GLOBAL RELATIONS FORUM YOUNG ACADEMICS PROGRAM
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TOWARDS SUSTAINABLE FOOD PRODUCTION: CHALLENGES, TECHNOLOGIES, AND POLICY RECOMMENDATIONS

OGEDAY RODOP

Ph.D. Candidate in Materials Science and Nano Engineering, Sabancı University

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This paper, entitled *"Towards Sustainable Food Production: Challenges, Technologies, and Policy Recommendations"* is authored by Ogeday Rodop as part of the GRF Young Academics Program Analysis Paper Series.

GRF convened the following group of distinguished members to evaluate and guide Ogeday Rodop's paper:

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Ogeday Rodop graduated from McGill University Materials Engineering, where his focus was developing light metal alloys mainly for the automotive industry. Upon graduating, he continued his studies in Materials Science at Columbia University, where he obtained his master's degree. Since 2018, he is pursuing his Ph.D. at Sabancı University, where his primary area of research is developing polymeric and nano-based active agent delivery systems. He is one of the inventors of a patented novel nanocomposite superabsorbent polymeric material that increases crop yields in rainfed agriculture and enables water conservation in irrigated farming.

Global Relations Forum Young Academics Program
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Towards Sustainable Food Production: Challenges, Technologies, and Policy Recommendations

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Abstract

Civilizations, spanning just a small fraction of the 2-million-year human history, owe their existence to agriculture. Using nature for our advantage brought us unprecedented food supply and prosperity. However, it also gave us the power to jeopardize the very ecosystems we rely on. Agriculture is vital for our survival, yet it accounts for the highest water usage (71%), pollution, deforestation, and nitrous oxide (265 times more potent than CO2) emissions, globally.

This article will present the major drawbacks of our current farming practices, and the anticipated effects of climate change on food production. Next, it will investigate various technologies that can be integrated into our farming methods. Finally, it will recommend crucial government incentives that can enable the transition to more sustainable agricultural practices. Discussions will extend to various existing technologies and social programs that mitigate food waste along the food supply chain.

Feeding the anticipated 10 billion people in 2050, within the ecological limits of our planet, requires a substantial change in our food production and distribution systems. The technologies needed to achieve this shift will usher in the next agricultural revolution.

1. Producing Ever More Food

Agriculture is the most important endeavor humankind has taken on to reproduce and foster in this world. For most of our 12,000 years as farmers, our practices were subject to little change, and so was our population. Within the scope of our agricultural history, there were two revolutions in food production.

First came the British Agricultural Revolution, which used many novel techniques to greatly enhance yield efficiency. These techniques included: (i) using machinery to plow the soil, instead of manual labor or animals, (ii) selective breeding, which allowed farmers to grow higher-yielding crops, and (iii) developments in infrastructure, e.g., canals, that allowed adequate irrigation of fields and translated into more production. Due to higher yields, fewer farmers were needed to meet food demand. Henceforth, the ratio of urban workers in the total workforce grew significantly higher than ever before, which facilitated greater manufacturing and industrial production. Thus, in effect, British Agricultural Revolution was the reason behind Industrial Revolution.

Next, the Green Revolution allowed us to grow even more food from the same area of land. There were many factors that led to large increases in yields, including selective breeding and genetic modification to achieve high yielding varieties and the use of pesticides and fertilizers to protect crops from pests and supplement the necessary nutrients in the soil to foster plant growth. Crop protection enabled great savings in yields, which would otherwise have been lost. Without any nutrient replenishment, high yielding varieties would render soil unfertile for future planting seasons. So, to permit such an aggressive growth in plants, fertilizers gained widespread use.

From 1950 to 1985, the world's population increased roughly twofold, whereas global grain output increased by a factor of 2.6.[1] This meant people had access to more food than ever before, and the GDPs of many countries increased. From the viewpoint of feeding people and growing the economy, the Green Revolution was extremely successful. However, it has also caused serious changes in our agricultural practices that have proven harmful to the environment, which now requires another revolution to reverse their effects. The fact that the global population continues to increase makes this task even more difficult. Continuing to increase agricultural yields while at the same time reducing the unsustainable practices that have permitted some yields is at cross purposes and essentially impossible.

