Crop Yields and the Prospect for Food Security

Marco Ferroni and Yuan Zhou
Syngenta Foundation for Sustainable Agriculture[1]

Introduction and overview

Long-held assumptions about world food security need to be reconsidered. Crop yields are not increasing fast enough to keep up with demand. The effects of the "Green Revolution" half a century ago are fading. The challenge of feeding the world is attracting attention again. The response to it will necessarily involve accelerated crop yield growth, as we explain.

The world's population reached seven billion in 2011 and could approach ten billion by 2050. Fuelled by population and income growth, urbanization, lifestyle changes and dietary aspirations, the global demand for food, feed and fiber is projected to grow at high rates for at least the next 30 years.

Population growth is expected to slow down at some point, mitigating the advance of aggregate demand. Incomes will continue to grow subject to economic cycles, implying continued growth in the demand for more and higher-priced food. Two rules apply, known respectively as Engel's and Bennett's Law: the proportion of income spent on food and the starchy staple ratio in the diet both decline as income rises. The presence of large numbers of people in developing and emerging markets with incomes well below the point where food demand satiation sets in, and the quest for animal protein, are the reasons why demand growth will remain high in the foreseeable future as long as there is positive per capita economic growth benefiting lower-income groups.

This poses challenges from the perspective of production. Food price inflation particularly affects the poor. If it is to be avoided, production needs to keep up with the growth in demand.

Commodity prices are low and declining at the moment. FAO's food price index hovered around a six-year low in August 2015. But this is deceptive. Production prospects are increasingly hampered by natural resource scarcities and degradation and are likely to be further affected by climate change. World cereal yields have increased on a steady linear path since 1960, but the annual rate of yield growth roughly halved since then (Figure 1), prompting speculation about biophysical ceilings on yield. Weather and other factors cause yield to fluctuate greatly between years and geographical areas. However, aggregate grain yield growth is now down to about the level of global population growth, as the Figure shows. This means there is little room to

[1] Draft prepared for the Emerging Markets Forum, 2015 Global Meeting, Tokyo, Japan (November 3-5, 2015). Contributions by Dominik Klauser, Viv Anthony, Paul Castle and Victoria Johnson-Chadwick are acknowledged.

accommodate income growth-induced additions to demand. These can force prices up, particularly when stocks are low and trade is curtailed, for example by export restrictions imposed by grain-surplus countries seeking to keep their domestic food prices low.[2]

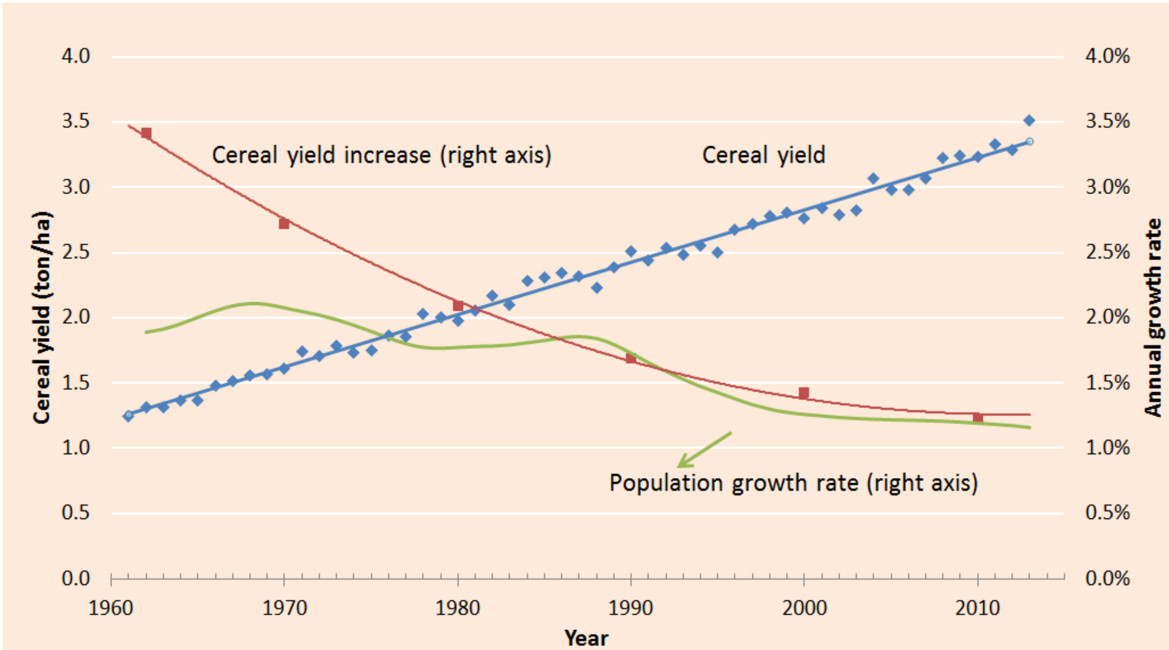

Figure 1 World cereal yield, annual yield increase, and population growth, 1961-2013 (Data source: FAOSTAT). R square of the fitted trend line of cereal yield is 0.99.

This situation needs to be addressed. Renewed agricultural intensification is unavoidable and (as we believe) feasible. But further intensification has to come about sustainably. This does not only mean that more will need to be produced from less. It also implies the need to curb the negative environmental impacts of agriculture and grow the sector's contribution to the formation of natural capital and the flow of environmental services (Pretty, 2011). A reduction in food loss and waste would ease the pressure on the production of food and feed. Decreased emphasis on biofuels until more efficient, cellulosic "next-generation" techniques are developed would further help.

Unused land and water offer another (limited) opportunity for reprieve, albeit arguably at the expense of future generations. Bringing the planet's remaining unused, un-forested und unprotected arable land under the plough would ease the need for intensification to a degree.[3]

[2] World cereal supplies are adequate in 2015 with a global cereal stock-to-use ratio of 25% according to the FAO (cf. www.fao.org/worldfoodsituation/csdb/en/ accessed October 9, 2015).

[3] The world's unused, un-forested and unprotected land suitable for crop production amounts to about 446 million hectares (about 30% of the overall crop area currently in use). Most of it lies in remote parts of mostly seven countries: Sudan, Brazil, Argentina, Australia, Russian Federation, Mozambique and the Democratic Republic of Congo (Deininger and Byerlee, 2011). By one estimate, the opening of new arable land to cropping approximately balanced arable land lost to non-agricultural uses during 1990-2010 (Fischer et al., 2014). Hanson and Searchinger (2015) offer criteria to help limit future cropland expansion to lands with low environmental opportunity cost. Biodiversity loss and carbon emissions are key environmental costs associated with land conversion for agricultural purposes.

But the bulk of the needed increase in production will still have to come from intensification, as it has on a world-wide basis for at least 40 years now. Crop yields are a key dimension of this – the core of the narrative of factor productivity in farming.

Depending on the analytical purpose, agricultural productivity can be measured in total or partial terms. Total factor productivity (TFP) is a measure of overall economic efficiency. It is "calculated as the ratio of total output to total input, and measures the average productivity of all the inputs used" (Hazell, 2014). Partial factor productivity refers to the returns to individual inputs. Crop yield, for example, measures the productivity of land (output per unit of land), but at the same time has much to do with labor productivity, farm income, returns to capital, management decisions and farm inputs such as fertilizer. Seen more broadly, crop yield also measures the success of agricultural research, plant breeding and the delivery of research goods to farmers.

Changes in crop yield over time are broadly a function of "genetic gain" and "management" (which interact with each other). In sophisticated agricultural settings with good agronomy and co-productive ancillary inputs, genetic gain (the increase in performance attained through artificial genetic improvement) explains the bulk of crop yield increase over time – 70% to 75% in maize in the US according to one long-term study (Butzen and Smith, 2014). This study also concluded that in observations since 1972, "yields showed no signs of plateauing" for maize "grown under irrigation, drought and natural rainfed conditions". However, other studies have found evidence of yield plateaus in different crops and cropping systems throughout the world. We will return to this topic below.

