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The new green revolution: bridging the gap between science and society

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By combining scientific excellence with social involvement, M. S. Swaminathan has put himself in the tradition of the great agricultural researchers such as Von Liebich, Vavilov, De Vries, Haber and his friend and colleague Norman Borlaug that have defeated the Spectre of Malthus. His ability to use his knowledge and insights to find solutions for complex social problems made him one of the founding fathers of the Green Revolution. And one of the first that saw the drawbacks of the extensive use of water, fertilizer and pesticides that came along with it. He became a staunch advocate for the Evergreen Revolution towards an eco-friendly, resource-poor, sustainable agriculture that is based on science and technology and aims for nutrition security for all. Challenged with the perspective of feeding 9 or 10 billion people with sufficient and nutritious food and producing enough raw materials for the developing bio-based economy we have to keep on learning by doing research and combining its results with the experience of farmers and others. Yet there seems to be a lack of belief – at least in Europe – in human learning; a general distrust in science, which might lead to paralysis in agricultural development. Hence the biggest challenge is to bridge the gap between the sciences and society and to engage society in the development of science to meet the challenges of tomorrow.

Keywords: Agricultural yield revolution, burgeoning population, evergreen revolution, social contract of science, Swaminathan in Wageningen.

Introduction

IT is the year 1949. The Netherlands is still recovering from the German occupation. At the small station of Ede-Wageningen a rather un-Dutch looking slender young man steps down from the train, a heavy suitcase in his hand. He looks around to find someone his host, but sees no one. Only a tall man who, with a firm gesture takes his suitcase from him. 'A porter', the young man thinks and feels embarrassed because he has no Dutch money on him as he came by overnight ferry from England and stepped immediately on the train upon arrival in Hoek van Holland. How is he going to tip the porter? Putting aside his diffidence, he asks the man if he perhaps knows how to get to professor Prakke at the Agricultural University in Wageningen. 'I am a professor Prakke', the man replies, so the embarrassment of the young man turns into astonishment. A professor who picks up a young researcher from the station and starts carrying his suitcase is something he could have never imagined (R. Rabbinge, pers. commun.).

The meeting at the station was Swaminathan's first encounter with Wageningen, not only as a city and a university but also as a concept. The agricultural university is quite small – it certainly was in those days – and its research and teaching were not only in the service of scientific progress, but also in the service of agriculture, rural development and healthy nutrition. But Wageningen was (and in a way still is) also a community where professors come to their laboratories and classrooms on a bicycle and where Dutch farmers' sons and daughters were propelled from the quiet rural areas of Holland into a place where they were confronted first-hand with the problems of global hunger and poverty, as well as students and researchers from all over the world. Among them was the newly graduated Swaminathan, who wanted to gain expertise in research into the genetics of the potato in the Laboratory of Genetics of the famous professor R. Prakke.

Another little anecdote about Wageningen at that time: Swaminathan boarded in the Java Street with a typical Wageningen family. Every night he got a typical Dutch meal consisting of potatoes, vegetables and meat. Being vegetarian he had to forego the meat – which in the Netherlands at the time was considered a luxury. From then on – so the story goes he was served eggs – fried, boiled or scrambled. Until one day his landlady served him a wonderful vegetarian meal. She told him she had taken a vegetarian cooking class because she felt so sorry for her guest for only getting to eat potatoes and vegetables.

Excellent

During his stay in the Laboratory of Genetics, Swaminathan managed to develop a standardized method for the introgression of genes from wild type potato that could protect potato cultivars against nematodes and other diseases. That was not easy, because potato cultivars are tetraploid, meaning that they have a quadruple set of

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chromosomes, while the wild varieties are diploid and thus have a double set of chromosomes. Together with Prakke he published a number of articles on the subject in the early fifties[1]. Although his first stay in Wageningen only lasted a year, it represented the beginning of a long cooperation and the beginning of an extensive network of friends and acquaintances in the Netherlands. In May last year, this first arrival at the train station in Ede-Wageningen was commemorated with a lecture from Swaminathan entitled '65 years of scientific research for food and nutrition security in a warming world'[2]. More than a quarter century before, in 1988, he already had received an honorary doctorate at the seventieth anniversary of the University of Wageningen for his commitment and his results in eradicating hunger and poverty by bringing science and technology to the farmer's fields.

