QUO VADIS
GLOBAL MEAT INDUSTRY
2050
Reporting from
the Frontiers of Science

Part 1
How to Feed the World in 2050
Four Resources and Innovation Driven Scenarios

June 2018
Discussion Paper

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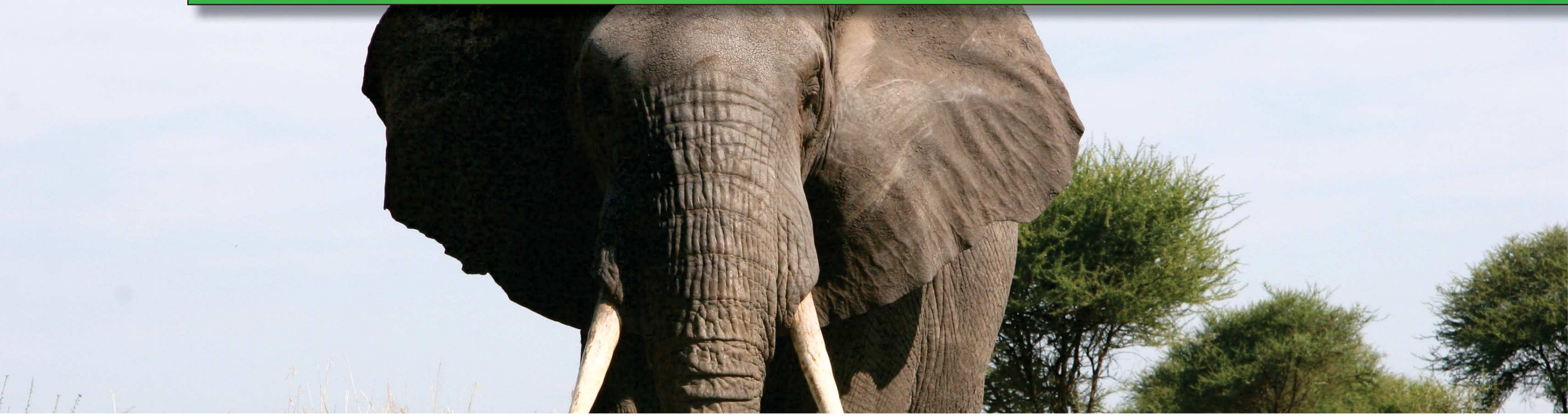

Quo Vadis Global Meat Industry 2050
The Challenge

> *The scourges of pestilence, famine, wars, and earthquakes have come to be regarded a blessing to overcrowded nations, since they serve to prune away the luxuriant growth of the human race*
> Tertullian, Historian of the Roman Empire, in *De Anima*, AD 209

The global meat industry is under pressure. Increasingly vocal civil society groups are calling for stringent curbs on meat consumption, and advocating for vegetarian and vegan lifestyles. In the affluent parts of the world, this movement is becoming mainstream. Regulators and governments are increasingly responding to these concerns. After tobacco and sugar, will meat become the third agricultural produce, whose consumption becomes socially disreputable, legally curtailed or even banned?

The argument against meat rests on four different, and largely unrelated, themes:

1. Today's global population is 7.5 billion people, growing to around 10 billion in the year 2050. Even today's level of human population can only be fed with substantial deployment of chemicals and technology on the fields. Agriculture is encroaching on natural habitats on every continent, threatening biodiversity and risking irretrievable extinction of species. The Cerrado and Amazon in Brazil or the tropical island of Borneo are prominent examples. Water shortages are a threat to humans and nature in many places. There are concerns that agriculture has already overstepped the limits of what planet Earth can produce on a sustainable basis, and even stronger concerns that these limits cannot support a further 60–70% expansion, which is estimated to be demanded by 10 billion people in 2050. Since the overwhelming majority of agricultural resources are used to feed animals in the livestock sector, a seemingly easy way to reduce the agricultural footprint would be to shift dietary patterns away from meat and towards plants. In this way, the agricultural production could be channelled directly towards plants. In this way, the agricultural production could be channelled directly to humans, instead of taking the indirect route via an animal's stomach.
2. Meat can only be obtained by killing and slaughtering a warm-blooded animal: the three most important ones being cattle, pigs and chickens. Also turkeys, goats, sheep and camels are important livestock animals raised for slaughter. Both the industrialized conditions of raising these animals, and the slaughter of these socially highly developed and complex animals, is seen to be cruel and lacking respect for the individual animals and the species, according to some animal rights advocacy groups. Out of respect for humanitarian values, and animal rights derived from these, animals should therefore not be slaughtered for the benefit of human consumption—thus is the argumentation.
3. Cattle in particular are also blamed for being a notable contributor to global warming. Their digestive system incorporates methane-producing bacteria to help them process their low-energy feed of grasses into high energy

nourishment. This methane is emitted via the cattle's mouths and might contribute to the global methane budget in the atmosphere. Methane is considered a potent greenhouse gas, and thereby the global herd of about 1.4 billion cattle is seen as a factor in global warming. Reducing the intake of cattle-related products, primarily beef and dairy, would therefore be a contribution towards slowing down global warming.

4. Red meat is suspected to cause colon cancer and, potentially, other diseases related to cholesterol levels. Though no causal relationships could be established so far, the World Health Organization rated the consumption of processed red meat as a IARC Group 1 health risk (meaning there would be sufficient evidence of carcinogenicity in humans, the same category in which also tobacco smoking and asbestos is listed). The consequence would be to lower the recommended levels of red meat levels.

This report analyses the future of the meat industry by looking at the veracity of each of the above claims. It is presented in four parts:

Part 1: How to Feed the World in 2050 – Four Resources and Innovation Driven Scenarios

Part 2: How Much Can Innovation Contribute to Improve the Efficiency and Animal Welfare of Food Protein Production?

Part 3: The Need to Clarify the Ethics of Meat

Part 4: Climate Change and Cancer – What the Numbers Say

The four parts will be published in four seperate papers in the course of 2018.

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Executive Summary – Quo Vadis Global Meat Industry 2050
Reporting from the Frontiers of Science

> *Men make history and not the other way around. In periods where there is no leadership, society stands still. Progress occurs when courageous, skillful leaders seize the opportunity to change things for the better.*
> Harry S Truman, President of the United States of America 1945–1953

The summary of the four parts of the entire report is:

Part 1: How to Feed the World in 2050 begins with the observation that the primary challenge of feeding the world in the year 2050 is concentrated on three population groups: sub-Saharan Africans, South Asians and children below the age of five years. These three groups suffer both in terms of quantity and quality of food already today, in particular by not having access to sufficient protein supply. Population growth from 7.5 today to 10 billion people in 2050 is mostly concentrated in Africa and South Asia, and will therefore aggravate this nutrition crisis further. A scenario analysis demonstrates that this need not be the case. Even with existing technology, and dietary preferences emphasizing livestock products of meat, dairy and egg for protein needs, there could be enough food production without needing more agricultural land than today. Recent new technologies would make the task even easier.

Even with existing technology, there could be enough food production without needing more agricultural land than today

By contrast, a reduction of the global meat industry will make the nutrition crisis of these three groups worse, not better. While becoming vegan or vegetarian may be an affordable luxury lifestyle choice for the most affluent 10% of the global population, it contributes little or nothing to the improvement of the already current nutritional crisis of children below five, sub-Saharan Africans or South Asians, let alone the future burden. On the contrary, these three population groups critically depend on the protein delivered by the livestock sector, and would be disproportionately hurt by a global reduction of the meat industry. The argument that a reduction of global meat production is necessary, or even only helpful, towards feeding 10 billion people within sustainable resource limits is therefore not correct.

A reduction of the global meat industry will make the nutrition crisis of these three groups worse, not better

Part 2: How Much Innovation Can Contribute aims to show, with a case study methodology, the potential impact of the advent of recent technological advances in genetics, genomics, robotics, sensorics and artificial intelligence. It argues that, with these advances, it will be possible to provide sufficient and nutritious food to 10 billion people in the world while significantly reducing the footprint of agriculture in terms of land utilization, water consumption and environmental burden. These technologies should be capable of overcoming the socio-economic hurdles that keep agricultural productivity depressed in African and Asian regions. The same technological advances will also enable the reduction or even elimination of animal's psychological stress or physical pain, and thus be able to improve the conditions of animal welfare to unprecedented levels. They will naturally not eliminate the ultimate need to kill an animal for meat consumption. The achievement of resource sustainability and of cruelty-free animal raising – to the degree that it has not yet been achieved – is therefore a function of speed and acceptance of technology.

With these advances, it will be possible to provide sufficient and nutritious food to 10 billion people

Part 3: The Need to Clarify the Ethics of Meat explores whether the deployment of these technologies requires the definition of an ethical position, and accountability for such ethics. Not everything that is allowed by the regulatory system is also acceptable to end consumers. Food is produced for consumption by humans, and for no other purpose. People increasingly demand the right to understand in what circumstances their food was produced, and be allowed to choose which of these circumstances they agree to for the food that is on their plate. Technology makes it possible to create such transparency. This might only be the first step. The second is for companies to define an ethical standard by which they want to conduct their business, and then use the transparency to create accountability against this standard. Companies that cannot make themselves accountable on their ethical position for food production circumstances may find it increasingly difficult to gain and maintain the trust of their final customer: the consumer who eats the food.

Companies that cannot make themselves accountable on their ethical position for food production circumstances may find it increasingly difficult to gain and maintain the trust of their final customer

Part 4: Climate Change and Cancer shows that the scientific evidence for either cattle contributing to global warming, or processed red meat causing cancer, is still much underdeveloped and contradictory. Much evidence to the contrary exists as well. Without more dedicated research, it is premature to make claims that cattle are a risk to the global climate, and that processed meat is a risk to human health.

It is premature to make claims that cattle are a risk to the global climate

Executive Summary – Part 1: How to Feed the World in 2050

The challenge of feeding the world in the year 2050 is fourfold:

1. already in the year 2018, the global food system does not feed its 7.5 billion people properly. 11% are hungry and every fourth child below the age of five years experiences stunting. At the same time, 39% of the global adult population is overweight and 13% is obese
2. the global population is expected to rise to around 10 billion people in the year 2050, an increase of 33% over today
3. the global population is expected to become more economically successful, which in the past has resulted in demand for more resource-intensive foods, in particular meat, dairy and eggs
4. The global food production system may be at, or already beyond, the limits of sustainability with its current level of resource utilization in terms of land and water

Food and Agriculture Organization (FAO) calculated that about 60% more food needs to be produced in the year 2050

Totalling these effects, prominent researchers at the Food and Agriculture Organization (FAO) calculated that about 60% more food needs to be produced in the year 2050 versus the base year of 2007. With only minor variations, this number is mostly agreed to by the scientific community.

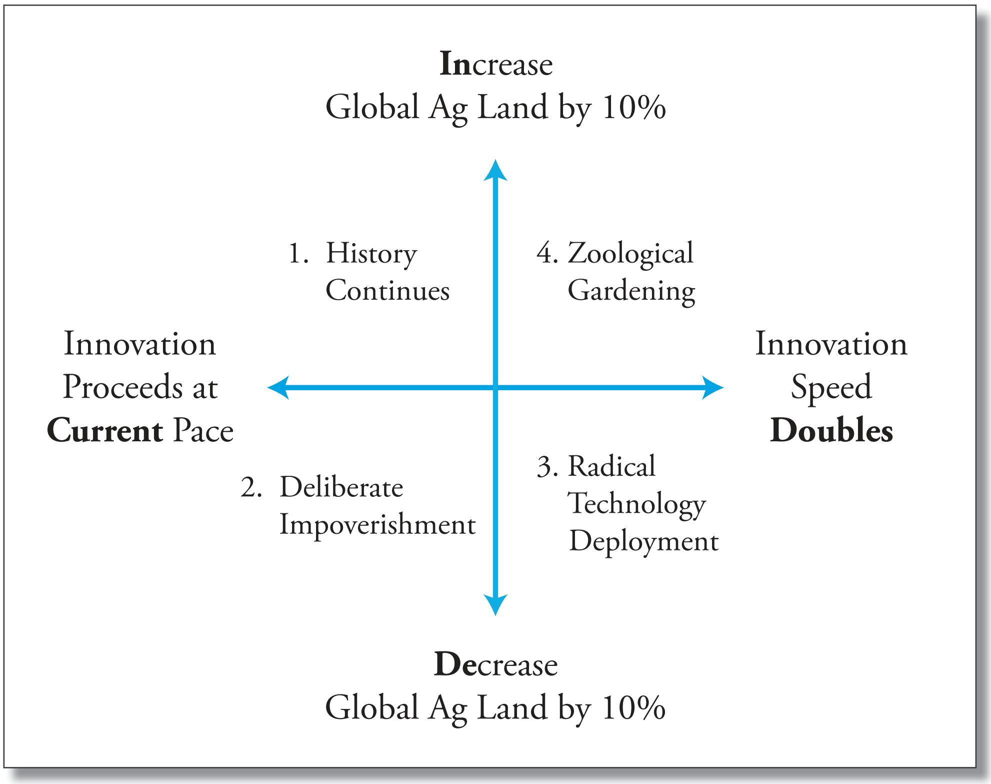
The challenge can, in principle, be met in three different ways:

1. increase the utilization of natural resources, particularly land and water, ignoring potential sustainability limits
2. increase productivity in food production and thus make better use of the resources
3. change the composition of diets in such a way as to need less of the natural resources, in particular this means reducing the consumption of meat, which is resource-intensive

The analysis in this report captures those three options by describing four different scenarios. By numerically defining the dimension of resource utilization with the proxy of amount of global agricultural land, and the dimension of innovativeness with the proxy of yield growth, the four resulting scenarios are 1. History Continues; 2. Deliberate Impoverishment; 3. Radical Technology Deployment; 4. Zoological Gardening.