In technologically and managerially less advanced settings, "management" plays a relatively more important role in yield gain. But plant breeding and genetic gain remain vital and the main hope for the needed step-change in addressing abiotic stress, raising crop productivity and shaping output traits related to nutritional quality and content. Expert assessments suggest the following distribution of contributions to grain yield growth in developing and emerging markets to 2030: 40 to 50% improved agronomy and other aspects of management and 50 to 60% improved varieties ("genetic gain"). Varietal improvement is brought about by a combination of plant breeding and seed systems that deliver to new markets. Plant breeding will use conventional and to a lesser extent marker-assisted methods in the settings in question. GM traits will play only a small role: the development pipeline is limited and many countries forbid their use.[4]

In this paper we discuss yield growth and (by implication) food security from a supply and price perspective. The first of two objectives is to clarify the rate of crop yield growth required on an aggregate basis to meet consensus estimates of projected demand for food and feed to 2050 and beyond. The second objective is to show how increased crop yield growth and therefore sustainable intensification are possible (although by no means easy to achieve), in particular in developing and emerging markets with strong demand and large numbers of small farms.

Our analysis and conclusions draw on secondary data and recent literature on these issues. The topic and literature are huge and our approach is therefore necessarily selective. Our commodity

[4] Dr. Marianne Bänziger, CIMMYT, personal communication.

focus in this paper is on grains and other staples, because these crops form the basis of food security. However, many other important crops and agricultural activities provide income to farmers and both enjoyment and nutritional benefit to consumers. Diversification should, and often does, go hand in hand with the intensification of farming systems.

From the literature we cite, notably Fischer et al. (2014), our main findings and conclusions are as follows. To keep real food price increases small (capped at 30% above the low 2000-2006 base), total grain supply must increase by 60% by 2050 relative to 2010. Yield progress will continue to supply the bulk of this increase. With an increase of 10% in crop area relative to 2010, a 45% increase in grain yield will be needed globally to feed the planet by 2050, implying an annual yield growth rate of 1.1% relative to 2010. In reality, the goal should be somewhat higher, perhaps 1.2% or 1.3%. This would build some reserves into the system to absorb shocks such as widespread adverse weather, resource loss or higher than projected population growth. Current average global rates of annual farm yield growth are about 1.0% for key crops and 1.5% for maize. Crop yield growth must rise, particularly in low-yield, high demand-growth jurisdictions.

To close yield gaps, accelerated genetic gain and better management are needed – plant breeding and agronomy. Both face challenges and must be taken seriously as there is no room for complacency. Management improvements refer to the adoption of technological change at scale by hundreds of millions of small farmers. This requires (i) relevant products and solutions they find attractive from a returns and risk perspective, (ii) “enablers” of farm demand, including agricultural extension, input loans and weather insurance, (iii) delivery systems operating as much as possible through commercial channels, and (iv) links to markets on the output side. Public-private cooperation is needed to overcome the market and institutional failures present in many settings.

The next section covers demand and the yield growth required to meet it. The third section discusses plant breeding for genetic yield gain. The fourth section shifts the focus to crop management for yield growth and sustainable intensification. The fifth section summarizes and concludes.

Global food demand to 2050 and required crop yield growth

As pointed out by Fischer et al. (2014), food demand over time is driven by four main factors, in descending order of predictability: population growth, increased income per capita, biofuels and prices. Global population is projected to reach 9.7 billion by 2050 (United Nations 2015, medium variant) – about 32% higher than today’s 7.3 billion with an annual growth rate of 0.8% between 2015 and 2050. Over 98% of this addition will take place in less developed regions and emerging markets, in particular Africa and Asia.

Projections of future income increases are more uncertain but (perhaps for this reason) there are many of them. A recent report by Pricewaterhouse-Coopers predicts that the world economy will grow at an average of just over 3% per annum during 2014-2050, doubling in size by 2037 and nearly tripling by 2050 (PwC, 2015). The Economist Intelligence Unit predicts China to overtake the US as the world's largest economy by 2026, India to move up to third rank by 2050 and Asia to account for 53% of global GDP by the same year (EIU, 2015). Long-term country-specific GDP per capita predictions are harder to find, though the IMF publishes short- and medium-term forecasts for many countries. In projecting global food demand, World Bank predictions used by the FAO assume a baseline compound rate of annual income growth per capita of 1.4% to 2050 (Alexandratos and Bruinsma, 2012). Nelson et al. (2010) use an economic growth rate of 2.5% per capita for their food demand projections from 2010 to 2050.

A key effect of income growth is increased demand for higher-value food items such as meat, dairy products, vegetables, fruits, vegetable oils and processed food. Meat demand growth stimulates growth in the demand for feed, including in particular maize and soybean (the demand for which is also up because of rising consumption of vegetable oils). Income elasticities to quantify the demand effects of changes in income by food category and income group are derived from household surveys. The analysis is straightforward. The results are as realistic as the income growth projections used. The margin of error can be substantial.

This is also true for predictions regarding the demand for feedstock for biofuel, which depends on a host of factors. They include energy prices, grain prices, biofuel policies and mandates, and progress in next-generation technologies. FAO expects the use of cereals for biofuel to peak at 182 million tons in 2030 and remain at that level till 2050 (Alexandratos and Bruinsma, 2012). Other projections foresee potential grain demand for biofuel at higher levels by mid-century (Fischer, 2011). Other (non-grain) feed stocks for biofuel also absorb water and land, in particular sugar cane and palm oil.

Prices are products of the interaction between supply and demand and key modulators of both. The relationship between what consumers are prepared to pay and farmers to grow should clear markets and balance demand and supply. As traced out by FAO's food price index, grain prices declined from the mid-1970s to the early 1990s, facilitating consumption growth. They then stagnated until 2003, when they began to rise, creating food insecurity for the poor. Prices peaked in 2008 and reached a new high in 2011 before they declined to today's level. Food price volatility has been an increasingly acute issue in recent years, and a potentially volatility-intensifying tightening of price linkages across commodity classes including energy, metals and food has been observed (Goedde et al., 2015). Price movements and volatility affect consumption security. Prices must be accounted for in equilibrium models that project and balance food grain demand and supply. Studies by authors at IFPRI, IIASA and elsewhere are based on such models and "hence the balancing price is a key part of their predictions" (Fischer et al., 2014; cf. Table 1).

According to FAO's "constant price" projections, the global expected demand for cereals amounts to 3.3 billion tons by 2050. This represents an increase of one billion tons (or 44%) from their base year 2005-2007 (Alexandratos and Bruinsma, 2012). Other studies report higher levels of growth in demand for cereals and agriculture as a whole (Table 1). Total agricultural demand growth is higher than that for cereals because of the higher demand growth for high-value (non-staple) crops as income grows (Fischer et al., 2014). Most of the increase in cereals demand comes from developing countries according to the FAO projections, particularly after

2030 when the use of cereals for biofuels is assumed to peak. Maize and soybean demand increases the most in the staples category, and rice the least. As stated by Fischer et al. (2014) with reference to the FAO projections, demand for rice from 2005-07 to 2050 increases by only 28% – less than the world population rise – because per capita consumption is peaking as incomes increase in Asia "and then declining as incomes increase further, as happened in Japan."

Table 1 summarizes recent demand and supply projections to 2050 for selected staple crops, cereals as a group and agriculture as a whole. The demand growth figures are substantial relative to base year values. The projected crop area expansion is modest, or in some studies assumed to be negative because of land degradation or conversion to non-agricultural use. The crop yield increases required to meet the projected demand are therefore significant, as shown in the Table. Moreover, with the exception of the FAO forecast, which did not endogenize prices, the models accounted for in the Table conclude that real food prices will rise by 2050 – between 10% and 44% relative to the studies' respective base years.

Table 1 Estimates of global cereal (food) demand and supply growth to 2050

Reference	**Commodities**	**Base year**	**Change from base year to 2050**				**Notes**
			Demand	**Crop area**	**Crop yield**	**Real price**	
Alexandratos and Bruinsma (2012)	Big four staples*	2005-07	47%	11%	33%	Constant	FAO forecasts
Tweetin and Thompson (2009)	All agriculture	2000	79%	0	57%	44%	
Nelson et al (2010)	Big four staples*	2010	36%	-8%	47%	25%	IFPRI
Fischer (2011)	Cereals	2000	59%	21%	31%	30%	IIASA
Linehan et al. (2013)	Cereals	2007	42%	-9%	56%	13%	Results from scenario S1
Lobell et al. (2013)	All crops	2006	102%	18%	72%	10%	Results from scenario S2

*Maize, rice, wheat, soybean. Source: Fischer et al. (2014)

The studies cover a range of plausible outcomes. Specific numbers diverge, however, because of differences in methodologies and assumptions, crop mixes and preferred per capita income trajectories. Nelson et al. (2010) use IFPRI's partial equilibrium IMPACT model to represent individual commodities, project demand and supply, simulate policy, water supply and climate change scenarios, *inter alia*, and trace different processes at varying levels of spatial resolution. The model balance required real cereals prices to increase by an average of 25% in this study, as shown in Table 1. The required rates of yield increase to 2050 calculated by Fischer et al. (2014) from this study are 1.5% per year for wheat and soybean, 1% for maize and 0.8% for rice.