Producing enough food for everybody is no easy task. It requires many inputs, variables, stakeholders, and potentially a third agricultural revolution. Water, plant protection, and fertilizers are the main inputs, and the next revolution should find solutions for their optimum implementation. Our greatest challenge is not just to produce more food but to fulfill the nutrition demands of 11 billion people in 2050 within the sustainable boundaries of our planet. Historically, the increase in food production was based on converting natural ecosystems into farmland, i.e., deforestation. Owing to agricultural revolutions, we produce much more food today per capita on much less land per capita. In 1961, arable land was 0.36 ha/person. This value decreased to 0.18 in 2020 and is expected to drop

[1] "Population trends 1950 – 2100: globally and within Europe," European Environment Agency, accessed July 1, 2022, https://www.eea.europa.eu/data-and-maps/indicators/total-population-outlook-from-unstat-3/assessment-1#:~:text=The%20world's%20population%20increased%20from,under%20most%20UN%20projection%20variants.

further to 0.16 ha/person in 2080.[2,3] These figures lay plain that food production must become more efficient.

2. Climate Change and its Effects on Agriculture

The effect that climate change will have on our food production is complicated. It is anticipated that climate change will result in a 1.5-2°C temperature increase along with irregular rainfall. Some regions are expected to receive more overall rainfall (e.g., Eastern Europe), while others are expected to face more drought (e.g., South Europe). Most regions will receive heavy rainfall in shorter durations and face prolonged dry spells. Even though the total annual rainfall received in most areas will track with past levels, such an increase in the intensity of rain is not suitable for plant uptake, while longer dry periods are also harmful for plant growth.

The irregularity of rainfall regimes is already evident today, and a few examples can be noted from the summer of 2022: Spain and Portugal suffered their driest climates in 1,200 years; one of the longest rivers in Italy, the Po, which supplies water for nearly a third of Italy's agricultural production, faced extraordinary drought; and extreme rainfall in South Africa caused flooding and landslides that destroyed 12,000 homes and killed 400 people.

It is further anticipated that the temperature increase will cause crop losses due to new or intensified pests. Crop losses will be most severe in regions where warming increases the growth and metabolic rates of insects, which is applicable mostly to temperate regions where most grain is produced. Also, new pest species are expected to emerge, which will pose an additional threat to crops. Combating new pest varieties requires the development of new plant protection product (PPP) formulations.

The Mediterranean fruit fly is one of the most invasive and dangerous insect pests in horticulture and is usually detected in temperate regions of North America and Europe. Due to climate change, temperate regions are expected to shift north. Therefore, northward expansion, an increased altitudinal limit denoting the presence of the species, and population increase in regions that will become more suitable, are expected. Examples of areas that are expected to be more suitable for fruit flies are inland France, southern Germany, Switzerland, Austria, and Hungary. However, fruit fly populations are expected to decrease in areas that will become less suitable due to climate change, such as North Africa.

The following scenarios are considered the most likely effects of climate change on our food production: (i) increasing droughts and floods and related soil erosion, (ii) decrease in average crop yields, (iii) increase in pest populations and emergence of new pest varieties, (iv) shift in sowing dates, (v) risk of extinction for some crop types.

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[2] "Arable land (hectares per person)," The World Bank, accessed October 20, 2022, https://data.worldbank.org/indicator/AG.LND.ARBL.HA.PC.

[3] Nikos Alexandratos and Jelle Bruinsma, *World agriculture towards 2030/2050: the 2012 revision* (Rome: FAO Agricultural Development Economics Division, 2012), 20.

3. Water Problem

Water is essential for growing more food. Although only 20% of agricultural land is irrigated, these farmlands provide 40% of the total food supply.[4,5] Only a very small portion of global freshwater resources is accessible, which makes them highly precious. Out of total global water consumption, agriculture accounts for 70%, a ratio that can even exceed 95% in some developing countries.[6] If we combine this with the vast amounts of chemicals used to combat pests and the fertilizers to promote plant growth, agriculture becomes the single biggest polluter of water.

Challenges with water usage in agriculture start even before the water reaches the field. Poor water pipe infrastructure can cause significant water loss, especially in open water canals. In fact, in Turkey, 50% of all irrigation water is lost in open canals through evaporation. A shift to a closed pipe system for water delivery can significantly increase water availability for agriculture, potentially reduce agricultural water use, and alleviate the depletion of our underground water resources. Although manual or surface irrigation is an inefficient and primitive method, it is still the most widely used to irrigate farmlands. In fact, surface irrigation is used on more than 83% of all watered farmland in the world, and it uses water only at 60% efficiency.[7,8]

Drip irrigation consists of a network of plastic pipes, which deliver water onto or into the soil at very low rates. It is the most efficient irrigation system and can achieve more than 90% water use efficiency.[9] These systems can also deliver nutrients directly to plants' root zones. They are applicable to vegetables, fruit trees, and vine crops, and are mostly applied to high revenue generating plants. Sprinkler irrigation resembles rainfall since it applies water over the crop canopy. These systems are typically 75% efficient and require lower investment and maintenance costs compared to drip irrigation.[10] Sprinklers can be a better choice for crops generating lower revenues and annual or perennial crops.