This would result in the irreversible destruction of the last remnants of large scale tropical pristine biospheres on Earth.

The analysis shows that in the **first scenario of History Continues**, it will be possible to feed 10 billion people by the year 2050 with sufficient food. However, this would require an expansion of agricultural land by 28% over today's levels. Most of this land would be converted in the tropical and subtropical belts of currently pristine nature: in Brazilian Cerrado and Amazon, in the African central jungles, and in Indonesia. This would result in the irreversible destruction of the last remnants of large scale tropical pristine biospheres on Earth.



The **second scenario of Deliberate Impoverishment** aims to reduce the need for natural resources by radically curtailing the availability of red meat to the global consumer. On a global scale this would be possible. If the global average citizen can be convinced to drastically reduce consumption of red meat, then everybody would have enough to eat, with no expansion of utilization of natural resources necessary. Versus today's lifestyle standards this would be a deliberate impoverishment. However, the world does not consist of average citizens. 80% of the additional food required by 2050 will be needed in Africa and South Asia, which are today already net importers of food. In this scenario, by 2050, even more of the agricultural production would be occurring in South and North America, while it is needed in Africa and South Asia. It is difficult to conceive how Africa can afford the financial means to import food on such a large scale. Even for South Asia it would be a burden and brake on its economic development. The three population groups which are most at risk are children, the elderly and the poor. Slowing down economic growth in Africa and South Asia will keep these three groups longer in poverty, and therefore at risk. Furthermore, food import dependency will make food relatively more expensive in the terms of trade for such countries, thereby exacerbating food affordability problems and making the three risk groups even more vulnerable. In sum, this scenario does not reflect the rules of economic reality. If the affluent part of the world agrees to eat less meat, this will reduce the agricultural footprint in the Americas and Europe, but it will not contribute to putting more and better food in front of undernourished children in Africa and South Asia.

This scenario does not reflect the rules of economic reality

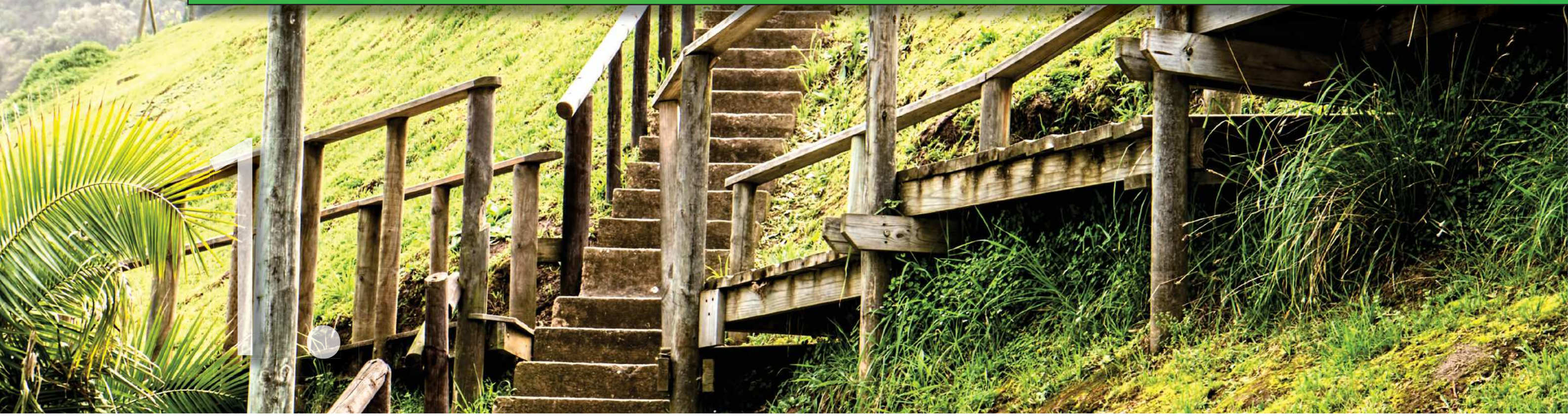
The **third scenario banks on Radical Technology Deployment**. If all known yield and technology gaps would be closed, especially in Africa, then the world would easily produce enough food to feed 10 billion people and more. Agricultural land could be retired and returned to nature. However, there are highly complex socio-economic hurdles to overcome for the yield gaps to be closed. The aspiration is that new technologies in communication, data science and robotization can help in closing the yield gaps better than efforts in the past could achieve.

If all known yield and technology gaps would be closed, especially in Africa, then the world would easily produce enough food to feed 10 billion people and more

The **fourth scenario of Zoological Gardening** is at best reserved for the 10% most affluent population in the world, mostly residing in North America and Europe. Thanks to its already high levels of agricultural productivity and almost no expansion of food demand until 2050, these regions can afford to deliberately reduce agricultural productivity and pursue quasi-zoological practices such as organic farming methods or staging cattle on Swiss mountains for attracting tourists. Such methods can be an affordable luxury for the affluent with aesthetic effects, but it does not contribute a solution to feeding the world at large.

The overall conclusion is that there are no easy choices. There are many serious challenges to be overcome to deploy technology on a sufficiently radical scale, to accelerate harvest yields fast enough, to be able to feed the world in the year 2050. But it is the only viable option that does not lead to tragic other circumstances. The scenario incorporating deliberate and severe reduction of global red meat consumption is not economically viable, despite first appearances. New economics and new people fitting such economics would first need to be created. The 20th century has shown several times, that attempts of large scale socio-economic engineering to change societies, people and economics, leads to tragic outcomes. On the other hand, the scenario of business as usual will destroy the last great pristine biodiversity habitats of Earth. Historically, the most successful method to solve a resource crisis has been deployment of technology. Such technologies exist, and get better by the day. What is missing is the social, political and ethical mandate to make full use of these technologies. That will be subject and consideration of Part 2 of this report.

Historically, the most successful method to solve a resource crisis has been deployment of technology



The Need for Scenarios

Every analysis about the future of food and agriculture begins with the realization that planet Earth will soon have to feed 10 billion people, that land and water is already scarce, and that therefore we – humanity – need to change our ways if we want to leave a habitable world to the next generations. Where opinions differ is what exactly needs to change.

The future is never a linear extension of today's circumstances. For this reason, predictions about the future have been wrong since antiquity, and will continue to be so. Neither has Malthusian pessimism so far materialized, nor have the hopes of Tertullian in 209 AD come true that the growth of population would be curtailed by disease and hunger. Instead, the human race keeps on growing by numbers and size. The underestimated force preventing the anticipated catastrophies is the degree and speed by which humanity can innovate itself out of existential crises.

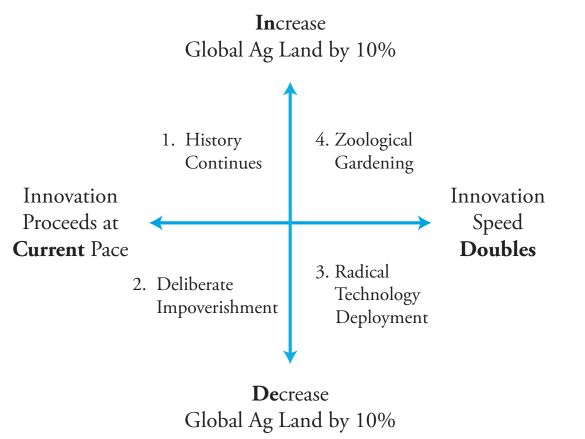
A discussion about the future of food and agribusiness should therefore incorporate a dimension of how much innovation becomes deployed, and how much innovation can achieve.

From the point of view of economics, there are two main levers for accomplishing and mastering growth (of food production in order to feed the world): either increase productivity or increase the resources. The second dimension should therefore be describing how many resources are utilized.

Plotted into a matrix, these two dimensions create four different scenarios and story lines, each combining either low or high levels of innovation, or low or high levels of resource utilization. In this report the four scenarios and story lines are called:

- History Continues
- Deliberate Impoverishment
- Radical Technology Deployment
- Zoological Gardening

Exhibit 1 Two dimensions and four scenarios



For the purpose of this report, the end points of the four coordinates have numerical values, which allows each scenario to be numerically analysed:

Innovation Dynamics

- Left end of Innovation Dynamics: is the 50-year trending rate of yield increases in agriculture for the four major crops of maize, rice, wheat and soybeans. These were calculated by Ray *et al.* in 2012 to have been respectively 1.6%, 1.0%, 0.9%, and 1.3% per year at a non-compounding rate[1], equal to 64%, 40%, 36% and 52% over the 40-year period between 2011 and 2050, or on a non-weighted average basis: 48% (non-compounding average of 1.2%).

- Right end of Innovation Dynamics: Increasing the global yield by 100% until 2050. This would require a doubling of the long term historic yield growth to 2.5% per year non-compounded. It would in consequence also double the total agricultural output by the year 2050, over 2011 output with the same resource intensity.

The achievement of yields for crops is used as a proxy for the degree of innovativeness and technology deployed in this dimension. Ultimately, most technologies will in one way or the other result in improved yields. The improvement of processing technologies or cultural behaviours can also contribute to a better or worse food situation in the future. In particular, reducing the rate of wasting circa 30% of all food produced, with the help of technologies or changed behaviours, can be a significant contribution and productivity improvement. Innovation achievements of this sort shall also be represented by the innovation dimension.

Resource Utilization

- Top end of resource utilization: Increase the total global amount of crop land and pasture land by 10% by 2050, which is approximately the rate by which it increased between the years 1960 and 2010.[2]
- Bottom end of resource utilization: Reduce the total amount of crop land and pasture land by 10%, and return this surplus land to natural biodiversity and human recreational purposes by 2050.

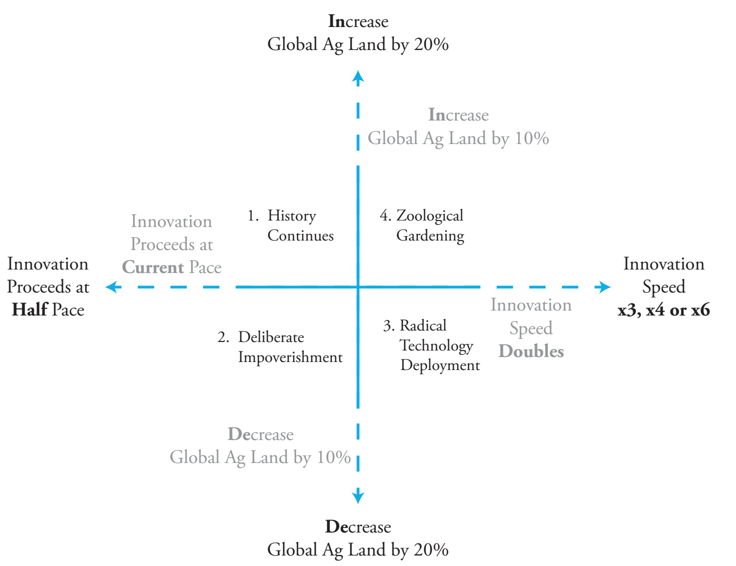
Agricultural land utilization is used as a proxy for resource utilization. Other resources are similarly precious and worthy of consideration, in particular water. Their expanded or decreased utilization shall be proxied by land utilization for the purpose of the four scenarios in this report.