With reference to the results summarized in Table 1 and an eye to hunger risk (which is linked to real prices, as well as other factors), Fischer et al. (2014) suggest that global real price increases to 2050 should not be allowed to go higher than 30% above the low world food price levels of 2000-2006. From this, the authors infer a minimum required supply increase of 60% for staples to 2050 relative to 2010, "with a somewhat higher increase for high-value non-staples". Allowing a 10% increase in cropped area, the authors conclude that "the minimum target for global yield increase for staple crops should be 1.1% p.a. relative to 2010 yield". The authors then caution that the rate should in fact be higher (perhaps as much as 1.3% per year) to build buffers and resilience into the system. These would help absorb shocks such as higher than projected population growth, widespread adverse weather, land loss due to various reasons, disruptive climate change and other challenges.

The authors also state that it will be progressively less difficult to feed the world after 2030 and particularly after 2050. Population growth will slow and biofuels should shift to cellulosic and other solutions. Furthermore, part of the shift toward food demand satiation in the context of higher incomes will have occurred in Asia (but likely not yet in Africa). The effects of climate change on farming and yields may, however, get worse.[5]

The linear nature of yield trends (Figures 1 and 3) implies decreasing relative rates of gain over time. The targets offered by Fischer et al. (2014) are therefore actually challenging to achieve. (The 1.3% target would require the declining long-term global yield growth trend documented in Figure 1 to be halted at the level of about 2010.) A number of recent papers offer assessments stating that the world food system remains yield-challenged. In a careful attempt to establish the right statistical framework for the analysis of historical yield data, Grassini et al. (2013) identify 14 intensive cropping systems (out of 36 studied in different parts of the world) where yields have reached plateaus without signs of a renewed upturn. Instances with statistically significant yield plateaus include cases representing 33% of global rice, 27% of global wheat and 5% of global maize production, according to these authors.[6]

Working from a higher demand growth scenario than Fischer et al. (2014) and seemingly allowing for no area increase, Ray et al. (2013) warn that crop yield trends are insufficient and "no longer improving" on up to 39% of the world's most important croplands. Their maps of observed rates of annual crop yield changes (Figure 2) are based on yield data from more than 13,000 jurisdictions between 1989 and 2008 and display variations in the rate of yield change among and within countries. The maps are instructive, pointing to yield hotspots in positive and negative terms for maize, rice, wheat and soybean, the world's most important staple crops. Priority areas for investment in yield improvement (where the corresponding crops are important contributors to dietary energy or animal feed) include West Africa[7] (but also parts of India and the Philippines) for rice; East, Central and Southern Africa and a segment of China for maize; parts of India and Eastern Europe for wheat; and parts of China and other jurisdictions for soybean. The Figure does not cover other staple crops, such as millet and sorghum, which are important in some parts of the world.

[5] Climate change (i.e., chronic global warming) affects grain yield by accelerating crop development at the expense of grain filling. Cereal yield sensitivity to growing season temperature increases ranges from -2% to -5% per degree Celsius of warming (Fischer et al., 2014). Increased CO2 concentrations benefit yields of C3 crops slightly (such as soybean, rice and wheat). C4 crops (such as maize) are largely unaffected. C3 and C4 refer to differences in metabolic pathways for carbon fixation in photosynthesis.
[6] Maize would be expected to be affected least because it is the recipient of much more R&D (mostly by private seed companies) than either of the other two crops.
[7] Extremely rapid demand growth for rice in West Africa is documented by Zhou and Staatz (2015).

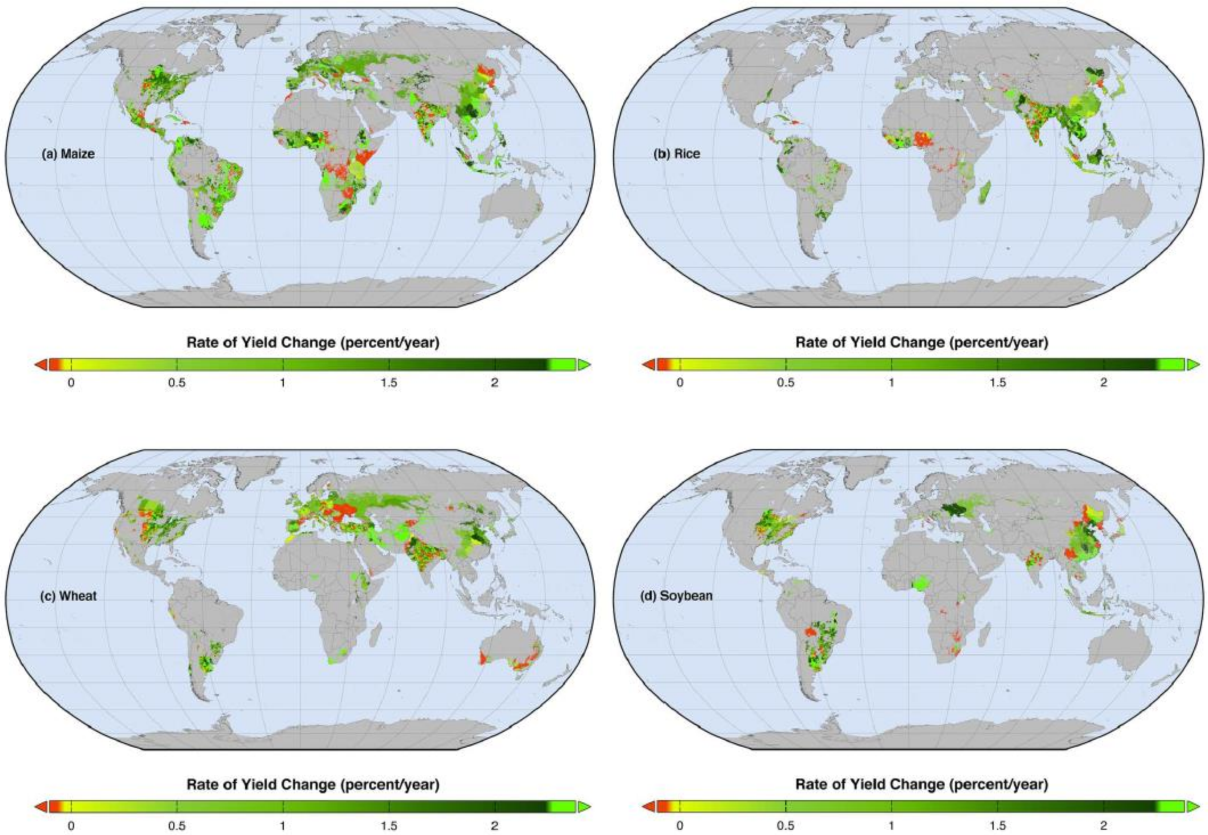

Figure 2 Maps of observed rates of percent yield changes per year (Source: Ray et al., 2013)