After his stay in Wageningen Swaminathan went to Cambridge (UK), where he not only got his Ph D, but also met his future wife, Mina Boothalingam. After graduation he did a post-doc at the University of Wisconsin, still with the genetics of the potato as the main subject. With his already considerable list of publications in leading scientific journals, it was quite likely that he – like many of his countrymen – would stay in the US to build an academic career. Although he was indeed offered a position there, he took a different road: he went back to India because he wanted to use his scientific knowledge to combat hunger in his country. After all that had once been the reason he went to study agronomy.

Concerned

That motivation is recognizable. As a 17-year-old town girl, living in Brussels, I myself choose to study in Wageningen because of the terrible images of the famines in Biafra and the Sahel region at the end of the sixties. Swaminathan explained his choice as a 17-year old boy for the Tamil Nadu Agricultural University in the following way:

'My personal motivation started with the great Bengal famine of 1943 when I was a student at the University of Kerala. There was an acute rice shortage, and in Bengal about 3 million people died from starvation. All of our young people, myself included, were involved in the freedom struggle, which Gandhi had intensified, and I decided I should take to agricultural research in order to help farmers produce more.'[3]

The special thing about Swaminathan is that he combines academic excellence with technical competence and the ability to use his knowledge and insights to find solutions to complex social problems. With that unique combination of talents he follows the footsteps of a series of predecessors and contemporaries such as Justus von Liebig, Nikolai Vavilov and his friend and co-worker Norman Borlaug. It is a type of scientists that does not fit into the traditional linear model of scientific progress.

Vannevar Bush, advisor to President Roosevelt, developed this linear model shortly after the World War II[4]. It implies that our prosperity is based on free, independent research, which is purely driven by scientific curiosity of the researcher. The insights yielded by this basic research are converted into innovations through applied research and hence in new products, processes and services that enhance prosperity. According to Bush, the linear model only works well if you do not mix fundamental and applied research or, as he put it: 'Applied science drives out basic science'.

Almost twenty years ago, the political scientist Donald E. Stokes already showed that the linear model does not reflect reality[5]. For many leading experts their scientific curiosity is led by sometimes-large societal problems for which a solution must be found. By trying to find these solutions they develop new insights and new scientific knowledge shedding a different light on reality. According to Stokes, this reality asks for a new model. For that he developed a quadrant model of scientific research with the pursuit of fundamental knowledge (understanding) on the vertical axis and the potential benefits of the research on the horizontal axis (use).

The axes produce four quadrants, i.e. four types of research, which he named after researchers that are characteristic for that quadrant. Scientists who focus solely on comprehension (understanding) without regard for possible use are located in the quadrant named after Niels Bohr; researchers who focus only on application and are not interested in new insights are in the quadrant named after Thomas Edison. For the quadrant with research that neither focuses on understanding nor on use, the Swede Linnaeus would qualify. In the fourth quadrant, named after Louis Pasteur, researchers try to combine the acquisition of fundamental understanding with the search for applications.

Spectre of Malthus

It is precisely this type of research, which combines scientific curiosity with social involvement that has ensured that we – through trial and error – have managed to defeat the spectre of Malthus. Thomas Malthus, the British theologian and economist, predicted in the late eighteenth century that the linear growth of agricultural production could not keep up with the exponential growth of the population and that therefore famines were an inextricable fate of human existence.

The first generation of researchers, who wanted to defeat the spectre of Malthus, could not dwell yet on the insights from modern science, which was just starting to develop. At the end of the eighteenth century non-governmental organizations of wealthy citizens, like the English Board of Agriculture, the Spanish Reales Sociedades Economicas and in the Netherlands the 'Maatschappij ter bevordering van den landbouw' (Society for the Promotion of the Agriculture) used mainly prize competitions to challenge the competitors to come up with techniques to increase farm yields and reduce the risk of disease and crop failures and hence of famines.

The focus was on combating animal diseases, plant and animal breeding, improved fertilization by among others clover cultivation, disease reduction and crop rotation. Although substantial, these improvements were still mainly the result of the systematic application of traditional knowledge based on practical experience. However, their efforts laid the foundations for a more scientific approach to increase yields and combat diseases.

Mid-nineteenth century developments accelerate, as representatives of the young science of chemistry are to apply their recently acquired knowledge to solve problems in agriculture. One of those scientists is Justus von Liebig[6] who, at the age of 21, was appointed as a professor of pharmacy at the University of Giessen. Although theoretically well grounded, he focused primarily on practical applications of chemistry. He was the first professor to introduce laboratory practice into the curriculum.

