Sustainable Food Production: Facts and Figures

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Farming must feed more people more sustainably. Zareen Bharucha looks at scientific approaches past and present.

Advances in agricultural science and technology (S&T) have contributed to remarkable increases in food production since the mid-twentieth century. Global agriculture has grown 2.5–3 times over the last 50 years. [1] This has let food production keep pace with human population growth so that, overall, there are enough calories produced per capita. However, progress toward reducing hunger is variable across the world. Hunger and malnutrition affect every aspect of human development and persist for various reasons including unequal access to land, to sufficient and nutritious food, and to other productive resources.

Adequate food production is necessary but insufficient to ensure national nutritional security. In India, for example, millions of households suffer from chronic undernourishment and malnutrition despite the fact that favourable years produce more than enough grain, and there is a public distribution system designed to supply poor households with subsidised grain. [3] Agricultural production needs to increase to address this unequal access to food and resources, and to meet the needs of a growing world population. It may need to increase by an estimated 70 per cent globally and by 100 per cent in developing countries by 2050 in order to keep pace with population growth and shifting diets. Reformed agrifood systems will also need to navigate complex resource limits imposed, in part, by environmental degradation to which modern agriculture has contributed. So the challenge for agriculture is three-fold: to increase agricultural production, especially of nutrient-rich foods, to do so in ways which reduce inequality, and to reverse and prevent resource degradation. S&T can play a vital role in meeting these challenges — for example, by developing innovations that smallholders with limited resources can afford and use.

Land and water pressures

About 12 per cent (1.6 billion hectares) of the world's land area is used for agriculture. Land degradation, or the loss of land's productive capacity, is a global problem (figure 2), but especially in dryland regions, a quarter of which are devoted to agriculture. [4] Drylands also support over 30 per cent of the world's population. [5]

Figure 1. 2012 Global Hunger Index scores [2] Source: von Grebmer et al.

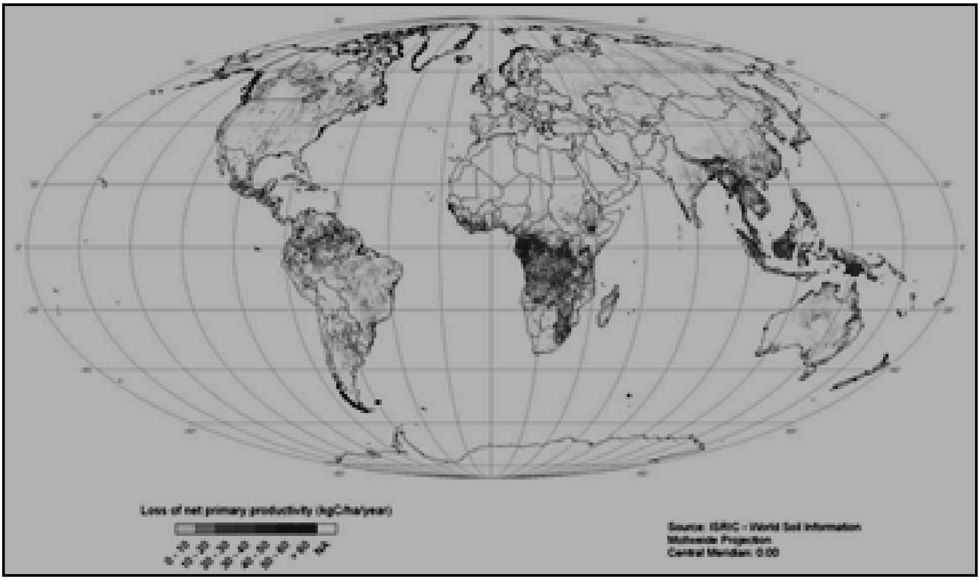

Figure 2. Global loss of Net Primary Productivity in degrading areas, 1981–2003 Copyright: ISRIC

Water management is another major challenge. Agriculture accounts for 70 per cent of all water taken from aquifers, streams, rivers and lakes. [1] To meet projected demands, the efficiency of water use (crop produced 'per drop') will need to improve in both irrigated and rainfed zones. Forty per cent of global increases in food production have come from irrigated areas. By 2050, the area under irrigation is projected to increase by six per cent over 2009 levels, and agricultural water withdrawals will need to increase by ten per cent over current levels. [1]

Rainfed systems are the world's largest agricultural system, taking up 80 per cent of cultivated land area and producing 60 per cent of the world's crops. In Africa, rainfed agriculture produces 97 per cent of staples. [1] Rainfed zones overlap with regions where risks of land degradation are highest, and where smallholder farming predominates. Yet, these are the very regions which will need to play a bigger role in providing food in the future — because the world's capacity to expand irrigation is limited, and the damage caused by over-irrigation and large-scale irrigation projects (such as land degradation and habitat loss) is now widely recognised.