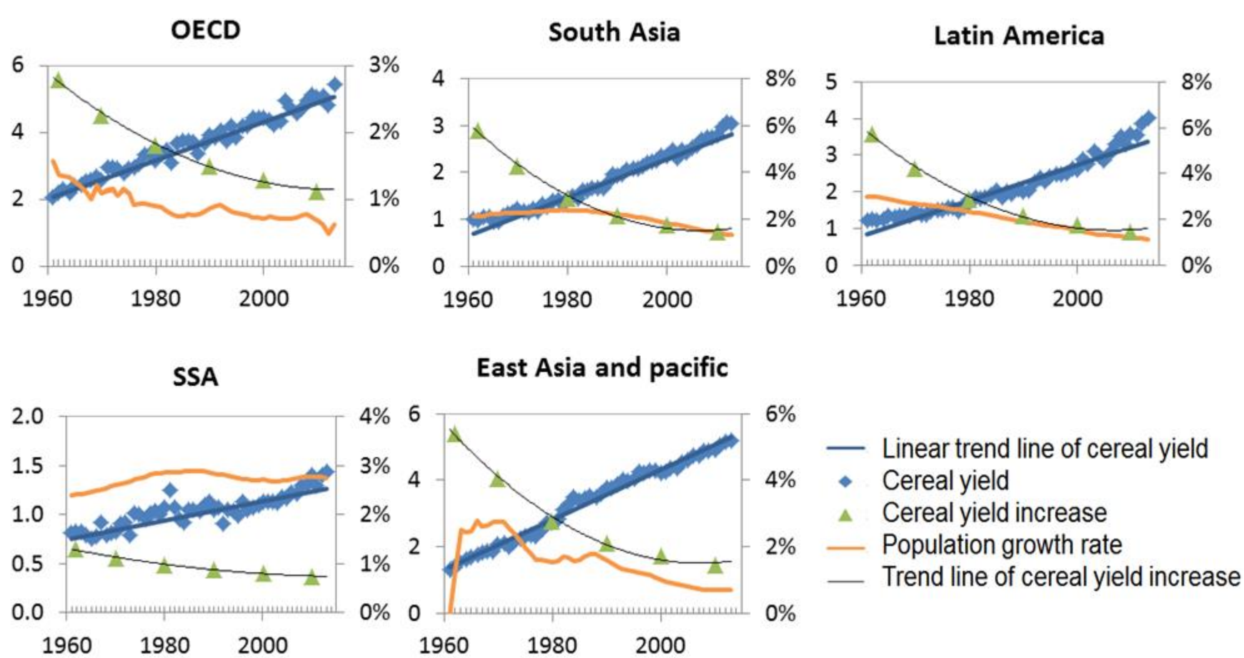

Figure 3 Cereal yield, annual yield increase, and population growth in major world regions, (Data source: FAOSTAT)

Figure 3 shows aggregate cereal yield and population trends for major world regions. Sub-Saharan Africa clearly emerges as the main lagging region, followed by South Asia. East Asia displays aggregate yield achievements almost as high as the OECD group. Policies and investment to increase yields are clearly needed in the lagging regions. Population and demand growth are high there, and better yields would help large numbers of farmers to improve their livelihoods.

This said, it is not "business as usual" in high-yield jurisdictions either. They are losing agricultural land to urban, industrial and transport development, just as is relatively low-yield India. Many of these countries have regulatory frameworks that reflect a special type of Western cultural values and fear of technology. Many regulators there overlook the realities and needs of agriculture, while politicians create subsidies and incentives both subtle and blunt to "extensify" farming. Bread baskets for the world, these high-yield countries face water and soil quality challenges in some instances, which need to be met by significant remedial investments. In parallel, these countries need to fund further plant breeding, particularly to overcome pathogens' increasing resistance to the defensive traits built into existing crop varieties.

One option for food deficit countries is to import commodities such as cereals, oil seeds and meat. Developing countries (in FAO's classification) have long been net importers, especially of wheat and coarse grains, but some Asian countries are net exporters of rice. The traditional net exporters of North America, Europe and Australia have held their volumes during the last decade. Newer market entrants (including the Russian Federation and Ukraine) are now supplying a growing share of world exports (Alexandratos and Bruinsma, 2012). International trade makes sense from a comparative advantage point of view, has been growing as a share of total consumption and is almost certain to continue to grow. Figure 4 identifies Africa and East Asia as leading food importers, followed by the Middle East. In low-yield countries with rapid demand growth and a large share of the population engaged in farming, imports are not an advisable substitute for investment in the primary sector.

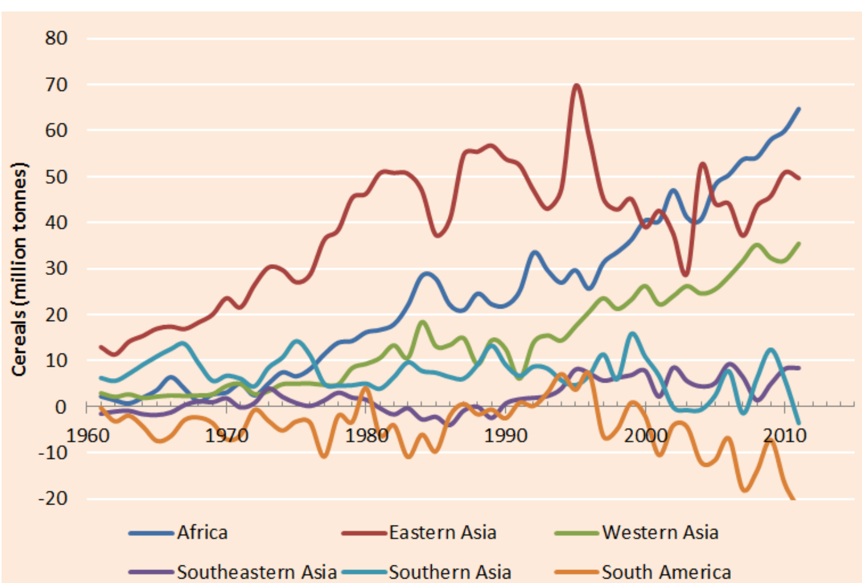

Figure 4 Net trade (import minus export) of cereals (Data source: FAOSTAT)

There are situations in which high degrees of import dependency are objectively not an option, given that world markets for staple commodities are relatively thin. Large countries (India and China above all) with heavy domestic demand relative to world markets will need to continue producing much of their own grain, especially rice. For a number of reasons, Sub-Saharan Africa cannot depend too much on trade. Infrastructure there is generally poor, incomes are low, and many countries lack not only foreign currency reserves but also access to the sea. In addition, increased imports displace farm incomes on a significant scale.[8] Sub-Saharan Africa needs to invest in agriculture. The food crisis of 2007-2008, in which availability of grain on world markets became a major problem, revealed the possible dangers of depending too heavily on trade rather than fostering domestic supply – in other words improving yields at home.

Plant breeding for genetic yield gain

Crop breeding along with seed systems that deliver improved varieties to farmers play a critical role in the quest for yield growth and food security. Future breeding targets are expected to cover in particular general crop productivity (for instance through efficiency gains in photosynthetic and respiratory pathways) and increased tolerance to mostly abiotic stress (Cooper et al., 2014). The latter reflects emerging needs as natural resources degrade and warming sets in, calling for crops that are more water efficient and tolerate salinity and heat better, for example. Disease resistance and insect control will also remain important targets for yield optimization, particularly with the uncertain impact of global warming and the changing landscape of biotic challenges.

Traits linked to productivity gains and abiotic stress tend to be multigenic (i.e., summoning the combined effects of multiple genes). They are thus difficult and time-consuming to breed following conventional approaches. Breeders today rely on an unprecedented selection of molecular techniques, as well as phenotyping platforms and data management tools. Genome-wide association mapping helps allocate desired traits to alleles, and genetic markers speed up the selection and screening process for parental lines and their progeny. Novel approaches in data generation and processing further support the identification of the genetic control of desired traits and effects. Many of these new technologies are knowledge, resource, equipment and infrastructure-intensive (for example, related to bio-informatics). This is likely to drive consolidation towards more centralized, advanced clusters of molecular breeding that use state-of-the-art genomics for gene discovery and broadening crop genetic diversity. Regional and national breeding platforms will still be needed to breed new traits into local cultivars (adapted to agro-ecological zones, local ecosystems and consumer preferences) using conventional breeding techniques and molecular markers.

The contribution of genetic engineering (also referred to as transgenesis, i.e., the insertion of genes from other organisms into the genome of a target species) to future trait development and thus yield gains is expected to remain restricted to major global crops. It may well also decline in the medium-term future (Fischer et al., 2014) – in good measure because of adverse and

[8] Food aid has had this effect in parts of Africa, as documented by Thurow and Skilman, 2010.

sometimes unpredictable regulatory environments that imply high costs and long delays in product development and registration. Philips McDougall (2011) estimate that it takes 13 years to develop a new genetically engineered trait from discovery to the marketable product at an average cost of 136 million USD. At least a fourth of this is typically the cost of compiling a regulatory dossier for product registration.