Later, when he had been appointed as a professor in Munich, he discovered that the vigour of plants is not determined by some form of vital energy (vitalism) which is passed through humus, but is the result of processes that involve carbon dioxide and water from the atmosphere and nutrients from the soil, more in particular nitrogen, phosphorus and potassium (NPK). A discovery that was based on experiments and logic, which made him the godfather of fertilizer application.

Around the same John Bennet Lawes, a representative of the English landed gentry acquired a patent on the production of superphosphate by treating phosphate rock with sulphuric acid. Although the first results in the field were very good, it would take until the end of the nineteenth century before superphosphate was used on a larger scale. That same Lawes was the owner of Rothamsted Manor that he turned into an experimental farm. It still exists as Rothamsted Research[7] and it houses the longest lasting agricultural experiment in the world: a field trial that evaluates the effects of inorganic fertilizer and manure on winter wheat.

Doubling population

The impact of modern chemistry on agriculture and food can hardly be underestimated. Traditionally, human and animal manure were used as plant nutrients, but after Von Liebig's discovery, a search for extra sources of nutrients started. Initially substances were used that occurred in nature, like Chili-saltpetre, a nitrate-rich mineral from Chile, called the 'white gold'. Nitrogen fertilizers, particularly urea, were also produced, but because of the cumbersome synthesis that never happened on a large scale.

The true chemical revolution in agriculture began in 1909 when Fritz Haber developed the first feasible process to make ammonia from atmospheric nitrogen on a large scale. The reaction itself was considered the Holy Grail of synthetic inorganic chemistry. The German chemical company BASF bought the discovery and Carl Bosch was given the task to scale up the process from laboratory to factory set up. He did that in record time: commercial production of ammonia began in 1913.

In spite of Bosch's speedy development of the process, it took a while before fertilizer was widely used in agriculture. During the First World War, the greater part of the synthetic ammonia was used for making nitric acid, one of the raw materials for explosives. The first fertilizers were prepared in the twenties, but due to the economic crisis of the thirties and subsequently World War II, the global production of ammonia remained under 5 million tonnes.

At this moment about 150 million tonnes of ammonia are produced worldwide, of which 80% are used as an ingredient in fertilizer. The amount of reactive nitrogen that is introduced into the biosphere rivals with the amount of reactive nitrogen that is produced by all bacteria naturally, significantly altering the amount of fixed nitrogen in the earth's ecosystems. On the other hand, writes Vaclav Smil in his *Enriching the Earth*[8], there would be no food for 40–50% of the world population without the Haber–Bosch synthesis. Or rather, they would simply not be around because they would not have been born or would have died at a young age for lack of food.

Dwarf varieties

During the fifties, the use of inorganic fertilizers as a means to increase production became an important topic in agricultural research in India. After returning to his home country, Swaminathan shifted his scientific attention from potatoes to rice, more particularly to the development of hybrids of two subspecies, *indica* and *japonica*, that would be more responsive to fertilizer. A problem was that use of fertilizer indeed led to larger ears but these became so heavy that the stalks would topple over. This occurred already at levels of 50 to 80 kg of nitrogen per hectare. A possible solution was to breed varieties with stalks that still had the heavy ears, but that were shorter and firmer. Swaminathan put his considerable knowledge and competence in the field of hybridization to work in order to develop the desired dwarf varieties. In doing that he used the insights on mutagenesis that had been developed 30, 40 years earlier by the Dutchman Hugo de Vries. Being a researcher that combined scientific curiosity with social commitment puts De Vries also in the quadrant of Pasteur.

Although his main work was in mutagenesis, Hugo De Vries – together with Carl Correns and Erich von Tschermak – is better known for his rediscovery of Mendel's laws of heredity[9]. The latter did his crossing experiments with peas in the fifties and sixties of the nineteenth century, which is about the same time that Von Liebig discovered the importance of fertilizer. Yet it was not until the early twentieth century before the insights into heredity were applied in agriculture. Until that time, plant breeding was primarily a craft, an art sometimes, based more on experience than on theory.

The artisan breeders achieved incidentally important and sometimes even spectacular results. The American Luther Burbank[10,11] only had elementary school education, but he developed a large number of new varieties of crop plants, including a white blackberry, a stone-less peach and a new species of fruit, half plum half apricot. However, he is best known as the creator of the Burbank potato, the predecessor of the successful Potato Russet Burbank that is still being used by McDonalds for its fries. In the Netherlands we are still proud of the Bintje potato, a variety that was developed by another artisan breeder, the Frisian headmaster Lieuwes Kornelis de Vries, and is still widely grown.

