses and waste, at consumption and pre-consumption stages, in different regions



Source: Gustavsson et al. 2011

Box 1

A chip to reduce waste

Monitoring the quality of perishables from right after they are harvested until they reach the store can reduce food waste. By placing a chip on a batch of fruits, vegetables, meat or flowers that constantly measures the environmental conditions during product transport and storage, product quality and ripening behavior can be determined more accurately and the "use by" dates can be predicted better. Also, 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 in store. Wageningen UR Food & Biobased Research participated in the development of the chip. The Pasteur Project, coordinated by chipmaker NXP, has led to the production of the first prototypes. This chip has sensors that measure various environmental conditions, such as temperature, humidity, acidity, oxygen content and ethylene content. 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. 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.

Fruit that has the best quality at the time of trading does not necessarily have a better shelf life than fruit that looks a little less good at that moment. To properly judge what the fruit will look like in the period to come, Wageningen UR Food & Biobased Research develops models that can predict the quality in the future based on the history of the fruit. This information can help to reduce food waste because it prevents lesser products (which might look better at the time of trading) from ending up in specialized stores with high standards. These stores might throw fruit away that a market salesman would still find acceptable to sell to his customers.

The sensors developed in the Pasteur Project are small, portable and wireless. They send information about the environment (like temperature and humidity) to a central computer. Within a few years it should be profitable to place a chip on every pallet of fresh food or flowers in order to trace the history of the products before they reach the trading grounds.

Energy

- Per capita food waste by consumers in Europe and North America is 95-115 kg/year, while this figure in sub-Saharan Africa and South/South-East Asia is only 6-11 kg/year.[5]
- In India, it is estimated that 35-40% of fresh produce is lost because neither wholesale nor retail outlets have cold storage.[6]
- Food waste has high energy content and could thus be used for energy generation, such as through biogas digestion or hydrogen recovery. This could enhance the economic feasibility of waste treatment.[7]

Water

- One-quarter of total water withdrawals is lost in food that never reaches consumers.[8]

Costs and benefits

- A campaign in the UK to persuade consumers to waste less food had cost £4 million and saved British consumers £300 million.[9]
- Roughly one-third of the edible parts of food produced for human consumption gets lost or wasted globally, which is about 1.3 billion tonnes per year, corresponding to approximately US$ 1 quadrillion.[10]

[5]Gustavsson et al. 2011, [6]Nelleman et al. 2009, [7]Han and Shin 2004, [8]Hall et al. 2009, [9]Stuart 2009, [10]Gustavsson et al. 2011

Productivity

- Production losses in developing countries are hard to estimate, but some authorities describe losses of sweet potatoes, plantains, tomatoes, bananas and citrus fruit as sometimes as high as 50%, or half of what is grown.[11]
- Food waste at the consumer level in industrialized countries (222 million tonnes) is almost as high as total net food production in sub-Saharan Africa (230 million tonnes).[12]
- Reducing waste would decrease food demand by about 10%.[13]
- The total amount of cereals transformed into biofuels in 2008-2009 was less than half the quantity wasted worldwide.[14]
- Smil[15] found that the food saved by curtailing waste by 20% just at retailer and consumer levels corresponds to at least 100 million tonnes of grain, which could feed the world's malnourished nearly four times over.
- Hall et al.[16] found per capita food waste in the US has progressively increased by 50% since 1974, reaching more than 1,400 kcal per person per day, or 150 trillion kcal per year.

Climate change

- In addition to the wasteful consumption of fossil fuels for food production and the direct impact of fossil fuels on climate change, food waste rotting in landfills produces substantial quantities of methane – a gas with 25 times more global warming potential than CO_2.[17]

[11]Kader 2005, [12]Gustavsson et al. 2011, [13]Connor and Minguez 2012, [14]Stuart 2009, [15]Smil 2004 [16]Hall et al. 2009, [17]Hall et al. 2009

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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.

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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.

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