Each of the four coordinates could also be considered to have plausible hyper-extreme endings:

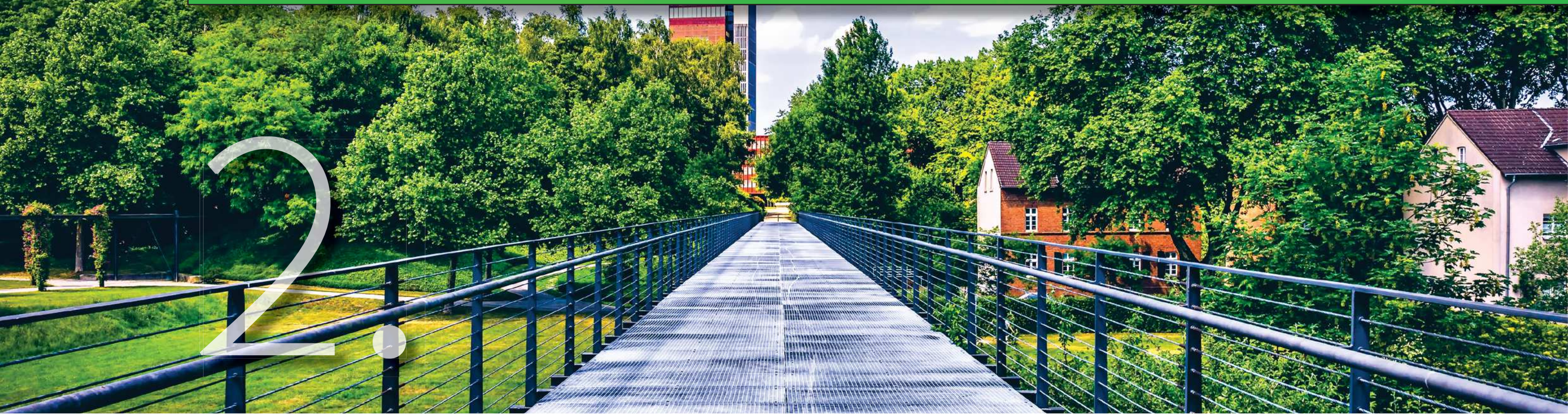
- Left extreme of Innovation Dynamics: due to an end to the technology race, yield increases may be half of the past experience, or stagnate altogether
- Right extreme of Innovation Dynamics: all known yield gaps by crop and region can be closed, leading to 3x, 4x or even 6x increases of output in today's poor productivity regions
- Top extreme of Resource Utilization: Double the historical speed of loss of natural habitat and expand agricultural area by 20% by 2050 (vs 2011).
- Bottom extreme of Resource Utilization: Return land to nature that was pristine until around the year 1900, by reducing agricultural land by 20% (vs 2011).

The hyper end points will only make the four resulting scenarios more extreme, but do not add deeper quality to the analysis.

Exhibit 2: Four realistic end points and four hyper end points



[1] Ray, D. K., Mueller, N. D., West, P. C. & Foley, J. A. Yield Trends Are Insufficient to Double Global Crop Production by 2050. PLoS One 8, (2013).
[2] Worldbank interactive data website, based on data provided to FAO: https://data.worldbank.org/indicator/AG.LND.AGRI.K2?end=2015&start=1961&view=chart



The Starting Point (referenced to circa 2009 - 2011)

Any scenario for the year 2050 is primarily influenced by four parameters: i) human diet composition, ii) land utilization, iii) biomass flows and iv) yield improvements. To understand the four future scenarios of whereto the world might develop, it is necessary to describe the current starting point with some of the most recently available numbers.

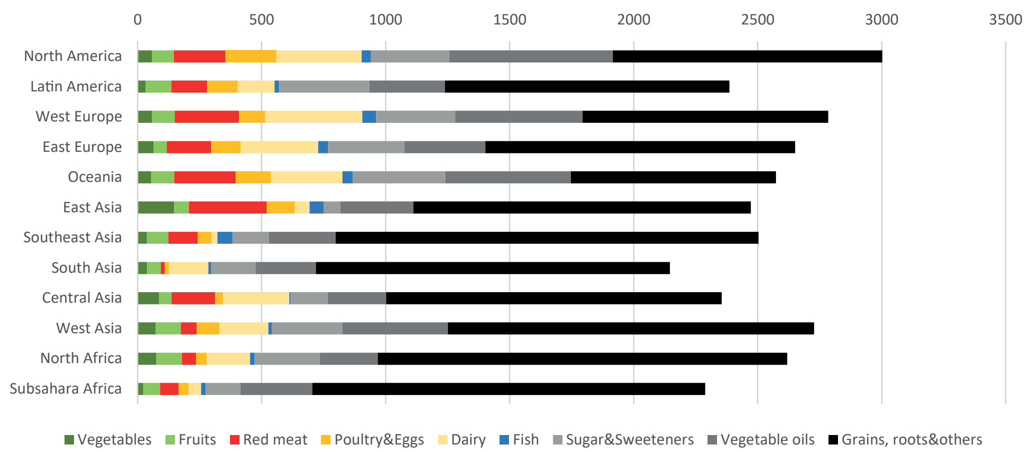
1. The Global Human Diet

The global diet in the year 2009, according to Food Balance Sheets by FAO, and as analysed by a team of University of Cambridge scientists around Bajzelj *et al*[3], can be shown by both region and food group.

Some aspects in these global diets are especially noteworthy:

a) Despite rapid growth, fish still represents only a negligible part of the global nutrition picture
b) In the global food diet, poultry meat and eggs contribute only a little bit more than half ofthe food energy contributed by red meat. This is despite poultry production requiring less resources, and accordingly being a more efficient source of protein

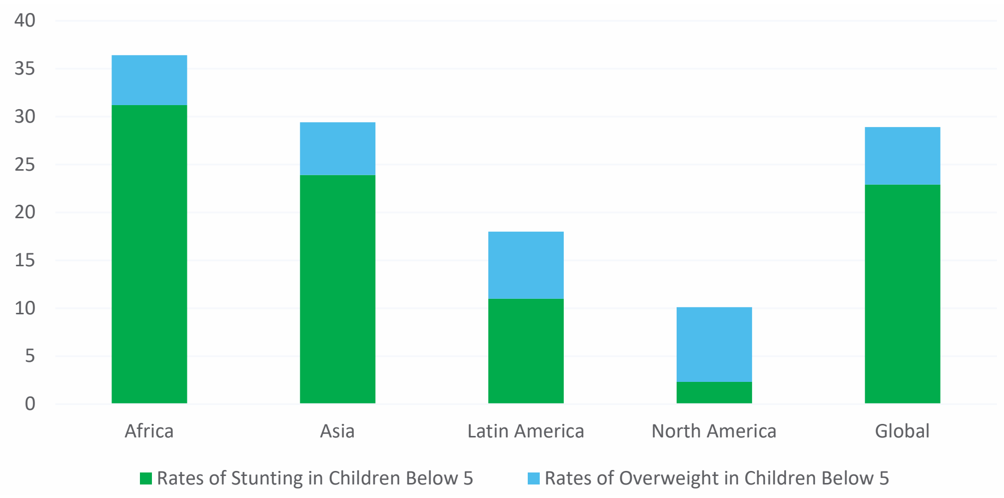
Exhibit 3 The global diet by food group and region in 2009



[3] Bajželj B, Richards KS, Allwood JM *et al.* (2014) Importance of food-demand management for climate mitigation. Nat Clim Change 4, 924–929. doi:10.1038/nclimate2353

c) The East Asians, i.e. the 1.6 billion people living in China, Korea and Japan, have the healthiest diet in terms of eating the highest amount of vegetables (more than 3x the global non-East Asian average), and the least amount of sugar (around 70% less than the global non-East Asian average). The East-Asians also consume the highest amount of red meat (50% more than North Americans, 20% more than West Europeans), and with an average of 2500 kcal per day they are also sufficiently nourished
d) The North Americans and West Europeans are over-nourished with 3000 kcal and 2800 kcal per day respectively. The main differences to the global average diet are a much higher than average consumption of vegetable oils and dairy products
e) The World Health Organization (WHO) recommends that people obtain less than 5% of the total energy intake from sugars.[4] The global average is 9.3%, with Latin America even reaching 15%. Since sugars have no nutritional value besides supplying energy, strong reduction of sugars would go a long way to solve the over-nourishment problem in many parts of the world
f) Even the two regions with the least amount of daily nutrition, South Asia and sub-Sahara Africa, reach on average circa the recommended threshold of 2300 kcal per day (2600 kcal for a moderately active male, 2000 kcal for a moderately active female, aged 26-45)[5]. However, the nutritional quality composition is poor with less than 300 kcal per day stemming from vegetables, fruits and proteins. Furthermore, the wide income disparity in these two regions also indicates that an average sufficient supply automatically means that the median supply is insufficient and that severe undernourishment is still prevalent at the bottom end of the society. Thus for a significant portion of the approximately 2.9 billion people that live in these two macro regions, making up around 40% of the global population today, undernourishment is still a health hazard and inhibits quality of life. In its latest estimate from January 2018, UNICEF estimates that around 35% of all children below the age of five years in South Asia and sub-Sahara Africa experience stunted growth due to undernutrition.[6] Globally, it is 23% of all children below five. In its 2017 report on food security[7], FAO reports that hunger is on the rise again, after a steady decline for about a decade. Currently 815 million people are undernourished, 11% of the global population.

Exhibit 4 Global prevalence of stunting and overweight in children below five



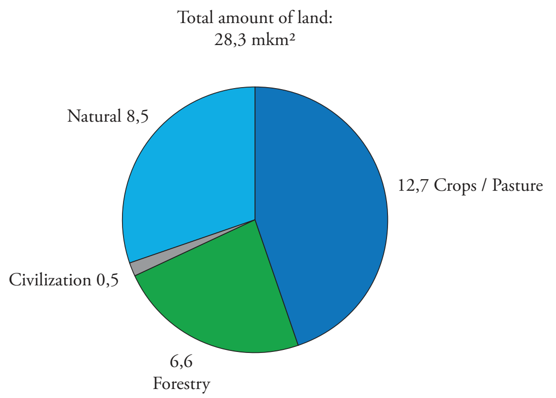
[5] Center for Nutrition Policy and Promotion at the US Department of Agriculture
[6] https://data.unicef.org/topic/nutrition/malnutrition/
[7] http://www.fao.org/state-of-food-security-nutrition/en/

2. Global Land Utilization[8]

Excluding the arctic zones, the earth has 130 million km2 (mkm²) of land available (150 if Antarctica, Greenland and Arctic Canada are included).[9] Of this total amount of land, 28.3 mkm² could be prime excellent agricultural land. Out of these 28.3, humanity is using 12.7 for either crops or pasture, 6.6 for forestry, 0.5 for civilization (settlements, roads and factories) and 8.5 are left natural.

Exhibit 5 a)

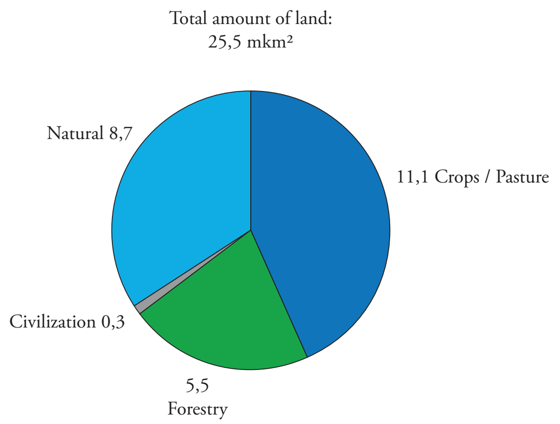
Utilization of prime agricultural land globally



A further 25.5 mkm² is good, suitable agricultural land. Of this amount, 11.1 is used for crops or pasture, 5.5 for forestry, 0.3 for civilization, and 8.7 are left natural.

Exhibit 5 b)

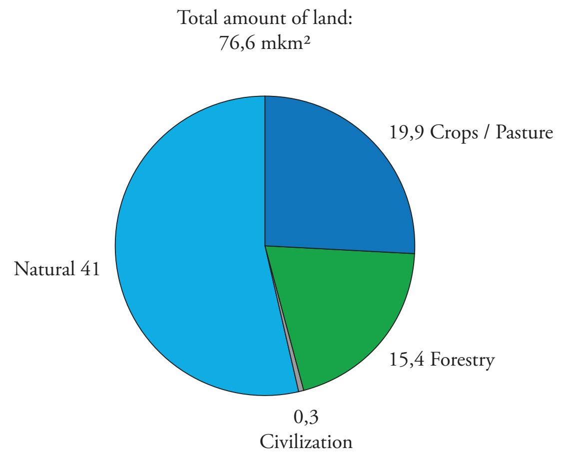
Utilization of suitable agricultural land globally



Out of the 76.6 mkm² of agriculturally unsuitable land, humanity is nonetheless using 19.9 for either crops or pasture, 15.4 for forestry, 0.3 for civilization and 41 are left natural.