Hugo de Vries (no relation) was a botanist who studied in Germany and the Netherlands. His focus was on improving crops such as red clover, potatoes and sugar beets. His scientific curiosity led him to study the evening primroses that grew spontaneously in an abandoned field near his home in Hilversum. He noticed that the primroses produce many different varieties within a generation. These sudden changes did not really fit in with Darwin's theory of gradual evolution. De Vries called these 'mutations' and postulated that they were an important engine of evolution. He was right about mutations in general, but not about the evening primrose. Later it was discovered that its 'mutations' were actually due to chromosomal duplication (polyploidy) and not with mutations as they are defined nowadays, i.e. changes in the DNA-sequence.

In his efforts to develop dwarf varieties of rice and – later on – wheat, Swaminathan made frequent use of mutagenesis, artificially inducing mutations by using chemicals and ionizing radiation, but it turned out to be too complicated a task. Eventually the solution was found with the discovery of so-called 'dwarfing genes' for wheat and rice. Those for wheat were found in Norin-10, a dwarf cultivar that had been registered in 1935 in Japan. It had two *rht*-genes (*rht* = reduced height 1 and 2), which ensured that the wheat plant grew no bigger than 60 cm while it also took up nutrients better.

The dwarf variety was picked up by a biologist in the occupation forces of General Douglas McArthur, which ruled Japan between 1945 and 1951. Eventually it ended up in the hands of Norman Borlaug in Mexico, who used the variety in his breeding programme aimed at the development of semi-dwarf, high yielding varieties of wheat, which responded well to fertilizer and (irrigation) water. That was the start of the green revolution in which Swaminathan played such an important role.

Myth

The Green Revolution is, what political scientists call, a political myth[12] that is a story, a narrative that is shared by a social group that gives meaning to the group's position in society. The Green Revolution, the leap in agricultural productivity at the end of the sixties, gives meaning to the work of agricultural scientists who are trying hard to prove Thomas Malthus and his neo-Malthusian followers wrong by using modern science and technology to increase agricultural productivity. This political myth has worked and still works witness the ambitions of AGRA (the Alliance for a Green Revolution in Africa) to transform African agriculture. At the same time, everyone knows that the term 'revolution' is a simplification. The Green Revolution in Asia and Latin America – and also in Africa – builds on previous green revolutions: For example, the green revolution that took place in the forties and fifties in Europe and North America. And before that the green revolution that took place at the end of the nineteenth century, when railways opened up the American Midwest and the grain that was produced there in large amounts filled the holds of steamships heading for Europe where it flooded the markets. And before that the green revolution that took place at the beginning of the nineteenth century when rather disorganized troops of mercenaries were replaced by huge tightly organized armies of conscripts who had to be fed, even during long campaigns. And at the beginning of course, the agrarian revolutions that took place from 10,000 year ago onward in Mesopotamia, China and Central America, during which the nomadic life of the hunter/gatherer was exchanged for the sedentary life of the farmer. In fact, you could say that there is a constant evolution, which occasionally bursts of sudden accelerations: A 'punctuated equilibrium', as Stephen Jay Gould baptized his theory of evolution, which also seems to apply to the production of food as a human activity.

The prelude to the Green Revolution was the Cooperative Wheat Research Production Program, set up during the World War II as a joint venture between the Mexican government and the American Rockefeller Foundation. One of the first employees of that programme was the already mentioned Norman Borlaug, a young plant pathologist[13]. In the fifties his research efforts were focused on the breeding of wheat varieties that are resistant to rust, a fungal disease. The hybridization of these varieties with the Japanese dwarf varieties produced a number of cultivars that were responsible for a huge yield increases in Mexican wheat cultivation in the early sixties. In 1963 the yield per hectare increased six-fold compared with ten, fifteen years earlier.

So the green revolution actually began in Mexico, but for several reasons its success in the fight against hunger was mainly projected on the Indian subcontinent. One reason was the good relation between Borlaug and Swaminathan. Already in the early stages of development Swaminathan obtained the dwarf varieties that were made resistant to various diseases and which later proved to be such a success in Mexico. In 1963, Borlaug travelled to India with a few hundred pounds of seed of four high yielding varieties that were already distributed in Mexico in his luggage plus another 600 promising hybrids that Swaminathan and his staff could develop further.