Soil health

Crop productivity is also constrained by land management practices that lead to erosion, waterlogging and salinization (salt build-up), and loss of nutrients from soils. Overgrazing, over-irrigation, using too much or too little inorganic fertilizer, ploughing and other mechanical disturbance all contribute to poor soils. Soil degradation is a particular problem in tropical developing countries, where soil is often less 'forgiving' of poor management. Across Africa, for example, agriculture that removes soil nutrients such as nitrogen, potassium and phosphorus without replenishing them (sometimes termed nutrient mining) contributes to low crop productivity. Phosphorus availability is a key concern. Phosphorus is essential for plant growth and, unlike nitrogen fertilizers, cannot be produced artificially. Phosphorus is mined from finite deposits that are expected to be depleted in 70-125 years. [7] Strategies for dealing with this include managing soil phosphorus by judiciously applying inorganic fertiliser, preventing soil erosion, recycling nutrient-rich biodegradable waste (a traditional source of soil nutrients across much of the developing world) and crop improvements which modify plant roots to enable them to better absorb available soil phosphorus.

Energy and climate change

Another key constraint is energy availability, specifically of fossil fuels. Modern agriculture is energy intensive - tractor and transport fuel, producing agrichemicals and storing and processing food all depend on affordable fossil fuels. So there are growing concerns about the carbon footprint of the agrifood sector. Agriculture contributes around 13.5 per cent of global greenhouse gas emissions

Region	Yield gap* (%) in 2005
East Asia	11
Southeast Asia	32
Northern America	33
Western and Central Europe	36
Australia and New Zealand	40
Western Asia	49
Southern America	52
South Asia	55
Pacific Islands	57
Northern Africa	60
Eastern Europe and Russian Federation	63
Central Asia	64
Central America and Caribbean	65
Sub-Saharan Africa	76

*The difference between optimal and actual yield affected by real-life conditions and challenges such as environmental degradation or poor management.

Table 1: Yield gaps for cereals, roots and tubers, pulses, sugar crops, oil crops and vegetables in 2005 [1]

as a result of cultivation practices and the expansion of agricultural land into forest areas, releasing stored carbon from above and below ground. And there are complex, context-specific impacts associated with climate change. Delayed or early onset of seasons, more variable precipitation and temperatures, and increasing incidence of climate 'shocks' — such as unpredictable dry spells — can all affect plant growth. To adapt to these changes farmers will need knowledge, financial and social support and a package of context-specific technologies (some old, some new).

Fundamental transformation

These challenges and constraints call for a fundamental transformation in agriculture across the world. Increasing food production could follow either *extensification* (converting forests, grasslands and other 'natural' ecosystems into cropland) or *intensification* (increasing the amount produced per hectare within existing cropland). Intensification is generally preferred as it spares other ecosystems from agricultural use.

To meet food demands, intensified agriculture will need to close so-called 'yield gaps' — the difference between current yields and those obtainable under optimal management — in ways that prevent, or in some cases reverse, environmental harm. Table 1 shows global yield gaps for key agricultural commodities.

A brief history of agricultural S&T

Farming depends on experimentation, observation, and carefully designed resource management systems. Mexican farmers' domestication of wild teosinte (maize's ancestor) 9,000 years ago provides one of the best-known examples of ancient crop-breeding. Careful husbandry of plant and animal biodiversity has been practised since antiquity in home gardens and through the domestication of edible species. [8] Soil and water management also has a long history. Careful husbandry of plant and animal biodiversity has been practised since antiquity in home gardens and through the domestication of edible species. [8] Soil and water management also has a long history.

In modern times, S&T have made key contributions through advances in plant breeding (notably improved varieties of maize, rice and wheat), by developing synthetic pesticides and fertilisers and by mechanising farming practices along the production chain from 'field to fork'. Applied in Asia and Latin America, these innovations contributed to substantial increases in food production in the early- to mid-twentieth century.