Exhibit 5 c)

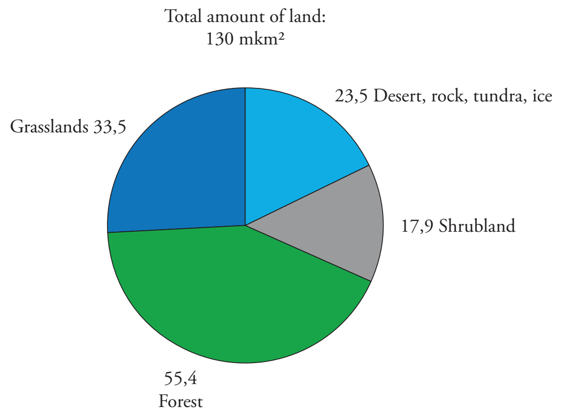
Utilization of agriculturally unsuitable land globally



A different slicing of the data is by original biome: 23.5 mkm² of land are desert, rock, tundra or ice, 17.9 are shrubland, 55.4 are forests and 33.5 are grasslands. From these different lands, humanity uses 1.1 for civilization, 15.6 for cropping and 32.8 for pasture lands.

Exhibit 6

Original Biome of Global Land



[8] All data in this section derived from GAEZ v3.0 of FAO and IIASA as analyzed by Bajželj *et al*

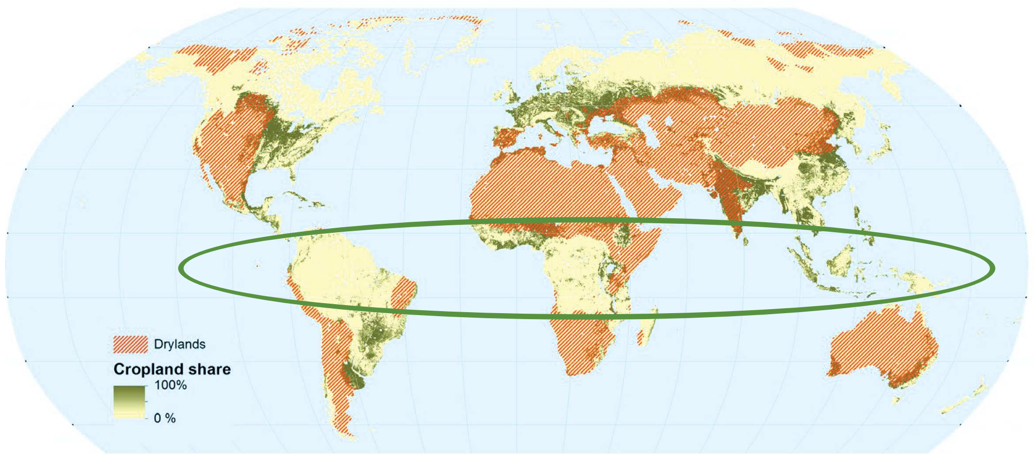
[9] 1 km² equals 100 hectare; therefore 1 million km² equal 100 million hectares

According to the above numbers, in theory, there seem to be 8.5 mkm² of prime and 8.7 mkm² of good agricultural land still available for utilization, which so far is left to nature: a total of 17.2 mkm². This is more than the total amount of cropland in the world today (the 15.6 mkm² reported above). So crop land area could still be doubled. In practice, almost the entirety of this land is situated in the tropical belt of central Africa in countries such as Congo or South Sudan, in the South American Amazon and Cerrado, or in the Southeast Asian tropical islands of Indonesia and Malaysia. Ploughing under these areas will destroy, without chance of recovery, these global lungs of tropical forest and biodiversity habitats.

Of these 20.5 petagrams C of net primary productivity potential, circa 6 petagrams C are not available due to erosion or cropping systems that do not make full use of the year-round potential of the land[12]. At the same time, fertilization and irrigation adds 4.3 petagrams C of production, resulting in a net total biomass production of 18.7 petagrams C via agriculture. (For comparison, the combined weight of the human population is 0.41 petagram, of which 18.5% is carbon weight, so the human population has a global biomass weight of 0.076 petagram C)[13]

Of these 18.7 petagrams C produced, 2.4 are useable crops, 2.0 are crop residues and 2.7 are forage, for a total of 7.1 useable biomass inputs into the human food chain. Of the other 11.6 petagrams C, about 1.0 is lost due to pests and weeds, 7.5 are roots and 3.1 are either ungrazed or other plants. These 11.6 are not waste as they will typically be recycled back into the next growing season (unless they are burnt or left to rot, in which case the recycling via the atmosphere will take longer).

Exhibit 7 Land belt where suitable cropland is not yet utilized



Source: UNCCD Global Land Outlook: Food Security and Agriculture, p130

3. Global Biomass Generation and Utilization[10]

The University of Cambridge team around Bajželj *et al*. also calculated current biomass flows in agriculture. The 15.6 mkm² of croplands can produce 9.5 petagrams of carbon content (C) biomass per year (1 petagram = 1,000,000,000,000 kilogram). The 32.8 mkm² of pasture lands produce 11 petagrams of C biomass per year.[11]

[10] All data in this section is taken from the analysis of Bajželj *et al*, if not otherwise referenced

[11] Bajželj explains that in the model the contribution from subsistence farming is likely to be underrepresented, and food sourced from aquatic systems or forests is excluded. Both omissions are minimal in effect.

[12] Bajželj writes in her article that the team's modelling calculations are a transparent, data-based biophysical analysis. While she has provided substantial supplementary material, unfortunately the text sometimes mentions slightly different numbers than are explained in the graphics, and these again are slightly different from the Excel calculation tables supplied. It is therefore not clear which are the actually calculated numbers. For instance, the text mentions that 5 petagrams of C would be lost due to erosion and timing, however the exhibit and its numbers suggest it should be 6. Nonetheless, despite some of these small inconsistencies in documentation, her modelling work is the most comprehensive analysis undertaken so far on the basis of biomass numbers, incorporating the most detailed inclusion of drivers.

[13] Own calculation: 7.55 billion people x average weight of 54 kg x 18.5% carbon content

Out of the 2.4 petagrams C useable crops, 0.3 become food directly to the consumer, 0.7 go into food processing, 1.1 become feed for livestock, 0.1 become fuel, 0.2 are lost as agricultural waste (8% of the respective biomass flow), and a miniscule amount is used as seeds.

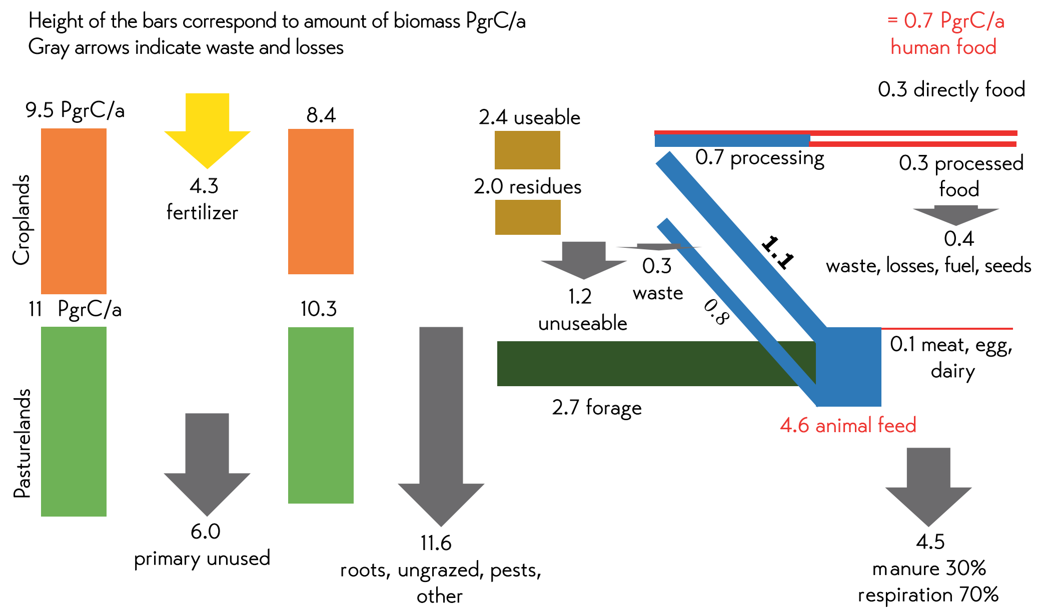
Out of the 0.7 petagram C at the processing stage, 0.06 are lost as waste (8% of the respective biomass flow), some processed foods go into animal feed, some into fuels and some are transformed, so that the consumer finally receives 0.3 of the processed foods on the table.

The global consumer receives 0.7 petagram C biomass, or 2490 kcal per person globally. Of this, another 0.08 is lost in the hands of the consumer before it reaches the stomach (12% of the respective biomass flow). Compared to the above number of the global weight of the human population, this indicates that humanity eats around eight times its C biomass weight per year.

Livestock consumes 4.6 petagrams C as feed. This is composed of 2.7 forage material from the pastures, 1.1 of feed from the crops, and 0.8 from crop residues. This 4.6 petagrams C of inputs is converted into 0.12 petagram of C (= 410 kcal per global person) of final food in the form of meat, eggs and dairy products. Thus only 2.6% of the carbon mass entering the livestock sector becomes food reaching the consumer. The other 97.4% become one third manure, and two thirds respiration, (exhaled CO2). While the 2.6% represents 17% of the C biomass on the human table (0.12 / 0.7), it represents a much larger share of the nutritional value of the total diet due to its richness of micronutrients, amino acids and longer-lasting-effect energy reservoir.

According to Bajželj *et al.*, only about 14% of pasture land would be unsuitable for cropping. In theory therefore, the other 86% could become crop land and produce crops that are directly consumable by people rather than being fed to animals.

Exhibit 8 Global agriculture biomass flow chart (from left to right)



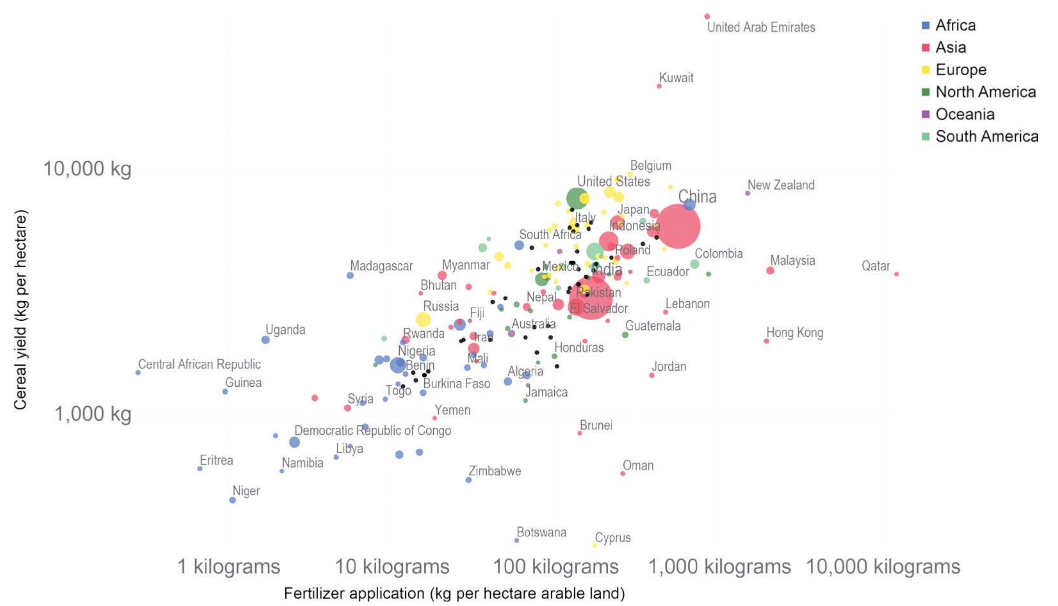
[14] Ray, D. K., Mueller, N. D., West, P. C. & Foley, J. A. Yield Trends Are Insufficient to Double Global Crop Production by 2050. PLoS One 8, (2013).

4. Global Yields by Main Crops and Regions

The fourth starting point for considering the future of 2050, is the current situation of yields and historical trends in yield improvements. Yields for crops are widely diverging around the world. This is the result of many factors, including soil quality, climate, availability of agronomic knowhow, quality of inputs, availability of finance, degree of mechanization—to name the most important. Even with the same rate of fertilizer application, yields can be dramatically different, as World Bank data demonstrates.