Science is evolving, however, and many plant breeding priorities are now addressable through "genome-editing", the targeted alteration of a genome without inserting foreign genetic information. Genome-editing is beginning to dilute the borders between cis- and transgenetics and regulatory policies will at some point begin to catch up (Lusser et al., 2012). In contrast to classical genetic engineering, the use of genome editing and other evolving technologies by breeders may be difficult or impossible to detect (Podevin et al., 2013).

Irrespective of technology, plant breeding will always rely on genetic diversity, the main source of which is natural diversity in crop cultivars and wild crop relatives (McCouch, 2013). In this respect it is worryingly clear that the ongoing degradation of natural habitats and the associated irreparable loss of biodiversity are rapidly depleting resources for future breeding. Global international efforts are needed to maintain and conserve genetic diversity of crop species and assure their accessibility in the future. State of the art molecular tools (including markers and sequence data) need to be applied to and characterize the genetic diversity in existing and new collections to facilitate the work of breeders going forward.

Conducive policies and incentives are needed to ensure the conservation and accessibility of genetic diversity. Current international legislation on the ownership of natural genetic diversity (cf. the Convention on Biological Diversity) creates significant barriers to sharing genetic material and thus limits the availability of suitable parent material for breeding purposes in both the public and the private sector (McCouch, 2013). Sensible measures to protect breeder Intellectual Property (IP) internationally could help attract more private sector investment in breeding and set the stage for productive public-private cooperation to develop cultivars for a range of crops across many geographies.[9] Novel rewarding remuneration models, such as for instance the royalty-based variety end-point system that finances wheat breeding in Australia, could help expand private sector commitment to crops and traits outside the "hybrid breeding comfort zone" (Fischer et al., 2014).

Breeding for major crops in OECD countries has shifted in recent decades from the public to the private sector. Six multinational companies are at the leading edge; hundreds of small and medium-sized national and regionally operating seed companies are doing business (and raising farm yields) in China, India, East and Southern Africa and other geographies. The trend toward privatization is supported by the spread of legislation for plant variety rights, hybridization technology and the use of patented transgenic traits in cotton, maize and soybean (Fischer et al.,

[9] "Triple A" ("accessible, affordable, Asian") maize is the work of a public-private partnership between CIMMYT and Syngenta (brokered by the Syngenta Foundation). The aim is to develop low-cost maize hybrids with improved dry-season yields. These could benefit agro-systems covering some 3.5 million hectares farmed by smallholders in India, Indonesia and potentially other countries. Local small and medium-sized seed companies should be able to commercialize the product from 2017. CIMMYT contributes genetic diversity, its field trialing network and experience in variety release. Syngenta contributes molecular screening platforms, elite germplasm, performance assessment and product development skills.

2014). The trend is beneficial from an innovation, varietal turn-over and productivity perspective, creating value for growers (including many millions of small farmers), consumers and seed companies alike (Qaim, 2009).

By definition, however, the trend toward privatization does not address the need for pre-breeding for many crops and areas of market failure represented by "orphan crops" in Africa like tef, millet and others. As with regulation, market failure in research is the domain of the public sector and public-private cooperation. Box 1 reports on a recent research break-through for tef driven by a team at the University of Bern (the "public sector") with support from the Syngenta Foundation.

Box 1 Tef crop improvement

Tef (*Eragrostis tef*) is the major food crop in Ethiopia where it is cultivated on more than three million hectares of land and is staple food for over 50 million people. Tef grows under marginal conditions, many of which are poorly suited to other cereals. However, average tef yield is much lower than for most other cereals. "Lodging" is the major problem: Tef has tall, tender stems which easily fall over.

The Tef Improvement Project (TIP) was established in 2006, aiming to boost the productivity of tef by developing lodging and drought tolerant cultivars. It was financially supported by Syngenta Foundation and the University of Bern, and hosted by the University's Institute of Plant Science. TIP applies modern genetic, molecular and genomic tools to improve important traits in tef, and promising tef lines are introgressed to high-yielding and widely adapted cultivars and evaluated at on-station and on-farm sites in Ethiopia before their release to the farming community.

As a result of phenotypic screening and TILLING (Targeting Induced Local Lesions in Genomes) for valuable traits, several candidate lines have been obtained. Among these, the semi-dwarf lines showed remarkable performance towards lodging tolerance at several field testing. In 2015, three promising cultivars are in the last year of multi-location field testing at about 15 locations in Ethiopia. In mid-2016, the same cultivars will be grown on a large area for approval by the national variety release committee. In addition, two drought tolerant tef lines were also obtained, which were crossed to high yielding cultivars and reached the F_6 generation.

Breeding in the public sector is often less effective than the world needs it to be. Inadequate and unsustainable funding is often a problem. But in both the international and national programs where this is the case, one invariably also identifies mission-threatening institutional and organizational challenges, including outdated business models. These challenges must be addressed along with the need for proactive public-private cooperation in plant breeding. Regulation of a kind that fosters innovation and benefit-sharing is also needed, as is the preservation and utilization of genetic diversity in genebanks and *in situ*, as mentioned above.

Achieving advances in science and technology is not going to be the problem. The real question is whether people, political systems and institutions will convert these advances into innovations that will close the yield gap needed to achieve global food security.

Crop management for yield growth and sustainable intensification

Plant breeding and improvements in crop management – agronomy in a broad sense of the term – are at the core of efforts to close (or materially reduce) yield gaps. Yield gap is defined as the difference between potential yield and farm yield, where potential yield refers to what can be produced with the best available technology including planting material and management of all inputs. Farm yields are usually lower than potential yield (perhaps as much as 25%, even under favorable circumstances), typically because it may be uneconomical from the farmer's perspective to go for the maximum she or he could theoretically achieve. So "closing the yield gap" is about eliminating the difference between farm yield and say 75% of potential yield. Many farms produce much less than this, leading to the yield deficits that are the subject of this paper. Plant breeding and new varieties raise potential yield. Crop management makes sure results in the field are as close to it as possible.

Crop management covers water management and irrigation, land and soil management, soil fertility and health, choice of planting material, seeding techniques and timing, crop rotation and changes in cropping intensity, weed, pest and disease control[10] and management of labor supply and mechanization, to mention just the main aspects. Competent crop management, however, is hard work and requires knowledge and skill – not just the local knowledge farm operators and their families accumulate over generations, but science and engineering-based knowledge from outside that must find its way to the farmer in ways she or he can absorb and put to use. This transfer works well in advanced farming systems, as reflected in the yields achieved, for instance in many OECD countries and locations in South America and East Asia. It works much less well in poorer countries where research-to-farmer linkages and agricultural extension are weak.

How technological innovations spread and what it takes for them to be adopted by farmers has been the subject of research for many years. Theories on the diffusion of innovation, such as "induced innovation" and "directed technological change" explain technology shifts with reference to the relative scarcity of factors of production. According to Acemoglu (2002), for instance, technological change is biased toward particular factors of production, with outcomes governed by price and market size effects, as well as the elasticity of substitution between the two. Price effects would encourage innovation in the relatively scarce factor of production (in agriculture, this could be water, labor or land, for example). Market effects might direct technological change to the more abundant factor to take advantage of the scope for cost-effective expansion of production and sales. Water scarcity would drive farmers to look for new sources, efficient application technology such as drip irrigation, cheap ways to harvest and conserve water and deliver it to the field, and smart ways to avoid its loss to weeds and evaporation. Labor scarcity would call for mechanization, among other aspects. Land scarcity leads farmers to invest in well-performing seeds, optimum plant density and effective fertilization and crop protection techniques. In practice, farmers seek combinations of all of this and more, for example digital decision tools, information and mobile communications. The adoption of one particular technology such as improved seed leads to demands for supporting

[10] In many farming situations, weeds are a more important yield depressant than pests and diseases combined.

solutions (such as pest management, irrigation and market intelligence on the output side) to protect the investment in seed.

The development and adoption of technologies are two sides of the same coin. Technologies (such as new seeds) are developed so farmers can use them. But adoption is not automatic or guaranteed; key determinants of it are as follows: whether the product, technology or innovation is relevant in farmers' eyes; the riskiness of the technology; the presence or absence of property rights over natural resources; farmers' ability to organize themselves for collective action (for example, to procure inputs and services such as extension); and farmers' access to four aspects – knowledge about the innovation, financial resources, market opportunities and required supporting inputs (Hazell, 2014).