To reduce our agricultural water pollution footprint, there are other technologies to increase the water retention capacity of the soil. One such method is using superabsorbent polymers (SAP) as water reservoirs. SAPs regulate water delivery to plants by swelling during rainfall and releasing water during dry periods. Since water spends more time near plant roots, plants take up more water, and their biomass and yield increase. SAPs are especially effective in fields where surface irrigation is applied and for non-irrigated agriculture. Depending on the crop type and field conditions, they have the potential

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[4] Michael F. Dowgert, "The Impact of Irrigated Agriculture on a Stable Food Supply," 22nd Annual Central Plains Irrigation Conference (2010): 1-11, https://www.ksre.k-state.edu/irrigate/oow/p10/Dowgert10.pdf

[5] "Water in Agriculture," The World Bank, October 5, 2022, https://www.worldbank.org/en/topic/water-in-agriculture

[6] "Annual freshwater withdrawals, agriculture," The World Bank, 2018, https://data.worldbank.org/indicator/er.h2o.fwag.zs?type=shaded&view=map&year=2018

[7] José Manuel Gonçalves et al., "Water-Saving Techniques and Practices for On-Farm Surface Irrigation Systems," *Biol. Life Sci. Forum 3, 46 (2021): 1-10.* https://doi.org/10.3390/IECAG2021-09675

[8] C. Brouwer, K. Prins, M. Heibloem, "Annex I: Irrigation efficiencies," in Irrigation Water Management: Irrigation Scheduling (Rome, Italy: FAO, 1989)

[9] Ibid.

[10] Ibid.

to reduce water demand by 25-50%, and result in a 20-40% yield increase.[11,12] SAPs are feasible mainly for annual crops, although they can also be applied to saplings or trees.

4. Misleading Public Opinion

One of the greatest challenges in applying the best possible practices in agriculture is the discrepancy between facts and public opinion, which appears to run entirely counter to the truth in certain cases. Here, we cannot ignore the strong influence of the media. Through a preferential representation of the data, it becomes easy to intentionally direct peoples' opinions in certain ways. Although this might not always be due to bad intentions, it doesn't alleviate the negative effects this has on both lawmakers and the market. A 1999 study showed that 40-60% of consumers trust the messages of non-governmental organizations (NGOs) regarding food safety, which is higher than those trusting scientists (29-49%), authorities (9-27%), and industry (2-6%).[13]

The discrepancy between public opinion and reality is evident in examining the risks associated with food production and nutrition. People are extremely sensitive to the health hazards of food. However, their ranking of risks from food consumption is the complete opposition of the ranking of risks by food scientists. This delusion about food risk is truly a challenge for government bodies in implementing appropriate strategies that are accepted by the public.

Table 1: Perception of risk from food consumption[14]

Public Ranking	Food Scientist Ranking
Food additives	Microbial contamination
PPP residues	Nutritional imbalance
Naturally occurring toxicants	Environmental contaminants
Environmental contaminants	Naturally occurring toxicants
Nutritional imbalance	PPP residues
Microbial contamination	Food additives

Views of most environmental NGOs or other groups on sustainable agriculture tend to focus on just one aspect of the general problem and, more importantly, tend to be strongly in favor of or opposed to a certain side. One may not directly think of this approach as problematic. For example, they might just be pointing out a chemical product that can be harmful to human health. However, unless we also consider the effects of not using that product for our crop yields and the problems this may cause on a larger scale, we can never truly judge the overall effect of the product in question as good or bad.

[11] Vito Aurelio Cerasola et al., "Potential Use of Superabsorbent Polymer on Drought-Stressed Processing Tomato (Solanum lycopersicum L.) in a Mediterranean Climate," *Horticulturae* 8, 8 (August 2022): 718. https://doi.org/10.3390/horticulturae8080718.

[12] shuai Mao et al., "Evaluation of a water-saving superabsorbent polymer for corn (Zea mays L.) production in arid regions of Northern China," *African Journal of Agricultural Research* 6, 17 (September 2011): 4108-4115. https://academicjournals.org/journal/AJAR/article-abstract/B3C721D31050.