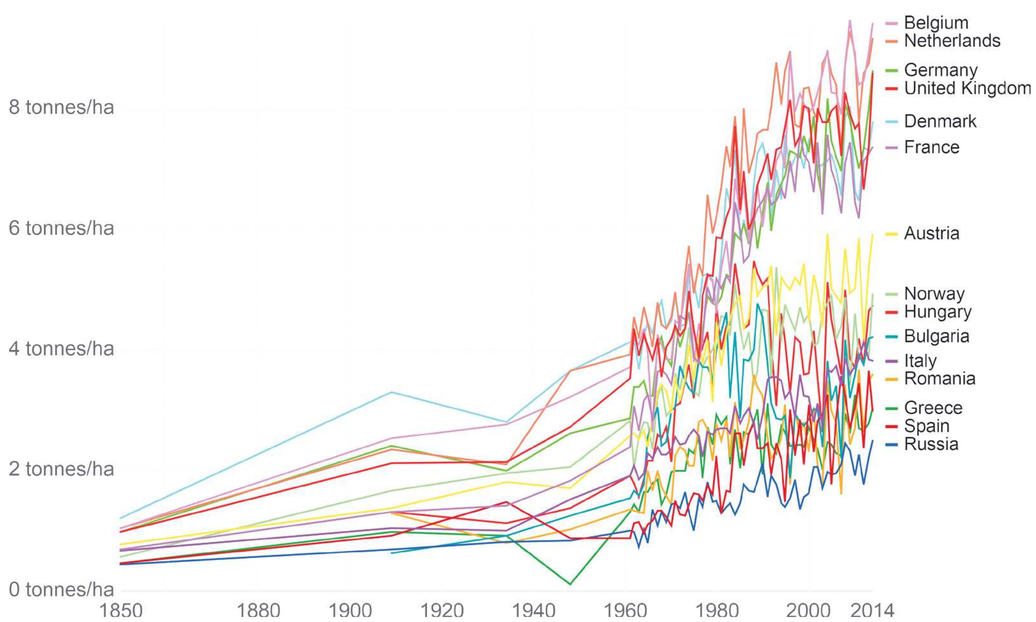
Also the growth of yields has been different, even within advanced agricultural nations. The long term growth of yield for wheat in Europe reveals two groups of countries with dual speeds of improvements over the past 50 years.

Exhibit 9 Cereal crop yield by country and fertilizer application



Source: World Bank, graphic by Our World in Data

Exhibit 10 Long term wheat yield in Europe



Source: FAO, graphic by Our World in Data

Ray *et al.* calculated the global average of yield improvements for the four major crops of maize, rice, wheat and soybeans by collecting 2.5 million data points from 13,500 political units over the past 50 years. The results were respectively 1.6%, 1.0%, 0.9%, and 1.3% per year at a non-compounding rate[14]. If these rates are extrapolated into the future, they equal 64%, 40%, 36% and 52% over the 40-year period between 2011 and 2050.

Using FAOSTAT data for the year 2009 and the historical rates of yield improvements as provided by Ray *et al.*, Bajželj *et al.* calculate the yields for major crops for 2009 and as a continuation of current trends in 2050.

Exhibit 11 Major crop yields by macro regions in 2009, in tonnes/ha

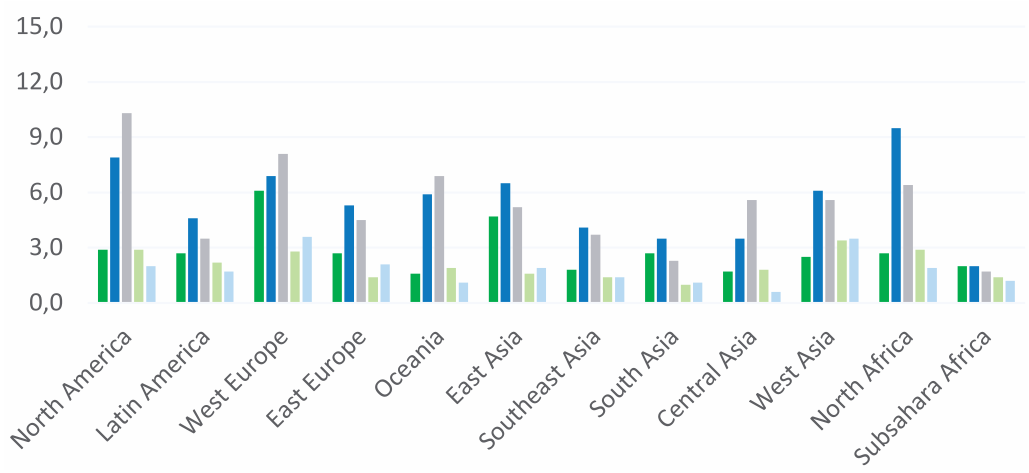
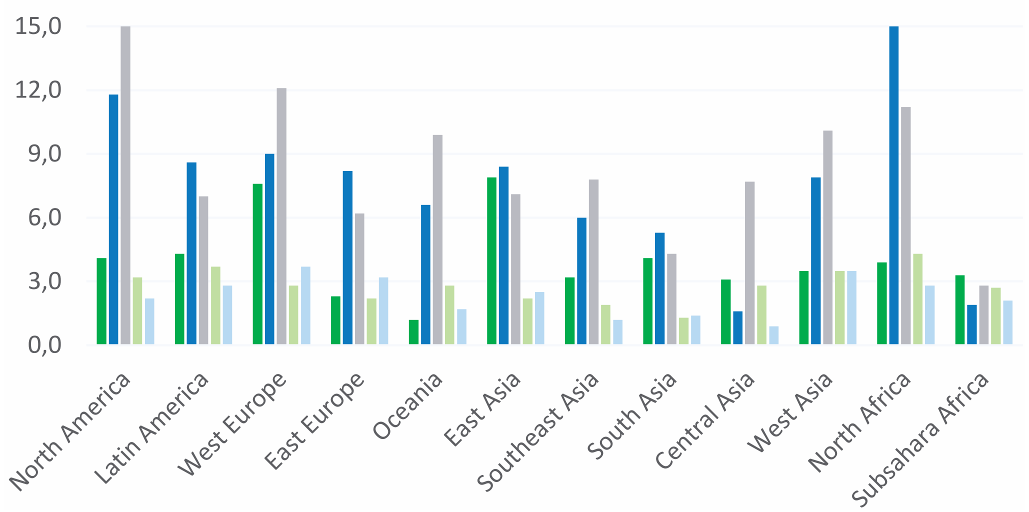


Exhibit 12 Major crop yields by macro regions in 2050 at current trends, in tonnes/ha



[14] Ray, D. K., Mueller, N. D., West, P. C. & Foley, J. A. Yield Trends Are Insufficient to Double Global Crop Production by 2050. PLoS One 8, (2013).

How much more food is required?

Due to the prominence of the subject of *How to Feed the World in the Year 2050* several high profile forecasting exercises have been undertaken by a number of research groups. Despite appearances to the contrary, they differ relatively little in their basic analytical assumptions and scale of the challenge to feed the world in 2050.

The first well recognized long term forecasts to 2050 were undertaken by Alexandros and Bruinsma for FAO during the 2000s. One such widely quoted report was published at FAO by these two authors in 2006. A subsequent 2009 revision suggested that food production would need to increase by 70% until 2050, which remains a widely quoted figure even today. However, in a 2012 revision, this number was reduced to 60%, which was primarily driven by the fact that the production data for the reference years 2005–2007 had been revised upwards (thus closing the gap until 2050).[15] Nonetheless, as the authors observed, the 70% number took on a life on its own and keeps on being used in popular discourse.

This 2012 revision with its 60% number is widely considered the most authoritative forecast so far and is, indirectly via the calculations of Bajželj *et al.*, also the basis for this report. More recent forecasting efforts could take into account a more recent base year, e.g. 2016, instead of 2006. This would reduce the additional food necessary by 2050, simply because the base year would have shifted ten years later and so part of the effort would already have been accomplished. On the other hand, there has been a continuous rise in the estimated population in sub-Sahara Africa for the year 2050. In the United Nations 2002 revision, the sub-Saharan population was expected to reach 1.557 billion people by 2050. In the 2010 revision this number had increased to 1.960 billion people. In the most recent revision, 2017, this number increased to 2.167 billion. These increases are driven by improving health outcomes experienced by African populations and what appears to be more precise census taking in recent years. The two effects broadly cancel each other: while a later reference year reduces the required food production increase, the rising African population in the target year 2050, increases that amount again.

In their paper, Alexandros & Bruinsma point out: *We hasten to add that the percent increase in the aggregate volume is not a very meaningful indicator.*[16] With that statement the authors refer to the fact that their 60% number refers to tonnage of agricultural production, which lumps together many starkly different agricultural commodities. In a different, often cited study by Tilman *et al.* in 2011, the conclusion was that the amount of food production would need to be approximately doubled by 2050.[17] Their unit was kcal of food produced instead of tonnage. While not directly comparable, this is broadly the same number as by Alexandros & Bruinsma, because the over-proportional increase of meat production requires a similarly over-proportional larger production of feed calories, and therefore a higher necessary increase is to be expected when measuring the increase in kcal rather than tonnage. But this is just a change in units of measurement, not in substance of the challenge. The unit that is the basis of the calculations for this report is biomass flows as measured by carbon content as modelled by Bajželj *et al.*

A more recent analysis undertaken by Bijl *et al.* in 2017, concludes: *In summary, our new approach yields results close to FAO 2012 projections and within the range of other model projections, although the method*

[15] Alexandratos, N. and J. Bruinsma. 2012. World agriculture towards 2030/2050: the 2012 revision. ESA Working paper No. 12-03. Rome, FAO

[16] Alexandratos, N. and J. Bruinsma. 2012. World agriculture towards 2030/2050: the 2012 revision. ESA Working paper No. 12-03. Rome, FAO, p 7

[17] Tilman D. *et al*: Global food demand and the sustainable intensification of agriculture; Proceedings of the National Academy of Sciences Dec 2011, 108 (50) 20260-20264; DOI: 10.1073/pnas.1116437108

[18] Bijl DL, PW Bogaart, SC Dekker, E Stehfest, BJM de Vries, DP van Vuuren (2017) A physically-based model of long-term food demand. Global Environmental Change 45, p 55

is quite different.[18] With that Bijl *et al.* confirm again that among the mainstream scientific community, the scale of the challenge is broadly commonly understood and consensual.

Many details of these extrapolations can be questioned, for instance will East Asians expand their red meat consumption by another 50% vs 2009? Will Africa's economic growth be as high as forecast and thus triple GDP per capita between 2010 and 2050, and triple their population, thus in total increase its GDP by a factor of 9? The answer to these projections cannot be known. The purpose of the projections is not to be able to know the future, but to compare different outcomes of extrapolating different sets of historic trends. Independent of such modelling details, the general thrust nonetheless remains the same across most forecasts: food consumption will increase over-proportionally faster than the rise in population, namely almost two times faster.

No study could be identified for this report in which the role of pet food was included in a global model of biomass flows and required agricultural production. This is not a negligible factor. In the United States, the food energy fed to cats and dogs reaches 19% of the amount of the food energy delivered to humans, and 33% of all animal derived energy.[19] US cats and dogs produce 30% as much faeces as the US human population, with the difference that the environmental impact of human faeces are typically neutralized by sewage plants, and that of pets typically not. Household penetration with pets is not as high in Europe as in the US, but not far behind. Keeping pets is strongly on the rise in China. There are already more than 100 million pet dogs in Chinese households, 50% more than in the US. Estimates vary widely, but it could be that the global pet dog and pet cat population is about 500 million animals each, of which about a third are living in the USA. Extrapolating these numbers indicates that 3% of the global food supply may be used to feed pets. This would be the equivalent to the entire food consumption of North Africa, or circa 200 million people. Of all the uses for food, the pet food sector has the fastest growth rates.

Another factor that could potentially make large differences for agricultural scenarios is the amount of biofuel production. The scenarios by Bajželj *et al.*, but also by other researchers, typically assume today's levels of biofuel production will remain largely as they are. For instance, the forecast by Alexandratos & Bruinsma in their 2012 revision assumes that biofuels will consume a mostly unchanged 180 million tonnes of grains per year, out of a total of 3 billion tonnes of grains worldwide in 2050.[20] Due to the large size of the global fuel market, even a minor change in biofuel production can make a large difference to the demand for agricultural production.