The second reason was more political in nature, according to political scientist Roger Pielke Jr in a recent lecture at the Pacita 2015 conference in Berlin, meaning both the domestic and foreign policy of the United States. The domestic political reasons were that the United States since the early fifties exported huge quantities of grain to the Indian subcontinent as food aid. The grain farmers in the Midwest – a small but high profile group of voters – were of course very happy with that. However, food aid came under pressure due to a revival of Malthusianism in the sixties: the proponents reasoned that food aid made no sense, because it only led to even more new mouths to be fed. And India was the main culprit. According to Neo-Malthusians like Paul Ehrlich, author of *The Population Bomb*[14], that country would never produce enough to feed itself.

The then American president, Lyndon Johnson was forced to withstand the pressure of the Neo-Malthusians. Not only to keep the American grain farmers of the Mid-West happy, but also for reasons of foreign policy: He wanted to prevent India from getting further into the sphere of influence of the Soviet Union. Scientists supported the efforts of the president, in particular Roger Revelle, the then director of the Harvard Center for Population and Development Studies (the Pop Centre). He was a very strong proponent of improving agriculture in developing countries to fight hunger. On his initiative a symposium on world food supply was organized by the National Academy of Sciences together with the Rockefeller Foundation, where scientists were challenged to win the race to feed the world. During a visit by Indian Prime Minister Indira Gandhi to the United States, President Johnson promised her the support of the United States, not only with shiploads of grain but also with knowledge and expertise to end the occurrence of food shortages.

Unprecedented revenues

The large-scale introduction of the new wheat varieties and later the new varieties of rice on the Indian subcontinent led to unprecedented revenues. The production of wheat in India almost doubled from 12 million tonnes in 1965 to over 20 million tonnes in 1970. In 1974 the country produced enough to feed its own population. The high yields per hectare saved land resources. In 2013 India produced 95 million tonnes of wheat on 26 million hectares. Before the Green Revolution, 95 million hectares would have been needed. The question is if we can attribute the high yields solely to high-yielding varieties, input of fertilizer, improved irrigation and the use of synthetic crop protection. What also helped was that after years of drought the monsoon rains reached their previous levels again in that period and also that the Indian countryside became increasingly accessible, stimulating farmers to produce for markets instead of only for subsistence.

Anyway, thanks to that high yields the apocalypse predicted by Paul and Anne Ehrlich that despite all food aid, hundreds of millions of people would die of starvation in the seventies, became already obsolete shortly after their warnings appeared in print. According to the *New York Times* in 1970 writing about the Nobel Peace Prize for Norman Borlaug, truly a green revolution had taken place[15]. Malthus was defeated and famine was no longer an inextricable fate of human existence. Which makes it inexcusable that still to many people have not enough to eat.

After the fall of the Soviet Union in 1989, trade in agricultural commodities and food products has increased by leaps and millions of smallholders are now included in the global food webs. Emerging economies have shown unprecedented economic growth, resulting in a rapidly growing middle class, who no longer, as before, half or three-quarters of the family has to spend on food and space for luxury foods like vegetables and especially meat. This change in menu leads to new challenges for agricultural science and technology that will be discussed later.

Disappointment

Around 1980, after the initial euphoria, people became more and more disappointed about the green revolution. The applications of scientific knowledge in agriculture and food had led to huge increases in yield, but also to all kinds of undesirable social and environmental consequences. Disappointment started in Western Europe and North America where agriculture went through a transition towards increased productivity per hectare and working hour in the forties and fifties. The transition was propelled by the (extensive) use of fertilizers and pesticides, the use of controlled seed and by up-scaling and mechanization. A Green Revolution avant la letter, you could say. But in particular, the use of pesticides, once seen as heralds of the modern era, led to major problems.

The first synthetic pesticides date from shortly after the First World War and were developed by the already mentioned Fritz Haber, the man who discovered a way to convert inert atmospheric nitrogen into reactive ammonia. In the twenties, he developed two synthetic insecticides, Zyklon A and Zyklon B[16]. The latter has become notorious as a poison gas in the extermination camps of Nazi Germany, but Fritz Haber, who was Jewish, did not live long enough to see his substances abused in such an horrific way. He died in 1934, having fled his homeland a year before when Hitler assumed power in Germany.

In the thirties, other synthetic agents were developed to protect crops against pests, diseases and weeds, including carbamates (dithiocarbamate, a fungicide), organic hydrocarbons, including DDT (already synthesized in 1874, but only in 1939 the insecticidal function was discovered) and organophosphates such as malathion and parathion. Gradually conventional, naturally occurring pesticides such as ash, lime, sulphur and bitumen and extracts from plants, such as pyrethrum, rotenon and veratrine were replaced by the usually much more effective synthetic compounds.