Beginning with new high-yielding wheat varieties developed in Mexico, the 'Green Revolution' raised global yields of wheat (208 per cent), paddy rice (109 per cent), maize (157 per cent), potato (78 per cent) and cassava (36 per cent) between 1960 and 2000. [10]

The science that made these increases possible was supported, in large part, by an enabling policy and funding environment (see figure 3) and a focus on preventing hunger in the developing world. [11] The S&T supporting the Green Revolution stemmed from developments in biology and chemistry in the 1800s and early 1900s. Advances in plant breeding were based on Mendellian genetics. In chemistry, the Haber-Bosch process (developed by the German chemist Fritz Haber) converted atmospheric nitrogen to ammonia fertiliser on an industrial scale. The improved seeds and fertilisers these developments brought were supported by irrigation infrastructure and machinery, expert advice and credit.

Long-term impacts

The Green Revolution potently demonstrated S&T's potential to increase food production. It was lauded for averting catastrophic famine in the developing world, and also for 'sparing' non-agricultural land from conversion to cropland.

GM controversy

There is controversy over whether GM can increase crop yields while conserving resources.

1943	Office of Special Studies (OSS) established in collaboration between the Rockefeller Foundation and the government of Mexico, to begin work on improving agriculture for food security.
1944	US agronomist Norman Borlaug joins the OSS and begins work on breeding wheat varieties resistant to stem rust.
1946 onwards	US plant breeders at the ARS-Washington State University engage in hybridisation programmes to develop wheat varieties. The research team shares germplasm with Borlaug.
1950s	Borlaug develops Dwarf Wheat varieties by crossing germplasm from Japanese semi-dwarf wheat varieties with the best Mexican wheat varieties. These varieties help Mexico to become self-sufficient in wheat.
1960s	The International Rice Research Institute (IRRI) is founded in Manila, the Philippines, in order to develop improved rice varieties.
1963 onwards	Bourlag travels to India at the invitation of M. S. Swaminathan, the Indian Minister for Agriculture. India imports improved wheat seeds for testing. The Indian government rolls out a programme to cultivate improved varieties, supported by irrigation development and inorganic inputs.
1970 onwards	Yields of wheat in India and Pakistan begin to improve substantially due to Borlaug's improved varieties, inorganic inputs and increased irrigation. As a result, India becomes self-sufficient in wheat. Cereal production in Asia doubles between 1970 and 1990, outpacing population growth.

GM crops in commercial cultivation mainly express two traits — herbicide tolerance and pest resistance. These traits promise higher yields with lower pesticide use. However, their impacts have been variable and depend on a range of external factors. For example, India, China and South Africa found that socioeconomic, agronomic and institutional factors have had a big impact on farmers' experiences with Bt cotton technology. [14] In Africa, an analysis of 11 improved varieties showed that success depended not only on new technologies, but also on partnerships between researchers and local farmers at every stage of the innovation process. [15]

However, it is now clear that this early input-intensive model carries unacceptable long-term environmental impacts, for example unsustainable demands on aquifers for irrigation and damage to aquatic ecosystems.

These input-intensive practices were catalysed, in part, by inappropriate incentives and subsidies — highlighting the importance of governance for new technologies. Where these incentives were removed, agricultural practice changed accordingly. For example, insecticide use fell after Indonesia dropped pesticide subsidies in the 1990s. [12]

There were social concerns, too. Farmers with plenty of land, irrigation and credit benefited the most, while resource-constrained farmers, smallholders, or those farming marginal land benefitted largely indirectly — as a result of lower food costs and an increase in farm employment in favourable areas. There were also unintended nutritional outcomes of the Green Revolution. For example, intensive cultivation of high-yielding staples led to less dietary diversity and may have affected the availability and use of nutrient-dense 'wild' foods. [12]

New developments in agricultural S&T

Since the 1990s, a second 'wave' of technology development has sought new crop varieties through biotechnology, with controversy focusing on genetically modified (GM) crops. Some say GM crops are now "being taken up faster than any other agricultural technology since the plough 8,000 years ago, and are presently being used by 16 million farmers". [13] S&T advances have been based on molecular genetics, specifically recombinant DNA technology. This lets scientists combine genetic material from multiple sources (e.g. from two different species), creating combinations not otherwise found in nature. The first GM crop to be released for commercial cultivation was 'Roundup Ready' soybean in 1996, which resists the herbicide glyphosate, allowing farmers to apply the herbicide without harming soy crops. Since then, recombinant DNA has been used to develop 'golden rice' (a variety fortified with the vitamin-A precursor beta-carotene) and crops resistant to herbicides, insects and viruses.