[18] Bijl DL, PW Bogaart, SC Dekker, E Stehfest, BJM de Vries, DP van Vuuren (2017) A physically-based model of long-term food demand. Global Environmental Change 45, p 55

[19] Okin G: Environmental impacts of food consumption by dogs and cats, in PLOS One, 2017 https://doi.org/10.1371/journal.pone.0181301

[20] Alexandratos, N. and J. Bruinsma. 2012. World agriculture towards 2030/2050: the 2012 revision. ESA Working paper No. 12-03. Rome, FAO, p 65

Changing the Parameters for Four Scenarios

The First Scenario: History Continues until 2050

The first scenario describes the linear extension of current trends in productivity and diets. This means it assumes that productivity improvements continue at the same pace as in the past, that dietary developments continue in the same way as in the past, and that population growth happens as forecast by the United Nations. It is therefore called History Continues.

The analytical model of Bajželj *et al.* calculates the change in global land utilization if history continues as it did for the past 40 years until the year 2050. This means primarily three dynamics:

a) Population will increase according to the United Nations medium scenario. In Bajželj's analysis this means it would increase from a 2010 level of 6.96 billion persons to an estimated level of 9.6 billion as per the 2013 UN Revision of World Population Prospects. (In the 2017 UN Revision the figures are respectively 7.55 billion for 2017 and 9.77 for 2050.)

b) Yield improvements for the major crops would continue at the same pace as calculated by above mentioned Ray *et al.* since 1960. Some assumptions were also made for increasing stocking densities of animals.

c) In line with expected per capita economic growth forecasts, the global population increases its food consumption by both quantity and quality in so-called socio-economic transitions. The standard reference work for these forecasts is also the FAO 2012 revision of World Agriculture 2030/2050 by Alexandratos & Bruinsma.[21] In line with their analyses, calculations for this report show that these transitions mean that the global average consumption increases from 2490 kcal to 2710 kcal per person, and that the livestock portion increases from 410 kcal to 470 kcal. Therefore, even though the population increases only by 37%, the total amount of food delivered to the table increases by 57% (from 17 trillion kcal per day to 27 trillion kcal per day). As there is a disproportionate rise in socio-economic preference for animal proteins, the total amount of kcal of animal proteins (red meat, poultry, eggs and dairy rises from 2.6 trillion kcal per day to 4.6 trillion, a jump of 75%. In this scenario, the 2050 diets would have eradicated hunger in all regions of the world, even if the nutritional composition quality in sub-Sahara Africa would still be precarious.

Given these three input dynamics, the model calculates that it will require 6.6 million km2 (mkm^2)more crop land, an increase of 42%, and 4.3 mkm^2 of more pasture land, an increase of 13% by 2050, in order to produce the required amount of agricultural output so that the socio-economic aspirations of close to 10 billion people in 2050 in the world can be served.

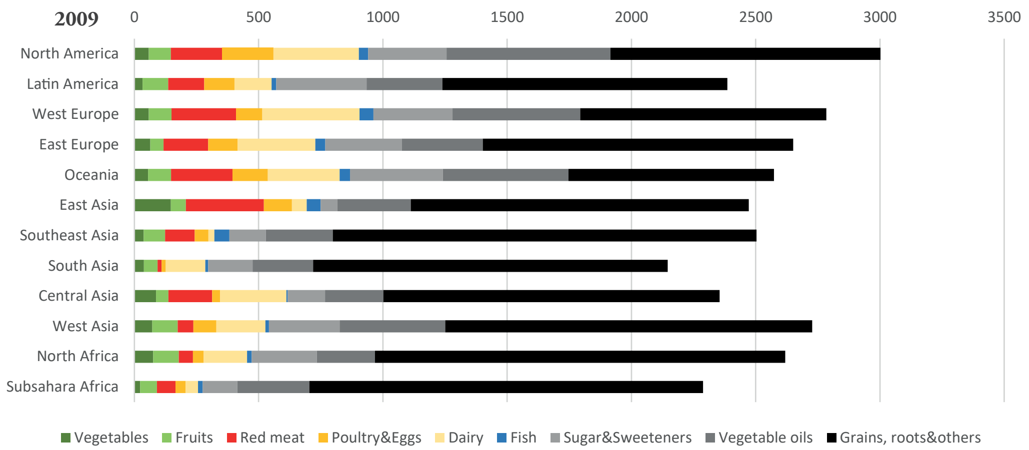
Such an increase of 10.7 mkm^2 of agricultural land, would amount to ploughing under around two thirds of the still available non-utilized prime agricultural land (mentioned in an earlier section to amount to 17.2 mkm^2). However, as mentioned, this land is mostly situated in South America, Africa and Southeast Asia in what are so far largely natural, pristine habitats. This would imply the final destruction of these giant natural eco-spheres. It would also be a destruction of unprecedented

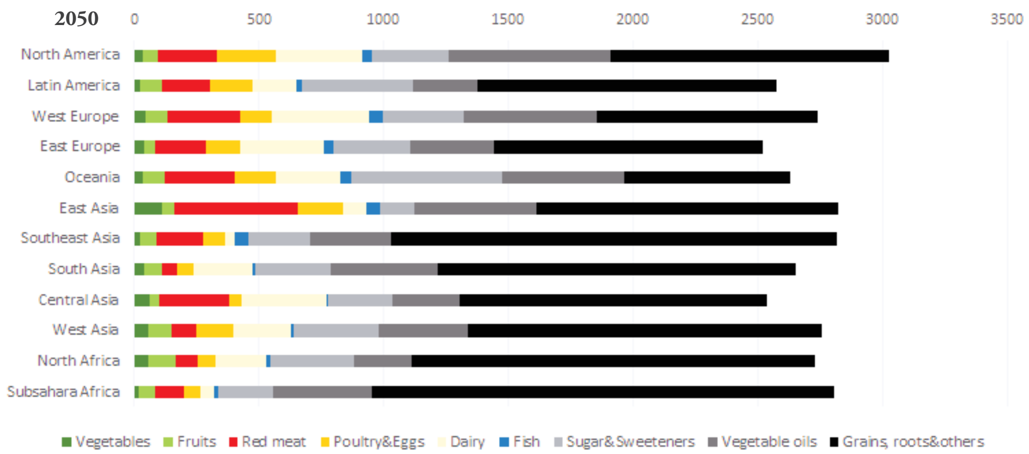
[21] Alexandratos, N. and J. Bruinsma. 2012. World agriculture towards 2030/2050: the 2012 revision. ESA Working paper No. 12-03. Rome, FAO

scale in human history. Over the past 50 years since 1960, agricultural land expanded by merely 3.7 mkm² globally[22], and not even all of this was pristine land. The scenario of History Continues would roughly triple the pace of loss of pristine nature towards agricultural land for the next 30 years versus the past 50 years.

levels of 11% of the global population suffering from hunger, and 23% of all children below five years of age experiencing stunting, represent a real humanitarian crisis, and this would strongly increase by 2050 if agricultural production does not rise.

Exhibit 13: Global diets 2009 and 2050 at current trends





The Second Scenario: Deliberate Impoverishment

The first scenario outlines a choice between two unappealing options. Either, dramatically convert natural habitat into agricultural land on an unprecedented scale, and in the process destroy some of the last large reserves of biodiversity and precious natural habitats. Or, curb the global population's aspiration for sufficient and healthy food, probably to a degree that hunger and child stunting would strongly rise in sub-Sahara Africa and South Asia versus current levels. Even today's

An alternative solution is therefore to reduce the production of foods that are the most resource intensive in providing energy and nutrition to the global diet. Namely, red meat. As mentioned in the previous section, livestock production consumes 4.6 petagrams C of biomass to deliver only 0.12 petagram C to the tables. It has been amply proven that adults can have a healthy and nourishing diet, even on a vegan basis and certainly on a vegetarian basis. (That does not apply to children whose healthy growth strictly requires energy dense foods rich in animal proteins.[23])

[22] Worldbank interactive data website, based on data provided to FAO: https://data.worldbank.org/indicator/AG.LND.AGRI.K2?end=2015&start=1961&view=chart

[23] for instance according to Lora Iannotti, associate dean for public health at the Brown School at Washington University

Many activists and even law makers are therefore advocating for the reduction of meat production and consumption, and in particular red meat production, to solve the global food crisis in the year 2050.

The modelling provided by Bajželj *et al.* calculates the effect if the diet of the global population in the year 2050 was radically altered from its current socio-economic preferences. This diet would entail four significant shifts:

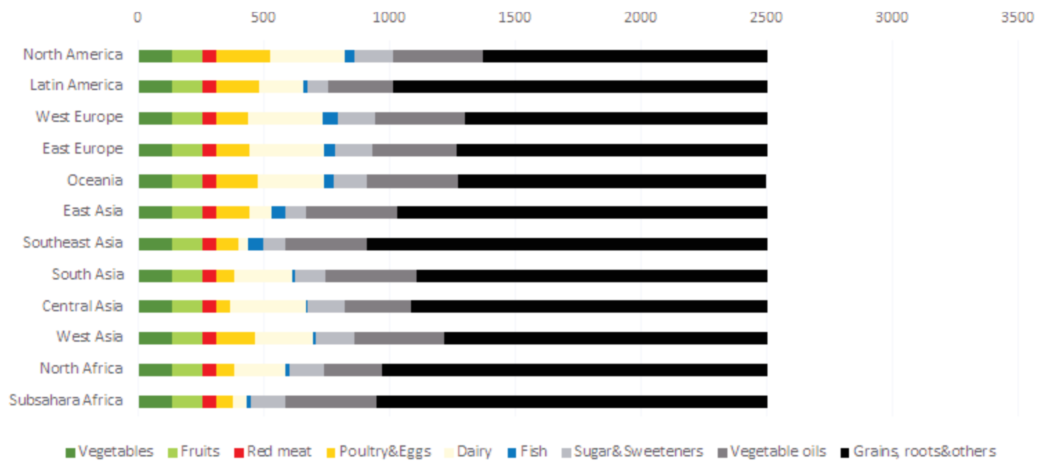
a) To cap red meat consumption at 57 kcal per day (down from today's 207 in North America and 314 in East Asia)
b) To increase vegetables and fruits consumption to 136 and 119 kcal per day respectively (up from today's global non-East Asian average of 43 and 75 respectively)
c) To cap sugar consumption at 150 kcal per day for those nations that are exceeding this number today (down from 315 in North America and 363 in Latin America)
d) Every citizen will receive an allocation of only 2500 kcal per day. While this is generally enough for an average weight person, this assumes that nobody will ever be allowed again to become overweight. Because by definition, in this scenario, every overweight person would cause somebody else to experience hunger

Deriving these figures from global diet recommendations such as WHO, USDA and others, Bajželj *et al.* call this the *healthy diet scenario*. Whether this scenario is really healthier or not is subject to a different debate. This report prefers to call this scenario *Deliberate Impoverishment*, because versus the socio-economic aspirations of the global population of today, it would certainly feel like an impoverishment if they were either not allowed or not capable of eating red meat anymore, or having to forego their favourite ice creams, cookies, soft drinks and other sweeties, which are part of their dairy-rich habits.

Suspending for the moment the question of whether it is possible to engineer such a large-scale socio-economic change of preferences away from meat and sugars towards vegetables and fruits, and to banish overweight: the question is whether this would solve the global food crisis, if it could be achieved. The answer is yes at first sight—but no, unlikely in the real world with its current set of economics.

The curtailment of red meat production on the above required scale would reduce the amount of red meat products delivered to the consumer from today's 1 trillion kcal per day to 0.56 trillion, almost a halving. According to Bajželj's model, this would permit a reduction of the global pasture land by around 4.9 million km2 (mkm²). Since more land is required for vegetable and fruit production, and since the total amount of kcal is still going to increase, the amount of crop land would have to increase by 5.4 mkm². However, the now non-utilized 4.9 mkm² of pasture could be converted

Exhibit 14 Global diet according to the scenario *Healthy Diet* by Bajželj



into crop land, and thus the land balance would remain almost unchanged versus today. So, at first sight the equation seems to solve itself.