In the early sixties it turned out that synthetic pesticides had all kinds of negative side effects. In her famous book, Rachel Carson[17] pointed out that the use of DDT and related pesticides would eventually lead to a Silent Spring, a spring where the birds could no longer be heard to sing, because they had died of pesticide poisoning. Later it turned out that pesticides also had serious consequences for people's health. Although its scientific base was not very strong, Rachel Carson's book had an enormous influence on the emerging environmental movement. Gradually other kinds of pollution coming from agricultural practice were put on the agenda, like the excessive use of mineral fertilizers leading to an overload of nitrogen in groundwater and surface water and of phosphate in soil.

Other consequences

The Green Revolution had just taken off in India when already Swaminathan pointed to possible negative consequences caused by the excessive use of fertilizers, pesticides and irrigation water[18]. His fears materialized nearly twenty years later in the form of silted fields, lowered groundwater levels, degraded soils and a growing incidence of cancer and other serious diseases related to the injudicious use of pesticides. Socially and economically the Green Revolution had serious negative consequences as well. Scaling and intensification of agriculture meant that many small farmers could not survive. Higher productivity, sometimes overproduction meant lower prices, which – asides from being beneficial for the urban population and the landless in rural areas – were devastating for the small (lease) farmers and in some countries even more so for women. In India, for instance, women are not entitled to land. When the man left the villages, they not only carried the burden of farming and taking care of the family, but as they could not get loans, the Green Revolution for them meant poverty and lack of access to financial capital to invest in machinery, seed, fertilizer and crop protection. For slightly larger farmers low prices meant that they had to try and produce even more to reap a reasonable income from their business, thus pushing a vicious circle towards even lower prices.

Another consequence – not just of the green revolution though – is the migration of mainly young people to the city looking for jobs, leaving an ageing population in the countryside. Japan is an extreme example, but also elsewhere young people see less and less perspective in a farmer's life of long hours, hard work and great uncertainty about earnings and income. Apart from the need to develop 'smart mechanization and automation' this calls for new labour arrangements, like cooperatives or family farms that are run by more than one family. An important consequence is also that policies are developed and executed to encourage the 500 million small farmers that are mainly producing for subsistence, to become agricultural entrepreneurs or else find a job outside farming in the countryside.

From a completely different character is the effect that the abundance of calories has had on the billion people worldwide that are overweight or obese – with all the negative consequences for their health. It is rather cynical to think that the amount of people that are overweight has surpassed the estimated 800,000 people who regularly have to go to bed with an empty stomach. Not to speak about the billion or so people, who get enough calories to quench their appetite, but whose menu is so one-sided that it adversely affects their health and wellbeing and – for growing children – their learning capacities. It seems that we have been focusing too much on producing enough calories, losing sight of the importance of the nutritional quality of these calories.

As said before, higher agricultural productivity has led to lower prices and hence a growing, urban middle class that is able to spend money on other things than just basic foods. Consequently there is a growing demand for animal protein. The most striking effect of this increasing demand is the on-going conversion of natural ecosystems into grazing land and fields for the production of animal feed. Other effects are the ruminant methane production that contributes to climate change and the increasing risk of animal diseases, including zoonosis that affects humans as well, like influenza, BSE and MERS. Also, the large-scale use of antibiotics, not only for therapy but also as growth promoters, undermines the effectiveness of these drugs for humans.

Changing land use and the use of fossil fuel for energy and as a feedstock for fertilizer also contributes to climate change. Change in rainfall patterns due to natural changes, such as the recurring phenomenon El Niño, has had a major impact on food supply over the centuries.

Besides drought or floods caused by shifting rainfall patterns, the expected higher temperatures may also lead to new pests and diseases. Predictions indicate an average decrease of crop yields by 2–5% with a sharp distinction between temperate zones where yields will increase, and the tropics and subtropics where they decrease by 10–15%. That seems like a lot, but we should keep in mind that the 'yield gap', the difference between potential and actual output varies between 60% and 70% in the tropics. With good management and the application of modern insights and techniques harvest losses due to climate change could be amply compensated[19].

Genetic heritage

The drawbacks of the Green Revolution have put us on the trail of new insights and new developments. One is the preservation of wild varieties and the varieties that have been cultivated by generations of farmers of crops as well as livestock. One of the consequences of the Green Revolution was that this (agro) biodiversity started to disappear with the advent of high-yielding hybrids. Swaminathan has always been at the forefront of preserving biodiversity. In that respect he is a true follower of the Russian biologist Nikolai Ivanovich Vavilov[20], again a researcher who combines scientific excellence and social involvement, in his case fuelled by the famines he saw as a child growing up in the poor countryside of Russia before the revolution.