Unlike the Green Revolution, which was funded and supported by public-sector bodies, the 'gene revolution' is primarily driven by a private and global research system where new technologies find their way to developing countries through the market. [10] There is tremendous private sector funding support for transgenic crops. As of 2005, for example, the top ten multinational bioscience corporations collectively spent nearly US$3billion per year on agricultural R&D — ten times more than that spent annually by the 15 CGIAR research centres, which together constitute the largest international public sector consortium supplier of agricultural technologies. [10]

Better varieties for smallholders

Smallholders deliver most of the food produced in developing nations, and their need for more productive, pest-tolerant and nutritious varieties is increasingly recognised. Several initiatives are seeking to develop and disseminate improved varieties of indigenous or traditional crops that have so far been neglected by privately funded biotechnology research.

For example, the African Orphan Crop Consortium (AOCC) aims to map and analyse the genomes of 100 so-called 'orphan' crops, selected by African scientists, which have so far been neglected as they were not economically important on the global market. The AOCC plans to make its data and findings freely accessible to researchers and breeders in Africa and elsewhere.

Case study of Quncho cereal in Ethiopia [16]

Tef (Eragrostis tef) is the main cereal grown in Ethiopia and vital for food security there. It is resilient to drought, waterlogging, diseases and pests. Research on improving tef varieties began in the 1950s, but had limited success due to the lack of funding and research. However, a new hybrid tef variety called Quncho was released by the Debre Zeit Agricultural Research Centre in 2006 and is proving popular with farmers.

Farmers participated in Quncho's development, helping select and breed the variety. Their involvement meant breeders developed a variety which closely matched farmers' and consumers' preferences. *Quncho* was also disseminated using an innovative approach. Instead of relying on conventional 'technology transfer', farmers were introduced to the new variety and its cultivation techniques through farmer-led testing, coordinated between research centres, administrative bodies, farmers and farmers groups, seed-growers associations, private seed growers and agro-processors. Farmers who adopted the variety were supported with seed loans, training, regular follow-up and assistance from researchers and staff from local development agencies. The number of farmers receiving training on tef production increased from 360 to 6,250 from 2006 to 2009. Farmers have saved and distributed seeds amongst themselves in a well-developed informal seed system — and the initiative has spread rapidly.

Development and dissemination of the orphan crop variety *Quncho* shows how S&T can deliver new varieties using participatory, inclusive and context-appropriate innovations.

Professor Tim Benton discusses issues around how to shape sustainable agriculture Breeding new crop varieties is only one of many options for resource-conserving and yield-enhancing agriculture. While the S&T of variety development is amongst the most visible innovations in agricultural science, a number of other innovations in crop management are promoting sustainable intensification by conserving resources, building environmental quality and increasing yields.

Crop management systems

Agroecology is developing new systems of crop management that increase yields while conserving resources. It is particularly effective at increasing food production while improving environmental and social outcomes. Agroecological methods rely on management rules and packages of technologies carefully calibrated to suit local conditions and farmers' preferences. Methods include systems such as agroforestry, conservation agriculture, the system of rice intensification, integrated pest management, the inclusion of aquaculture and small livestock into farming systems, water harvesting, soil conservation and integrated nutrient management.

A 2006 analysis of agroecological methods based on 286 projects in 57 countries in the developing world, showed that projects increased crop yields by 64 per cent on average while improving water efficiency and carbon sequestration and reducing pesticide use. [17] In 2009, agroecological methods were endorsed by the International Assessment of Agricultural Knowledge, Science and Technology for Development, a process consulting some 900 participants over three years. [18] These new management systems, and new crop varieties, promise to enable the world to produce more food while conserving resources and protecting the environment. But more needs to be done to further develop these approaches and examine their potential. There is controversy, for example, about the yield-increases reported by proponents of the System of Rice Intensification and the methods used to evaluate the outcomes of agroecological practice. [27]