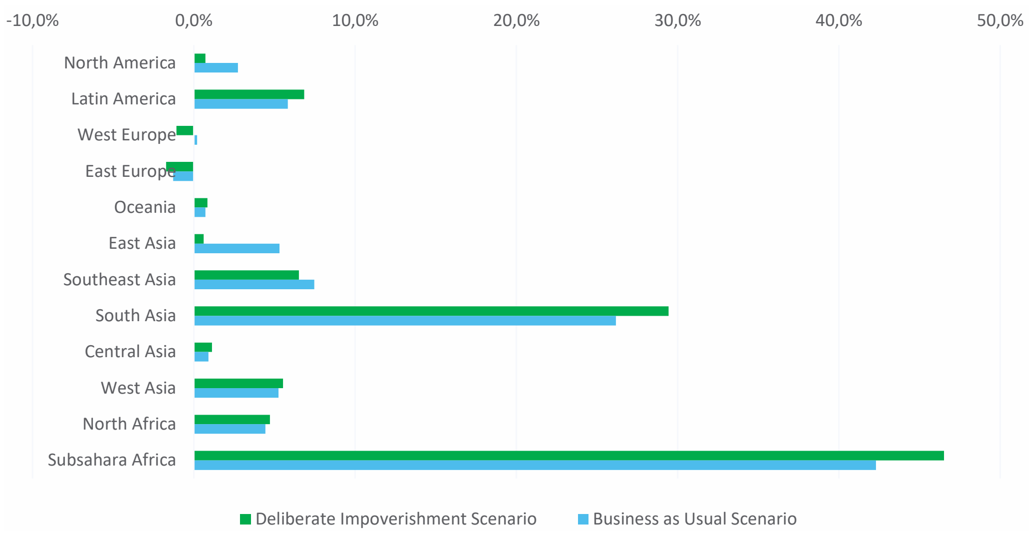
A further reduction of livestock production of food could improve the land balance even more. Red meat consumption could be eliminated almost entirely, and the dairy and poultry sector could also be further reduced. The East Asian experience shows that it is possible to live healthily and with satisfaction with a much smaller dairy sector than in the Americas or Europe. With this more drastic reduction of the animal protein sector in the global diet, the total agricultural area could thus easily be reduced by 10% or 20% and then return to nature the amount of land that was taken from it over the past 50 to 100 years.

However, the model of Bajželj *et al.*, and the solution approach underpinning it and favoured by several advocates for global change, does not consider the effects of international trading and geographical distribution. Under the scenario of Deliberate Impoverishment (or Healthy Diets, depending on viewpoint), 29% of the additional food required between today and 2050, will be needed in South Asia. 47% of all additional food will be needed in sub-Sahara Africa. The scenario of History Continues has almost the same distribution.

While close to 80% of the additional food is required in South Asia and Africa, the land utilization decreases due to abandonment of red meat production will mostly happen in North America, South America and Europe, which is where the feedstocks for the meat production are grown today. This is in addition to the impact of the absolute amount of yield increases also happening in these three macro regions, because they have the highest yields already today. (The same relative increase of yield across the board in all regions will deliver a very much higher absolute yield of produce in the Americas and Europe.) Under this scenario, all this newly available land in the Americas and Europe would instead be producing vegetarian food stuffs for Africa and South Asia. The result would be gigantic trade flows of cereals, fruits and vegetables from America and Europe to South Asia and Africa.

While it is marginally conceivable that India or Bangladesh could pay for these food imports with textiles from Dhaka or IT services from Bangalore, this is not thinkable for Africa. Africa can hardly afford, neither today nor in the future, to pay for food imports from Americas and Europe on the required scale. Whatever Africa is able to export, it needs those incomes dearly to invest in machinery and infrastructure to climb up the productivity scale and enter industrialization. Spending it on food imports instead would condemn Africa to continuing poverty. The population groups most affected by this economic retardation would be the same as those who are suffering from malnutrition today: children, elderly and the poor.

Exhibit 15 Distribution of the additional food required by 2050 by region



The importance of livestock production especially for the African poor can hardly be underestimated. For instance, the well-reputed International Livestock Research Institute wrote in 2015:[24]

Across the food-challenged regions of sub-Saharan Africa, the sustenance provided by livestock and seafood – milk, meat, eggs, and fish – is far more important than it is in wealthy countries. For most Africans, particularly the poor, there are no alternatives that can supply anywhere near the same level of protein and micronutrients

Similarly, in a 2014 policy brief by the UN Secretary General for Food Security and Nutrition, co-created with researchers from CSIRO from Australia, USAID from USA, IIASA from Austria, ILRI from Kenya and IFAD of the UN, one of the key points is:[25]

Sustainable intensification of livestock production will yield significant benefits for food security, incomes, trade, smallholder competitiveness and ecosystems services. These benefits need to be widely appreciated: at the present time farmers face major challenges when attempting to increase their investments in livestock production especially when the sector's contribution to sustainable development and economic growth is not appreciated

The likely macroeconomic outcome of a drastic reduction of agricultural production in the Americas and Europe, by either forced or voluntary reduction in red meat consumption, would be that the agricultural sector in these two regions would slide into long term and structural recession, thus inhibiting innovation and technology development. At the same time, it would contribute little or nothing to alleviating the food shortage in either South Asia or Africa, because these two macro regions will not be capable of paying on the required scale for the required food imports that could theoretically be produced in the Americas and Europe. If anything, the inhibition of innovation and technology development will dampen the prospects of solving the food crisis in these two regions. A scenario in which the reduction of red meat consumption could help the nourishment of African and South Asian populations would first need to fundamentally change the laws of economics before having an effect. Trying to change such economic laws and the socio-economic behaviours underpinning them has variously been tried in the 20th century, with always disastrous results.

Can Africa afford food importation?

The question of whether Africa could afford the importation of food is tied into many questions of socio-economic development, for which no consensus exists. The historical experience in Europe and Asia is that widespread industrialization and urbanization requires professionalization and productivity improvements in the rural sector first. Whether it would be possible to skip this step in Africa, importing its food requirements instead of producing them, is a controversial proposition.

The scenarios for 2050 are also impaired by uncertainty in some African data. For instance, the amount of crop lands for North America and sub-Sahara Africa are nearly the same: about 2.1 mkm^2. According to FAO production statistics, there were 735 million tonnes of crops harvested in North America, and 597 million tonnes in Africa in 2010.[26] At the same time, the average yield productivity is supposed to be three times higher in North America than in Africa. These numbers do not match together. The discrepancy is likely to be a combination of factors: a) higher quality of crops in North America, which implies higher caloric value and less waste, b) a significant under reporting of available crop land in Africa, c) an over reporting of net harvest volumes in Africa.

Depending on which figures one assumes and which rates of technology deployment over the next years in Africa, this leads to dramatically different shortfalls of food in Africa in 2050. Alexandratos & Bruinsma assume that the net trade balance in wheat, rice and coarse grains for sub-Sahara Africa will

[24] International Livestock Research Institute, Nairobi and Kampala, 2015, Delia Grace and Kristina Roesel
[25] Policy Brief of UNSIC: African Livestock Futures - Realizing the potential of livestock for food security, poverty reduction and the environment in Sub-Saharan Africa, 2014
[26] http://www.fao.org/faostat/en/#data/QC

increase from a deficit of 23 million tonnes in 2006 to a net deficit of 56 million tonnes in 2050.[27] If this were true, then the increase of this food importation would be easily affordable by the Africans in 2050. In that same period African GDP would have risen by a factor of 8 from 475 billion USD to 3764 billion USD.

However, the above calculation by Alexandratos implies an accelerated technology deployment. If the 597 million tonnes number is correct and historical yield improvement levels are assumed, then the total shortfall of food in sub-Sahara Africa would be around 700 million tonnes in 2050. Assuming a cost of USD 500 per tonne of importation cost, this would amount to an annual import bill of USD 350 billion, or roughly 9% of sub-Saharan GDP in 2050. Such an import bill would be unaffordable.

The Third Scenario: Radical Technology Deployment

A third scenario banks on radical acceleration of the rate of development and deployment of technology and innovation, in order to move towards the right on the innovation axis in the matrix. This scenario suggests intensifying land usage and actually reducing the amount of agricultural land. The reason for this reduction would be to recreate natural habitats that were destroyed over the past decades, and to protect the biodiversity of the planet.

There are various technology areas that can be tapped into, to achieve higher food production from less land:

a) Waste avoidance technologies and practices: several seminal studies have analysed in which regions in the world, in which section of the value chain, in which products, and for what reasons, food is wasted. A prominent survey was for instance published by FAO in 2011.[28] There is no single large lever; it is many small areas of wastage across the food system, which in total accumulate to about 30% of our potential food being wasted. Various technologies of tracking and tracing of material flows, condition monitoring, demand/supply matching and forecasting, product shelf life extension, consumer information services and regulatory practices can tackle this number and reduce it
b) Crop yield enhancement technologies: the genetic toolset has rapidly expanded in only the past few years. Genomic analysis and gene editing are possible at a fraction of the cost of only five years ago. Crops can be better customized to environmental conditions, whether this requires drought resistance, photosynthesis conditions, soil composition, harvest cycles etc. There is reason to believe that yield growth enhancements will experience a step change difference on the basis of these new technologies versus the past 50 years
c) Animal health enhancement technologies: a healthier animal is a more productive animal. The same advances in genetic toolsets that are available for plant crops are also available for animals. Farm animals can be genetically enhanced or be treated with better disease prevention technologies, which allow them to stay healthier and have a higher metabolic rate—growing faster with the same feed consumption
d) Agronomic knowledge distribution and education technologies via the availability of smart phones among the rural population of Africa and South Asia
e) Robotization and automation technologies for small-scale farming and small-scale processing operations, which are particularly suitable for the smallholder farms of Africa and Asia

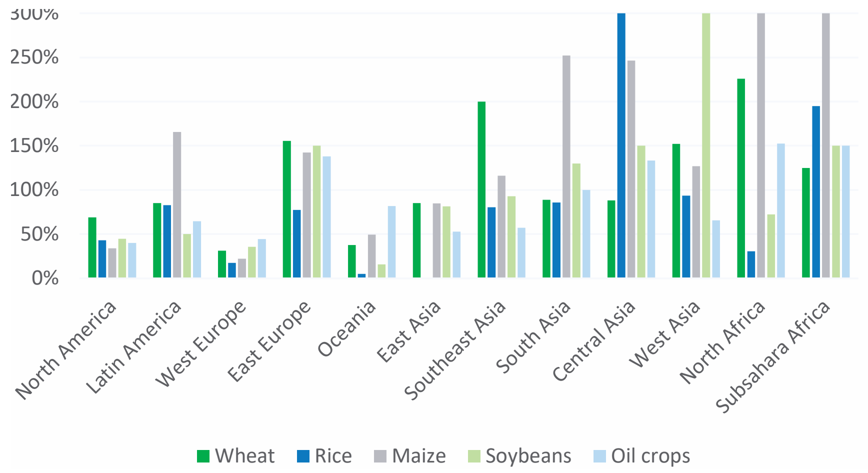
Only a partial selection of the above mentioned technologies are sufficient to solve the global food crisis until the year 2050. Bajželj *et al.* calculated in their model two assumptions:

a) The amount of food waste is halved
b) All known yield gaps are closed in all regions of the world (implying that not even new technologies are required, as the yield gaps can be closed with existing technologies)

[27] Alexandratos, N. and J. Bruinsma. 2012. World agriculture towards 2030/2050: the 2012 revision. ESA Working paper No. 12-03. Rome, FAO, p 71
[28] Global Food Losses and Food Waste, Extent, Causes and Prevention, by FAO and UN, 2011

These two levers would result in a reduction of crop lands required by 1.4 million km2, equal to 9% of all crop land. It would also require expansion of pasture land by 1.1 million km2, equal to 3% of all pasture land, to accommodate all the red meat production.

Exhibit 16 Total growth of yields if yield gaps are closed 2009 – 2050



The value of biodiversity

It is uncertain whether humanity needs biodiversity for its own survival. The evidence that this is the case is slim, especially given the current advances of genomics. Modern technology, as in 2018, has almost reached the point where humans can create new species, or recreate extinct species. Therefore, if there is a biological compound of any commercial value, researchers do not need to look for it in tropical forests but can design it in their laboratories.

Such utilitarian considerations apart, it seems that some members of humanity derive aesthetic pleasure or ethical benefits from a sustained and rich biodiversity of nature surrounding them. If so, then there is a problem. For instance, across Europe, the population of wild breeding bird pairs in agricultural zones shrank by 57%, or 300 million, over the past 20 years.[29] Some common bird species in Germany, such as lapwings, were reduced by 80%. The key reason is assumed to be increasingly effective eradication of insects in agriculture and in human settlements. The official estimate for Germany is up to 80% reduction of insects since 1982.[30] Less insects equals fewer birds.

Biodiversity is under threat everywhere in the world, and the largest pressure arises from intensive agriculture encroaching on natural bio-systems: whether it is the tropical rainforests of Malaysia and Indonesia falling to palm trees, or the Cerrado savannah in Brazil turning into soybean farms. A further threat to biodiversity and agriculture alike is over-utilization of water reserves. Shifting climate patterns or unsustainable depletion of aquafers threaten the balance of the elements on which any biosphere depends.