Household characteristics, including demographic aspects, gender, farm size, educational levels and – critically – distances to markets are key determinants of the scope for adoption of technological change. Policy and the incentive environment play important roles. Even the best micro (or farm) level disposition for adoption can be overridden by macro level distortions such as farmer-unfriendly trade, exchange rate and price policy regimes. Cyclical phenomena such as commodity price booms or busts and rainfall irregularities as in El Niño/La Niña years are likely to affect adoption behavior as well. Violence, civil strife and epidemics can make farming impossible.

Adoption must occur at scale for aggregate yields to move up and "sustainable intensification" to take hold (Box 2). Policy-makers and many others (including donors, foundations, local officials and NGOs) know this and so talk about the need for scaling up – the adoption of innovations by large numbers of farmers, ultimately through market mechanisms and commercial channels.

Scaling up is also about the adaptation and expansion of successful policies, programs, approaches or projects in different places and over time to reach a greater number of people. There are different though interconnected dimensions of (and ways of thinking about) scaling up, i.e., quantitative (i.e., replication, sometimes referred to as "scaling out"), functional (i.e., broadening the scope of an activity), institutional (i.e., building capacity for value addition and reach), political (by influencing the political process), and partnership-based approaches (see below).

Drivers of the process include relevant products and solutions, leadership and vision of scale, incentives and accountability, external catalysts and recognition that "time is ripe". Further important impulses come from demonstration by leading farmers or new business approaches by produce buyers (Hartmann and Linn, 2008).

Worryingly, perceptions and claims about scaling up are sometimes exaggerated and difficult to verify. Examples of this are seen in the realms of foreign aid, philanthropy, impact investment and sometimes agricultural research. People have a (probably natural) tendency to claim "feel-good successes". They tout numbers of "farmers reached" or "jobs created" that are impossible to confirm without published professional assessments of the business models and results chains in question, and their resilience to shocks and disturbances over time.

Bold claims may reflect the need to justify programs and resource use, but they are unhelpful. The landscape of interventions is mixed. There are dedicated and well-run projects working with farmers in every part of the world. There is also “projectitis” in agriculture, i.e., an inflation of well-meaning “me-too” efforts (some ignorant of farming) that may not amount to more than creating expectations while occupying farmers’ attention and time. Professional evaluation is scarce, as are coordination and bundling in a world characterized by large amounts of funds from many sources that are chasing a limited offer of good projects and ideas. There should be room for pluralism and experimentation and one should remember that delivering “proof of concept” takes time. But some endeavors are not set up, let alone stage-gate managed, appropriately. It is therefore hard for outside observers to judge which concept is being tested and how, or which method of scaling up (if warranted) would be most suitable.

Box 2 Sustainable intensification

Farming carries an environmental cost, which must be kept as low as possible. Land-clearing reduces biodiversity and increases carbon emissions. Wasteful input use and agronomic practices can lead to resource scarcity and negative environmental consequences, both locally and globally. Nitrous oxide linked to fertilization, carbon dioxide from fossil fuels or net losses from soil, as well as methane from cattle farming and irrigated rice, all cause ‘greenhouse gas’ emissions. Intensification based on modern management and crop varieties is the only way to mitigate these effects and feed a hungry world sustainably. The main environmental benefit of high and rising crop yields is the reduced need to open new land for cropping.

While requiring more physical inputs, intensification increases the use-efficiency of water, nitrogen and other nutrients, as well as energy. The scope for improvement is huge. There are many ways to reduce water use, from breeding water-efficient crops to building solutions such as drip or micro-irrigation. Appropriate pest management requires skillful use of products with modern environmental and operator safety profiles. Breeding crops that are more resistant to pests and disease helps reduce the use of chemical treatments. Soil-testing, tailored agronomic recommendations and the availability of suitably applied fertilizers all contribute to field fertility. Crop diversity is desirable, and possible in many settings. In others, however, monocultures will continue to enable the most efficient production of food. Organic farming provides some lucrative business openings, particularly in the developed world. However, organic farming is labor-intensive, its inputs are often antiquated, and the low yields waste farmland. Globally, it will not be a sustainable contributor to food security.

Sustainable farming implies growing “more with less”. Increasingly, it should also include ecosystem services that farmers can provide, and for which they should get paid. This will build natural capital while opening up new sources of income, particularly for smallholders in developing and emerging market economies. As the largest land and water user, agriculture depends on and generates a wide variety of environmental processes. Paid ecosystem services could, for example, address carbon sequestration, biodiversity conservation, watershed protection and landscape value additions. Farm management can enhance or degrade ecosystems. Paying farmers to adopt positive practices will encourage them to invest in and manage new techniques for sustainable, resource-efficient production.

Reflection on how innovations emerge and disperse and how catalytic support can facilitate both under described circumstances is therefore vital. The difference between supply and demand-driven approaches is an aspect of note. So far, the focus of much of the attempted scaling work in agriculture has been on the supply side of technologies. This is unlikely to be successful on its own. The right combination of “demand pull” and “supply push” is needed at both the development and dissemination stage of an innovation. In addition, farmers’ demand for the product or service in question needs to be cultivated (for example, by providing appropriately designed credit and/or risk management and transfer tools such as agricultural insurance). Routes to the farmer (marketing methods) also need to be developed and applied. Box 3 reports on a partnership-based effort to introduce market-responsive plant variety design techniques into African crop breeding programs.

Box 3 Demand-led crop improvement

Currently, the perplexing reality in sub-Sahara Africa (SSA) is low adoption of modern improved crop varieties by smallholder farmers as seen in Table 2 in the main text. There are multiple well documented contributing factors, such as lack of awareness about new varieties, insufficient quality seed and seed distribution systems, as well as lack of finance and credit for seed purchase (Mwangi and Kariuki, 2015). Variety design as a driver for farmer adoption is not often highlighted, but is a key ingredient for private sector seed and breeding companies to achieve enduring commercial success. New product design is central to innovation, but is typically a discipline that is under-researched within public sector crop improvement programmes. Higher adoption rates will be achieved by creating and delivering superlative new variety designs that meet the needs of not just farmers, but also their markets, and the preferences of customers along whole crop value chains.

Syngenta Foundation for Sustainable Agriculture, together with the Australian International Food Security Research Centre and the Crawford Fund has formed an alliance to encourage and promote sharing and implementation of best practices from the public and private sectors in new variety design and development. This is to support African breeders to raise demand and adoption of their varieties, by creating high performing cultivars that serve whole value chains and enable smallholder farmers to better participate in their local and regional markets.

The Alliance is partnering with the University of Queensland and leading African postgraduate education and capacity building institutions across SSA, including: West African Centre for Crop improvement, Ghana (WACCI), Biosciences East and Central Africa (BecA), Agriculture Centre for Crop Improvement, South Africa (ACCI), University of Nairobi, Kenya, Makerere University, Uganda, Regional University Forum for Capacity Building in Agriculture (RUFORUM), AGRA, the Sub-regional organisations CORAF/WECARD, ASARECA, and SADC, and also NEPAD and FARA. A specialist pan-African group of educators from these organisations and private sector experts have developed a syllabus and training module to provide state-of-the art knowledge and methodologies in demand-led plant variety design. The education module will form part of PhD/MSc postgraduate programmes and be available for continuing professional development of breeders in both public and private institutions. Implementation of best practices into African plant breeding programmes is also taking place through partnerships with National programmes. The needs of tomato growers and their value chains in Ghana and bean growers and their markets in Rwanda are the first programs to test these new approaches.

It takes many years and resources for International Agriculture Research Centres and the National Agriculture Systems in Africa to develop tailored new varieties suitable for their constituencies. Using demand-led approaches to (i) understand farmer and market needs and demand drivers, (ii) actively involve and encourage partnerships between breeders, farmers, seed distribution system and value chain actors, (iii) strengthen active foresight and engagement with policy makers and (iv) optimize variety development delivery and decision-making will contribute to accelerating the use of new improved varieties and achieving Africa's imperative for food security.