Agroecological innovations for sustainable intensification

Agroforestry:
Agroforestry incorporates trees or shrubs into cropping systems, offering a range of benefits such as replenishing soil fertility and providing food, fodder, timber and fuelwood — and so helping produce greater value than single crops. [19] The system's potential is most powerfully demonstrated in the Sahel, where agroforestry supported by soil and water conservation has 're-greened' the desert. In Niger, for example, five million hectares have been rehabilitated, benefitting some 2.5 million people. [20]

Agroforestry can also increase yields substantially. In Burkina Faso, for example, planting trees and shrubs on farms across 200,000–300,000 hectares of farmland has boosted food production by some 80,000 tonnes a year. In Cameroon, maize yields have increased by 70 per cent on average, where leguminous trees and shrubs were planted on croplands. [21] Across Africa, using 'fertiliser tree' systems has increase the yields of food crops such as maize while reducing the use of expensive inorganic fertiliser. [22]

Integrated Pest Management (IPM):
IPM combines targeted use of agrochemicals with growing practices and biological techniques to control pests. Assessments of IPM show that it is possible to improve crop yields while reducing overall pesticide use. An assessment of 62 IPM initiatives in 26 countries revealed a 35 per cent increase in yields of various crops, alongside a 72 per cent decrease in pesticide use. [23] An innovative new IPM system, called 'push-pull technology' has been developed by Kenyan scientists in collaboration with UK researchers to control pests (notably stem-borers and *Striga* weed). It attracts pests to nearby plants (*pull*) while driving them away from the field using a repellent crop grown among the farmers' main crop (*push*). This system is now widely deployed across Africa — an estimated 30,000 smallholders in Kenya, Uganda and Tanzania use it. In a recent assessment of push-pull IPM, researchers report 3–4-fold increases in maize, 2-fold increases in sorghum, improved soil health and increased farm biodiversity. [24]

Conservation agriculture (CA) and the *System of Rice Intensification (SRI)*: CA consists of three interlinked principles: minimal soil tilling, maintaining permanent organic soil cover, and cultivating diverse crop species. CA was first developed in Latin America, and is now practiced on around 106 million hectares of arable and permanent crops. SRI, based on principles such as minimal use of water and transplanting of young seedlings, is widely used across Asia, Latin America and Africa, and has resulted in substantial yield increases while improving water-use efficiency. SRI benefits include 20-100 per cent or more increased yields, up to 90 per cent reduction in required seed, and up to 50 per cent water savings. [25] Both of these management systems may contradict conventional advice from agricultural research institutes and the agriculture service, and often clash with what farmers think works best. [26] For example, cultivating SRI rice involves an unconventional irrigation schedule where fields are periodically drained rather than perpetually saturated. However, applying them while involving farmers as co-creators at every stage can help both farmers and research and extension agents to engage in creative and transformative change, rethinking established practices and exploring new ideas. [26]

Participation is key

It is clear that innovation by itself is not enough to ensure increased food production, resource conservation or social-ecological well-being. Farmers, rural workers, local groups and community leaders need to participate in innovation, rather than being treated as passive recipients of new technologies. Participatory models work — a recent analysis of 40 cases of sustainable intensification of agriculture in Africa shows the ways in which farmers, public and private -sector partners have developed, adapted and disseminated agroecological systems that have increased yields while delivering environmental and social benefits. [15] All the cases highlight the importance of farmer engagement, peer-to-peer learning, and of developing and using local institutions.

Professor Tim Benton on building links between researchers in the global north and south There is no single technical or managerial fix to the interlinked problems of global hunger, poverty and environmental degradation. The role of S&T will be one of developing a diverse menu of options which farmers can use, share and tailor, providing a range of social, economic and ecological benefits over and above increased productivity.

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Hunger Index Map:

von Grebmer, K., D. Headey, T. Olofinbiyi, D. Wiesmann, H. Fritschel, S. Yin, Y. Yohannes, C. Foley, C. von Oppeln, B. Iseli, C. Béné, and L. Haddad. 2013. 2013 Global Hunger Index — The Challenge of Hunger: Building Resilience to Achieve Food and Nutrition Security. "Global Hunger Index Scores by Severity" map. Bonn, Germany: Welthungerhilfe; Washington, DC: International Food Policy Research Institute; Dublin, Ireland: Concern Worldwide.