If humanity treasures biodiversity enough, then there is probably a case to be made for a significant reduction of agricultural lands, to return them to nature and make long term sustainable nature conservation more possible than today. Unfortunately, many years of experience has shown that most end consumers do not treasure biodiversity enough to be willing to pay more for sustainably produced products. For instance, for years, the price for sustainably produced palm oil has been nearly the same as for non-certified palm oil, and typically does not cover the additional costs. In another example, currently, 80% of sustainably produced cotton cannot be sold as such, because consumers do not demand enough of it.

[29] http://www.zeit.de/wissen/umwelt/2017-05/voegel-bestand-landwirtschaft-gifte-kiebitz-braunkehlchen-uferschnepfe-feldlerche
[30] http://www.spiegel.de/wissenschaft/natur/insektensterben-80-prozent-weniger-insekten-als-1982-a-1157898.html

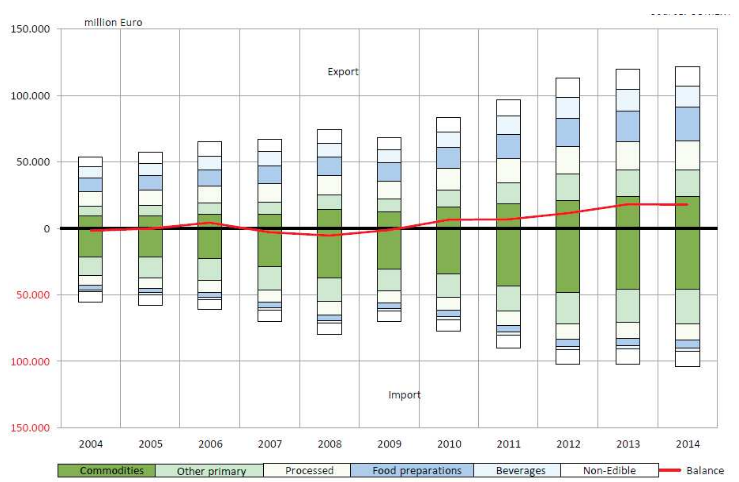
The Fourth Scenario: Zoological Gardening

The full scale and rapid deployment of technologies that have become available in only the past few years, and which are sketched out in the third scenario, seems to be sufficient to produce enough food for everybody even on a planet with 10 billion people. In addition, it would do so without needing to change their socio-economically formed dietary preferences in terms of red meat consumption or other livestock products and it would allow for large-scale retirement of current agricultural lands in favour of nature and biodiversity.

In that case, the question becomes, what to do with all this newly available land which can be renatured? Several options are possible and are summarized under the heading of Zoological Gardening, which constitutes the fourth scenario of combining accelerated innovation with expansion of agricultural land utilization:

a) Recreating true nature-only zones, which are either completely untouched or only marginally managed by human interference. Examples of these would be the national parks in the USA, which have been copied many times throughout the world.
b) Recreating nature zones in which the conservation or enhancement of natural biosystems has strict priority, but where agricultural practices that do not interfere with these biosystems, or are an essential part of these biosystems, are permitted or encouraged.
c) Creating low intensity mixed nature and agricultural zones: in some parts of the world of high density populations, such as Europe, India or China, it would be difficult to recreate large zones of land that can become wholly natural again. There would be too many settlements, roads, canals and other examples of human presence that have formed this landscape over thousands of years. Nonetheless, the agricultural intensity of these zones could be reduced for microniches of nature to establish or be promoted. An example of this approach is the cattle stocking practice in the Alps of Switzerland. These cattle have an agricultural purpose, but they are also part of the biosphere of the Alps, and have a certain zoological character for the Alpine tourists. Their dairy and meat productivity is low, but in combination with their other functions, this kind of mixed utilization of land serves many purposes at once.
d) Organic agriculture: if sufficient food is produced to serve all of humanity's needs, and if nature has enough land to preserve its biodiversity, then it should also be possible to reserve some agricultural land for the luxury of bio-organic agriculture. Whether for aesthetic or taste or philosophical reasons, some consumers may prefer agricultural products that are either entirely untouched or only lightly touched by modern technologies. These agricultural practices require extensive pieces of land and have low productivity yields. However, there is no reason why in a world of agricultural abundance, it should not be permitted to have such luxury goods on offer. These products will be more expensive because they consume more land and human resources to be produced, but that in itself is not a reason to disallow them—provided that no other person in the world is forced to suffer due to shortages of land arising from such luxury utilization. Organic agriculture products may be particularly suitable in the European context, where the land is productive enough to feed the entire European population and still generate an agricultural trade surplus, despite Europe's high population density.

Exhibit 17 EU food trade structure and surplus



Source: FAO, EU 2015: Agri-food trade in 2014: EU-US interaction strengthened

None of these four options for utilization of land are strictly necessary for the healthy survival of humanity. It would be ethically highly questionable to promote these utilizations of land if there were not sufficient intensification of agriculture in other geographies to produce enough healthy food for the total global population. But, assuming that this intensification is proceeding with the help of the technological tools mentioned in the third scenario, there is no reason why humanity should not permit itself the luxury of living amidst a large, extended and varied zoo of a wild and lively variety of creatures.

Several different scenario exercises for How to Feed the World in 2050 have been published by various organizations. As is common to all scenarios, the choice of the dimensions shapes the answers that the analysis produces. The dimensions for this report ask the question, in which ways technological progress can or cannot replace resource utilization to meet the global food demands in the year 2050. By choosing different dimensions, other analyses find different answers.

For instance the OECD in 2016 calculated and published three scenarios named: (i) Individual fossil fuel-driven growth, (ii) Citizen-driven sustainable growth, and (iii) Fast, globally-driven growth.[31] Its answers revolve around the question of what could be the drivers of growth. It does not allow a no-growth scenario.

The World Economic Forum published four scenarios with the dimensions of demand shift and market connectivity. The scenarios were only qualitatively described and not numerically calculated.

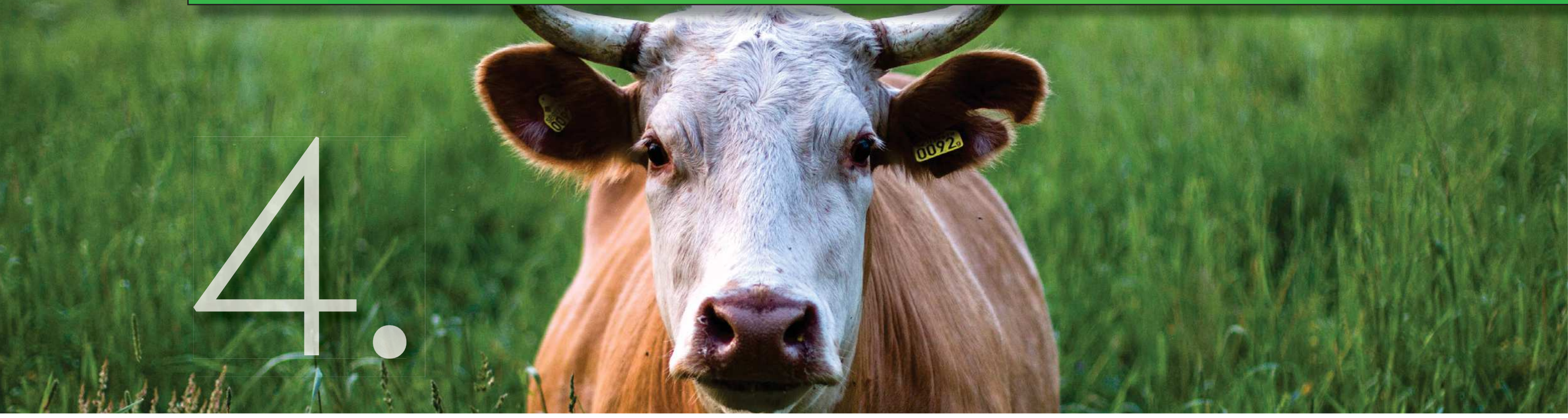
Other famous scenarios are the five Shared Socio Economic Pathway Scenarios (SSP) by the climate change science community. Their two dimensions of adaptation and mitigation assume inherently that every scenario except SSP 1 is by definition non-sustainable. Therefore, no degree of innovativeness in any of the SSP 2, 3, 4 and 5, can bring about a sustainable future, because it has been a priori precluded by the choice of the dimensions.

Another significant analysis effort was undertaken by an EU-funded research project called FOODSECURE. It analysed the 2050 challenge along the dimensions of equality and sustainability, with four resulting scenarios of i) a 1% World, ii) Too Little Too Late, iii) Food for All, but Not Forever, iv) Ecotopia.[32] Again, the choice of dimensions precludes the type of answer that is possible. If innovativeness is not a dimension, as in the FOODSECURE research project, then the analysis cannot assess whether this factor can or cannot be a solution.

In order for the various modelling tools and scenario reports to preserve intercomparable results and high standards of reliability, the American USDA and British UKaid founded a project called the Agricultural Model Intercomparison and Improvement Project (AgMIP), which is still underway.[33] As a starting point for AgMIP, Lampe *et al.* in 2014 published an overview of the ten most widely used agricultural modelling tools.[34] They concluded that the models mostly differed by their story lines and model variables, and not by working with different foundational datasets. This reinforces the previous observation, that the scale and dimension of the challenge for feeding the world in 2050 is mostly agreed upon by the mainstream scientific community. The differences mostly surround the question, which pathway will solve the challenge. Only scenarios in which the degree of innovation is made an explicit variable can provide an answer as to how much of a solution innovation can be.

[31] OECD 2016. Alternative Futures for Global Food and Agriculture. OECD Publishing, Paris. http://dx.doi org/10.1787/9789264247826-en
[32] http://navigator.foodsecure.eu/Guidance/Briefs.aspx?ID=286
[33] http://www.agmip.org/
[34] Lampe *et al*: Why do global longterm scenarios for agriculture differ? An overview of the AgMIP Global Economic Model Intercomparison; Agricultural Economics Vol 45, 2014, pp 3-20; https://doi.org/10.1111/agec.12086

Chapter 4



4.

Conclusion

There are no easy choices. The challenge of providing enough and nutritious food for nearly 10 billion people in the world is immense under any scenario. The task is aggravated in that as of today, in 2018, the global food system cannot even feed 7.5 billion people properly. Every fourth child in the world below the age of five experiences stunting, which is nearly irrecoverable during the later life. And 11% of the global population experiences hunger.

The two scenarios continuing with the current low levels of innovativeness, create particularly unpalatable choices. The History Continues scenario represents business as usual: in this mode the last grand eco-spheres left on the planet will be ploughed under by 2050, at an unprecedented rate in human history. Or failing that, there will be a heart-wrenching humanitarian crisis of hunger and child stunting. Or a combination of the two.

The Deliberate Impoverishment scenario attempts to solve this problem by enforcing or convincing the American, European and East Asian population that it shall generally eat less to avoid overweight (in the case of North Americans this means much less), eat substantially more fruits and vegetables, and drastically reduce the consumption of red meat by a factor of 75% to 85%. This approach has two shortcomings: a) it is unclear how social engineering on this scale can be brought about for North Americans, Europeans and Chinese to impoverish themselves either voluntarily or forcedly; b) if the social engineering would be successful, then the result will be a structural long term recession of agriculture in the Americas and Europe, and still massive food shortages in South Asia and Africa, as these areas are unlikely to be able to afford the importation of food on such a large scale.

The analysis shows that both of these scenarios with continued levels of current innovativeness solve little, and have tragic consequences for people and nature. However, just because the outcomes of these two scenarios are tragic, and produce additional problems of so far unexperienced proportions, does not mean that such two scenarios cannot occur. They are decidedly possible outcomes of where the world might find itself in the year 2050.

The third scenario aims for accelerated innovation, and thus a Radical Technology Deployment, especially in Africa. It is a tall order to close the yield gaps around the world, and particularly so in Africa. This would mean that in Africa the agronomic practices would need to be revolutionized and yields multiplied. However, with the new tools of agronomic knowledge distribution via smart phones, remote access data information analysis, and robotization technologies for small scale farming, these possibilities might be within reach.

The same applies for a halving of food waste. Given heightened levels of awareness to the opportunity, sufficient political and regulatory will power and an enlarged array of technologies, this target should be attainable.

With sufficient technology deployment, the global population could be fed with even less of the primary resources used than today. Substantial portions of land could be returned to nature and water stress could be reduced. In the highly developed and densely populated regions of Europe and the Far East, where pristine nature has disappeared, at the latest by around 800 years ago, this will hardly be possible. Managed nature with co-existing nature rehabilitation and agricultural practices are the more likely outcomes, a scenario that this report calls Zoological Gardening.

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