History shows that adoption of technological change at scale is possible on the part of resource-poor small farmers, as the East Asian cereal yield trajectory in Figure 3 implies. A major recent adoption success story is that of Bt cotton in India (obviously, not a food crop). Just ten years after first introduction in 2002, this product covered close to the totality of the area planted to the crop in the country. This is a prime example of how the relevance of a technology determines the speed of adoption. The seed industry invested in marketing and extension, but also in the development of large numbers of locally adapted hybrid varieties incorporating the Bt gene (VIB, 2013).

Agriculture displays other recent examples of rapid adoption of new products and techniques. Pockets of modern maize cultivation for the poultry feed market can be observed in a growing number of countries in Asia and Sub-Saharan Africa, for example (personal observation). The aspect driving adoption in these instances appears to be the presence of a ready market for the product – "demand-induced adoption" supported by what must be useful varieties, one might say.

Overall, however, the record of adoption of technological change by farmers is often unsatisfactory, although (as the maize example demonstrates) the situation is dynamic and undergoing constant change where economic growth and urbanization drive demand. A recent report by Walker et al. (2014) on the state of adoption of modern varieties (MVs) in Sub-Saharan Africa estimates that MVs were planted on 35% of Africa's farm area on a crop-weighted basis in 2010 – a level Asia reached in 1970 according to the report, and Latin America in the mid-1980s (Table 2). It is worth noting that the report applied a generous definition of MVs, i.e., many of the cultivars classified as "modern" do not embody state-of-the-art genetics or parental material based on tropically adapted elite germplasm.

Table 2 Adoption of modern varieties of food crops in SSA in 2010

Crop	Country observations	Total area (ha)	Adopted area (ha)	% MVs
Soybean	14	1,185,306	1,041,923	89.7
Maize–WCA	11	9,972,479	6,556,762	65.7
Wheat	1	1,453,820	850,121	62.5
Pigeonpea	3	365,901	182,452	49.9
Maize–ESA	9	14,695,862	6,470,405	44.0
Cassava	17	11,035,995	4,376,237	39.7
Rice	19	6,787,043	2,582,317	38.0
Potatoes	5	615,737	211,772	34.4
Barley	2	970,720	317,597	32.7
Yams	8	4,673,300	1,409,309	30.2
Groundnut	10	6,356,963	1,854,543	29.2
Bean	9	2,497,209	723,544	29.0
Sorghum	8	17,965,926	4,927,345	27.4
Cowpeas	18	11,471,533	3,117,621	27.2
Pearl millet	5	14,089,940	2,552,121	18.1
Chickpea	3	249,632	37,438	15.0
Faba bean	2	614,606	85,806	14.0
Lentils	1	94,946	9,874	10.4
Sweetpotato	5	1,478,086	102,143	6.9
Banana	1	915,877	56,784	6.2
Field peas	1	230,749	3,461	1.5
Total/weighted average	152	107,721,630	37,469,577	34.78

Source: Walker et al., 2014

We believe the low level of adoption of improved planting material documented in Table 2 can be traced to four challenges: product relevance, the absence of a seed industry for most of the crops in the Table (except for hybrid maize and some vegetables), a lack of risk mitigation and financing options for farmers, and inadequate market linkages connecting farmers to remunerative value chains. Box 4 reports on a program to facilitate the emergence of small and medium-sized companies delivering improved market-preferred seed to farmers, in particular smallholders.

Box 4 How seeds could be

Access to seeds remains a key constraint to sustainable intensification of smallholder agriculture worldwide. In Sub-Saharan Africa (SSA) alone, critically important crops such as sorghum, potatoes, beans and cassava grow on more than 29 million hectares and support over 100 million smallholders. Yet only a tenth of the seed used is of certified quality. Business models are often lacking for non-hybrid (open-pollinated and vegetative/clonal) crops, and the markets are uncertain. This situation is the single most important reason for the region's yield gap. Market entry for small and medium-sized companies needs to be made much easier.

The seeds program of the Syngenta Foundation for Sustainable Agriculture (SFSA) and its partners, known as Seeds2B, is designed to strengthen seed systems in emerging markets. It is a demand-led match-making initiative for technology transfer and capacity building for local seed production. Seeds2B currently runs in SSA, South Asia and ASEAN. The operating models for Seeds2B, called Connect and Build, help smallholders raise their incomes and improve food security by increasing the choice of seed.

Seeds2B Connect facilitates the introduction of quality seeds to local businesses. It links a wide range of public and private breeders with seed producers and distributors. Services include trialing, selection and registration. This approach is particularly suitable for technology transfer where demand is initially unproven, and for niche markets and vegetables. The focus is on low-volume, high-value products.

Seeds2B Build helps establish local seed production based on variety licensing. This approach is particularly relevant for bulky and perishable seeds, where local demand is significant but transport expensive. It builds the market through investment and technical/regulatory advance, and helps link breeders with local producers for seed multiplication.

Seeds2B is at an early stage and has so far catalyzed partnerships which give at least 55,000 smallholders access to quality seeds with new genetics. Bean and potato seed has been multiplied to satisfy local demand, and seed enterprises can now serve smallholders profitably. A further major aim is to provide a self-sustaining technology transfer platform to make the most of public and private breeding investment.

Historically, the seeds industry has achieved little success in Sub-Saharan Africa. Informal seed systems (sometimes known as "farmer seed networks") are playing a bigger role than formal seed markets as of now and can be efficient for seed dissemination (Coomes et al., 2015). However, they can only progress advanced breeding products to farmers to the extent that they can access such products from public breeding institutions in the first place. Investment in breeding for genetic gain is useful if improved seed can be delivered to farmers through appropriate channels. For many non-hybrid crops this is challenging. Most seed providers are not equipped to do their own plant breeding. They therefore rely on the public sector for germplasm. This means that licensing and intellectual property rights issues arise, in addition to the need to determine who will provide foundation seed. Box 4 reports on an effort to address this and other difficulties.

Small and medium-scale seed producers are reluctant to invest at early stages of the process when the size of their addressable market is unknown. To resolve this it is necessary to define as best as possible the level of demand for seed from aggregators, NGOs, farmer organizations and product off-takers supplying agri-food value chains. In the absence of this information, there is likely to be a need for financing on soft terms for seed producers commensurate with the risk they perceive. Advanced market commitments by governments, donors or established market participants can address the same need.

The cost of seed production is an often overlooked aspect of both a seed company's business risk and the adoptability of seed. Established seed companies conduct research into this question and are constantly optimizing the process. They know their seed production cost and have skills that could be transferred to newer entrants through business partnerships.

Good seed policy is also vital for the seed outlook. Sound policy on the registration of varieties, mutual recognition of registrations between countries, and on aspects such as international movement of seeds would support the establishment of a flourishing private seed sector. Free movement is important not only for seeds within Sub-Saharan Africa's regional economic zones, but also of suitable material from other relevant agri-ecological areas such as Latin America or Asia.

Overcoming these and other systemic hurdles requires strong partnerships between public breeders, seed companies and potential seed purchasers. So far, however, such private-public partnerships have been few in number and limited in scope. There is a clear need for trusted and independent intermediaries to broker these relationships, in order to provide smallholders with access to improved planting material. Ultimately, seed companies, large or small, will only enter markets in which they see a genuine chance of recouping their investments. There must therefore be enough customers able to pay a fair price for the seeds. Detractors of formal seed supply solutions claim repeatedly that smallholders have neither the inclination nor the means to buy better-quality certified seed. In our experience, the first of these claims is contradicted by observation in the field; the second cries out for innovative solutions.

Clearly, new technology initially costs more than old versions. Buying seed is more expensive up front than saving it from the previous harvest. What are required are therefore smart ways to lower the entrepreneurship threshold – in other words, to make it easier for smallholders to invest in their harvests. Government subsidies may help kick-start a change, but are not a sustainable option. Making credit and/or insurance affordable and accessible is a better way to encourage investment, year after year. Well-designed insurance products not only help shift the burden of risk from smallholders' shoulders. By acting as security they can also open the door to loans. With the initial barriers to investment reduced, smallholders can wait much more confidently for the increased yield and income brought by better seed. A virtuous circle begins, replacing the poverty trap caused by a very understandable reluctance to spend already limited cash resources several months before a harvest can be sold.