In the twenties and thirties Vavilov made many trips including trips to the countries of the ancient Silk Road and to the mountainous regions of Central America, in search of wild relatives and locally grown varieties of crops. According to the hypothesis he worked from, the greatest genetic variation was to be found in what he called the areas of origin, now often called Vavilov centres, like maize from Mexico, wheat and barley from the region between the Tigris and Euphrates and apples from Kazakhstan. He collected more than a quarter of a million seeds and fruits, which were stored in what was probably the largest seed bank in the world at that time.

Being a staunch defender of evolution and the laws of heredity, Vavilov got increasingly into conflict with Lysenko, a protégé of Stalin, who rejected these Mendelian genetics in favour of the theory that hereditary traits are not hereditary but can be changed by changing the conditions instead of the cumbersome and time-consuming process of crossbreeding and selection. At a conference in Moscow in 1939, there was an open clash between Vavilov and Lysenko, resulting in the arrest and sentencing of Vavilov to twenty years in prison. He died in captivity in 1943, but was publicly rehabilitated in 1955, during the de-Stalinization period.

An equally tireless advocate of biodiversity, Swaminathan luckily has not met with Vavilov's fate. On the contrary, it might have taken a while, but eventually his plea for conserving agro-biodiversity was acted upon with the establishment of the Svalbard Global Seed Vault, which opened in 2008. There the starting material of approximately 4.5 million different species are kept at a temperature of –18°C, thus creating a safety net for food security in the world. Cryogenic storage, however, is only part of the story. Another, equally important part, is the preservation of the environmental integrity of these crops by growing them – preferably – in the areas of origin, so new varieties can arise. According to Swaminathan, (small) farmers have a role in preserving the ecological integrity of these crops and should receive compensation for their cultivation. He has put a lot of effort in establishing field stations to stimulate conservation of traditional varieties. Also his efforts to legally protect plant breeders' rights can be seen in that light as they are based on his idea that the genetic diversity that farmers have accumulated over the centuries is their common heritage. A very topical question is to what extent the rights of traditional growers and farmers can be legally protected as natural properties introduced through traditional breeding can be patented. A major consequence could be that third parties – like traditional breeders – are denied access to the starting material if they want to use it for further breeding.

Evergreen Revolution

In response to the drawbacks of the Green Revolution new technologies have been developed. For instance drip irrigation has been introduced, which substantially reduces the need for water for growing crops. Combining old and new insights and technologies for no till or less till farming can prevent erosion and loss of organic substance. Leaving crop residues in the field also increases organic matter, while erosion can also be prevented by sowing an in-between crop or by mixed cropping, whereby trees can be the other crop (agroforestry). The Green Revolution was associated with a type of mechanization that focused on large-scale mono cropping. At the moment small machines are being developed that are relatively easy to use – even in mixed crops – and are affordable for small farmers. To combat pests and diseases farmers are increasingly switching to Integrated Pest Management (IPM). This means no more fixed spraying schemes, but monitoring of crops, evaluating possible damage and, if necessary, control diseases or pests by deploying predatory insects, fungi and bacteria, using synthetic chemicals only as an *ultimum remedium*, a means of last resort. Microorganisms have been used before to combat pests and diseases, mostly in organic agriculture, but nowadays these so-called biologicals have attracted the attention of the large producers of agrochemicals as well, fuelling hope that they will be 'mainstream' in the near future.

In the light of these developments conditions seem to be met for a new 'Evergreen Revolution' as Swaminathan has named it[21]. At the core of this revolution is the 'farming systems' approach, which looks beyond the field and even beyond the farm gate considering the farm as part of a larger ecosystem. The objective is no longer to achieve the highest yield possible but to close the cycles of nutrients, water and chemicals. The Evergreen Revolution also calls for institutional changes. An example of these kind of changes is the Women Farmer's Entitlement Bill that was introduced by Swaminathan in the Rajya Sabha of the Parliament of India to provide legal rights to land for women in farming.

Such an evergreen revolution seems the only way to produce enough food – and raw material for the chemical industry – while at the same time minimizing the effects on human health and the environment. Doubling yields and halving impact seems quite feasible, provided that agricultural policy and regulation will be pointing in the same direction and new models for production and consumption (circular economy) include sufficient economic incentives for behavioural change among consumers and businesses.