Summary and conclusion

The challenge facing world agriculture is how to produce more from less, to meet the increasing food demands of a rapidly growing population. This paper discusses the projected food demand to 2050, the crop yield growth required to meet it, and how such yields can be achieved.

Aggregate cereal yields have kept up with population growth during the past fifty years; the world has been fed by agricultural intensification and technological change. This trend is expected to continue, but to make sure it does, scientific advances will need to be fostered and their fruits delivered to food systems and farmers. Demand growth will remain high for another forty years. It will then decline, according to current demographic and consumption growth projections.

Today, however, aggregate yield growth is showing signs of fatigue. In addition, land conversion to non-agricultural uses, natural resource degradation and global warming are all putting additional pressure on agricultural production. Complacency is therefore not an option.

To make sure supply keeps up with demand, better agronomy and management as well as accelerated genetic yield gain from plant breeding are required. This is particularly true in regions with already lagging productivity, typically dominated by small-scale farming.

Continued crop improvement depends heavily on genetic diversity. However, this diversity is rapidly narrowing as species are lost worldwide. International efforts are needed to ensure its conservation and accessibility. Plant breeders' rights also need better protection, and this would attract more investment into breeding. Increasingly, it is the private sector that invests in commercially attractive breeding, while the public sector focuses on staple foods or crops of less commercial interest. The challenges faced by the public sector's breeding programs need to be addressed, as well as the need for strong public-private cooperation.

Farmers need innovative products and services that help them manage their crops better. They also need links to lucrative markets, and a regulatory environment that helps rather than hinders. The products and services have to provide value, and must be affordable as well as accessible. Only innovations that meet all three requirements will be adopted on a large scale. In cases of market failure, public-private partnerships can develop and supply services for farmers, and link farmers to output markets and agri-food value chains. Public policy in areas such as price and subsidies plays an important role in determining the delivery of relevant products to farmers. Further contributors include demand-led agricultural R&D, appropriate extension, investments in rural infrastructure, and regulatory environments that support the production and movement of seed and crops.

References:

Acemoglu, D., 2002. Directed Technical Change. The Review of Economic Studies 69 (4), 781-809.

Alexandratos, N. and Bruinsma, J., 2012. World agriculture towards 2030/2050. The 2012 Revision. ESA Working paper No. 12-03, April 2012. Food and Agriculture Organization of the United Nations: Rome.

Butzen S. and Smith S., 2014. Corn Yield Gains due to Genetic and Management Improvements (Crop Insights), accessed in September 2015, https://www.pioneer.com/home/site/us/agronomy/corn-yield-gains/#

Coomes, O.T., McGuire, S. J., et al. 2015. Farmer seed networks make a limited contribution to agriculture? Four common misconceptions. Food Policy 56, 41-50.

Cooper, M. , Messina, C.D., Podlich, D., Totir, L.R., Baumgarten, A., and et al, 2014. Predicting the future of plant breeding: complementing empirical evaluation with genetic prediction. Crop and Pasture Science 65, 311-336.

Deininger, K. and Byerlee, D., 2012. The rise of large farms in land abundant countries: do they have a future?, World Development 40(4), 701-714

FAO, 2011. Payment for ecosystem services and food security. Rome Italy. http://www.fao.org/docrep/014/i2100e/i2100e.PDF

Fischer, G., 2009. World Food and Agriculture to 2030/50: How do climate change and bioenergy alter the long-term outlook for food, agriculture and resource availability? Accessed in September 2015, http://www.fao.org/3/a-ak972e.pdf

Fischer, R.A., Byerlee D. and Edmeades G.O. 2014. Crop yields and global food security: willyield increase continue to feed the world? ACIAR Monograph No. 158. Australian Centre for International Agricultural Research: Canberra.

Goedde, L., Horii, M., and Sanghvi, S., 2015. Pursuing the global opportunity in food and agribusiness, Mckinsey Insights, July 2015, http://www.mckinsey.com/insights/food_agriculture/pursuing_the_global_opportunity_in_food_and_agribusiness

Hanson, C. and Searchinger, T., 2015. Ensuring Crop Expansion is Limited to Lands with Low Environmental Opportunity Costs, Installment 10 of "Creating a Sustainable Food Future". World Resources Institute working paper, September 2015

Hartmann, A., and Linn, J., 2008. Scaling Up: A Framework and Lessons for Development Effectiveness from Literature and Practice. Wolfensohn Center Working Paper No. 5. Brookings.

Hazell, P., 2014. Topic Guide: Agricultural productivity. Evidence on Demand, UK. DOI: http://dx.doi.org/10.12774/eod_tg.may2014.hazell

Lobell, D.B., Baldos, U. and Hertel, T.W. ,2013. Climate adaptation as mitigation: the case of agricultural investments. Environmental Research Letters 8, 015012. doi:10.1088/1748-9326/8/1/015012.

Linehan, V., Thorpe, S., Gunning-Trant, C., Heyhoe, E., Harle, K., Hormis, M. et al., 2013. Global food production and prices to 2050: scenario analysis under policy assumptions. Conference paper 13.6. Australian Bureau of Agricultural and Resource Economics and Sciences: Canberra.

Lusser, M., Parisi, C., Plan, D., Rodriguez-Cerezo, E. 2012. Deployment of new biotechnologies in plant breeding. Nature Biotechnology 30, 231-239

McCouch, S., 2013. Feeding the Future. Nature 499, 23-24.

Mwangi, M. and Kariuki, S., 2015. Factors affecting adoption of new agricultural technology by smallholder farmers. Journal of Economics and Sustainable development 6(5), 208-2017

Nelson, G.C., Rosegrant, M.W., Palazzo, A., Gray, I., Ingerstoll, C., Robertson, R., 2010. Food security, farming, and climate change to 2050: scenarios, results, policy options. Research Monograph. International Food Policy Research Institute, Washington, DC. doi:10:2499/9780896291867.

Phillips McDougall, 2011. The cost and time involved in the discovery, development and authorization of a new plant biotechnology derived trait – A consultancy study for Crop Life International.

Podevin, N., Davies, H.V., Hartung, F., Nogue, F., Casacuberta, J.M., 2013. Site-directed nucleases: A paradigm shift in predictable, knowledge-based plant breeding. Trends in Biotechnology 31, 375-383.

Pretty, J. , Toulmin, C. & Williams, S., 2011. Sustainable intensification in African agriculture, International Journal of Agricultural Sustainability, 9:1, 5-24

PwC, 2015. The World in 2050: Will the shift in global economic power continue? February 2015.http://www.pwc.com/gx/en/issues/the-economy/assets/world-in-2050-february-2015.pdf

Qaim, M., 2009. The economics of genetically modified crops. Annual Review of Resource Economics, 1, 665-693.

Ray, D.K., Mueller, N.D., West, P.C., Foley, J.A., 2013. Yield Trends Are Insufficient to Double Global Crop Production by 2050. PLoS ONE 8(6): e66428. doi:10.1371/journal.pone.0066428

The Economist Intelligence Unit Limited, 2015. Long-term macroeconomic forecasts: Key trends to 2050, A special report from The Economist Intelligence Unit. http://www.eiu.com/public/topical_report.aspx?campaignid=ForecastingTo2050.

VIB, 2013. BT cotton in Indi: a success story for the environment and local welfare VIB, Belgium. http://www.vib.be/en/about-vib/plant-biotech-news/Documents/BackgroundReport_BT_Cotton.pdf

Walker, T., Alene, A., Ndjeunga, J., Labarta, R., Yigezu, Y., Diagne, A., Andrade, R., Muthoni Andriatsitohaina, R., De Groote, H., Mausch, K., Yirga, C., Simtowe, F., Katungi, E., Jogo, W., Jaleta, M. & Pandey, S. 2014. Measuring the Effectiveness of Crop Improvement Research in Sub-Saharan Africa from the Perspectives of Varietal Output, Adoption, and Change: 20 Crops, 30 Countries, and 1150 Cultivars in Farmers' Fields. Report of the Standing Panel on Impact Assessment (SPIA), CGIAR Independent Science and Partnership Council (ISPC) Secretariat: Rome, Italy.

Zhou, Y. and Staatz, J., 2015. Projected demand and supply for various foods in West Africa: implications for investments and food policy, SFSA working paper, Accessed in September 2015, http://www.syngentafoundation.org/index.cfm?pageID=131