Distrust

However, the Evergreen Revolution is threatened by a growing distrust of the achievements of modern science induced by the aforementioned shortcomings of modern agriculture: intensification accompanied by the abundant use of agro-chemicals and fossil fuels and the growing anonymity due to economies of scale and international trade. Instead of trying to do better by being more critical about the possible negative consequences of applying science and technology in agriculture and food, more and more people are rejecting the use of science and technology. Fearing a biological meltdown they seek salvation in locally produced and organically grown food with dogmatic of exclusion fertilizer, crop protection and genetic modification.

The negative perception of agricultural science and technology is no longer limited to a few bearded hippies on health sandals, but also appeals to the middle classes, which are growing with more than 10% per year in the emerging countries. More and more people see science as a blind faith in technocratic solutions that are imposed from the top down without taking into account environmental and social diversity, animal welfare and damage to the environment. People do not seem to realize that our growing prosperity to a large extent is the result of the precise formulation of hypotheses, testing these experimentally and using peer review to critically evaluate the results; in short the scientific approach. They tend to see the results of scientific research as just another opinion, one among the many that circulate on the Internet. Even politicians tend to negate scientific research, especially when the outcome is contrary to their vision and policy.

Genetic modification

The effect of this negative perception of the agricultural sciences is aptly illustrated by the chain of events surrounding genetic engineering, the genetic modification of plants and animals. After the Asilomar Conference in 1975, when guidelines were formulated to work safely with recombinant DNA, the debate about possible biohazards seemed to be over, but with the arrival of the first shiploads of genetically modified maize, in the mid-nineties it flared up again in full violence, at least in Europe. The environmental movement, the development NGOs and even a British pretender protested against the growing and use of these Frankenstein Foods[22].

Soon elsewhere in the world opposition arose against the cultivation and import of genetically modified crops. In India, for example Vandana Shiva has been conducting a twenty-year crusade against these 'seeds of the devil' the use of which will only lead to 'food totalitarianism'. A type of agriculture where a few large, global seed companies impose their model of large-scale, intensive monocultures to selected farmers, leaving those who cannot compete with the choice between poverty and suicide. In her books, articles and speeches she not only opposes genetic modification, but the Green Revolution as such, because it is wrecking the traditional way of life in India.

Although the claims of Vandana Shiva have been refuted several times[23], she has a large crowd supporting her, not only in Western Europe and North America, but also among the growing middle class in emerging countries. And – like in Europe – politicians are also afraid of public opinion and rather support a wide moratorium on genetically modified crops without weighing the benefits of this technology against the possible disadvantages, for instance in the case of disease resistance or the addition useful traits like salt and drought tolerance.

Dialogue

Social research shows that as controversies become severe, factual information is no longer relevant. New facts or insights, even if they come from peer-reviewed scientific research, are interpreted in a way that confirms the earlier position[24]. A scientist who says something about the Higgs boson or the Andromeda Galaxy will meet little suspicion, but an equally honest scientist highlighting the potential benefits of genetic modification to protect cassava and bananas against diseases is being considered as someone who is paid by large companies that want to push genetically modified food down our throats. Precisely this mechanism makes it difficult, if not impossible, to conduct a dialogue with opponents on the other side of the controversy.

The question is then how to actively involve civil society in the development of science and technology, so that not only the societal and political willingness to invest in scientific research will increase, but also the ability to assess the results of research? It is my opinion that a new green revolution is necessary to bridge the gap between agricultural science and society. On the one hand by challenging the public to try and assess their presumptions on the origins of their food and how it is produced and processed, for example by encouraging school gardens, allotments and other forms of urban agriculture. On the other hand by actively involving people in setting the research agenda and – where possible – taking part in research. And finally, by entering into a debate where people are queried about their values and assumptions and confronted with the inconsistencies between behaviour and attitudes. For example, that abundant and cheap food for everyone is not compatible with small-scale organic farming, where all the work is done by hand and the animals are hopping merrily in the meadow. Conversely, the public can confront researchers with the implicit values that are hidden in their research proposals and with the trade-offs and side effects of the solutions they propose.

The success of the Evergreen Revolution depends on our willingness to enter into dialogue with the community about the importance of science and technology for agriculture and food. We have to make it clear that science does not have all the answers and that mistakes will be made, but that it is the least bad way to learn about reality and use that knowledge for our benefit and that of future generations.

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