[13] Wouter Poortinga, Paul Dekker, and Judith van Male, "Vertrouwen en risicopercepties," *The Netherlands Institute for Social Research* (SCP) (October 13, 2000): 28. https://repository.scp.nl/bitstream/handle/publications/1200/Vertrouwen_en_risicopercepties.pdf?sequence=1&isAllowed=y.

[14] Fred Whitford, "Pesticide Facts and Perceptions," *Journal of Extension* 31, 1 (Spring 1993). https://archives.joe.org/joe/1993spring/a2.php.

In fact, almost all studies on this subject show that the complete elimination of plant protection products is not an option for sustainable food production for a variety of reasons. Unfortunately, people tend to trust NGOs more than scientists, authorities, and industry.[15]

5. Plant Protection and Organic Farming

Arable land is limited, and to feed the ever-growing population, we need to maximize it. Harmful pests have a drastically negative effect on crop yields, and not taking any preventative measures, e.g., using pesticides, could result in up to a 70% loss in crop yields.[16] So, unless we double the amount of land used for agriculture, this is not a viable option. However, significantly increasing the amount of arable land would also be detrimental to biodiversity, because making up land for agriculture is usually through deforestation. In fact, almost 90% of global deforestation is due to food production and animal husbandry.[17] So, a strategy that aims to increase the amount of arable land at the expense of lower crop yields with the use of less pesticides (PPPs) is not a sustainable option.

Crop protection involves not only PPPs but also other strategies, such as crop rotation, biological control, resistant cultivars, and soil management. However, the use of PPPs is much more effective in decreasing crop yield losses and is also the subject of many controversies, especially with regard to biodiversity and possible environmental and health hazards.

Table 2 below provides data for actual and potential yield losses for major crops. Potential losses represent the total percentage of crop loss in the case of no crop protection while the percentage loss without PPPs denotes an estimated loss in practices that exclude PPPs but include crop rotation, biological control, soil management, and resistant varieties.

Table 2: Yield losses with and without the use of plant protection products (PPP)

Crop	% losses with PPPs[18]	% losses without PPPs (estimation)	% potential losses[19]	Yield gain by PPPs
Wheat	21% (10.1-28.1)	40%	50%	19%
Rice	30% (24.6-40.9)	62%	77%	32%
Maize	22% (19.5-41.1)	55%	69%	33%
Potato	18% (8.1-21)	60%	75%	42%
Soybean	21% (11-32.4)	48%	60%	27%

[15] Poortinga, "Vertrouwen en risicopercepties," 28.

[16] Alyssa Gordon, "Yield Losses Due to Pests," AGRIVI, September 7, 2022, https://www.agrivi.com/blog/yield-losses-due-to-pests/.

[17] "COP26: Agricultural expansion drives almost 90 percent of global deforestation," FAO, November 6, 2021, https://www.fao.org/newsroom/detail/cop26-agricultural-expansion-drives-almost-90-percent-of-global-deforestation/en.

[18] Serge Savary et al., "The global burden of pathogens and pests on major food crops," *Nature Ecology & Evolution* 3 (2019): 430-439. https://doi.org/10.1038/s41559-018-0793-y.

[19] E. C. Oerke, "Crop losses to pests," *Journal of Agricultural Science* 144, 1 (2006): 31-43. https://doi.org/10.1017/S0021859605005708.

As can be seen from Table 2, PPP usage provides significant yield gains for all these crops, which are major staples of global food-demand security.

Although the usage of PPPs has doubled since 1980, the development of synthetic PPPs has declined, and the number of biopesticides has increased. The increase in PPPs was largely due to the shift from broad spectrum PPPs to more specific PPPs, which only target specific pests and avoid non-target organisms. Strict regulation is a significant hurdle in developing new formulations. New PPPs are subject to extensive, science-based risk assessments. In fact, the average cost of such assessments per active substance is US$71 million, almost double their cost from 15 years ago. The evaluation of PPPs' toxic effects on humans and other organisms, strict control of their residues, and a safety factor of a 100 when determining their maximum allowed doses, allow for lower environmental impacts and fewer negative health effects. It can be concluded that PPPs are much safer than in the past if applied properly.[20]

The "Panel for the Future of Science and Technology", which was sponsored by the European Parliament, determined that: "based on the required extensive risk assessments, plant protection products and their active ingredients are one of the best-studied and safest products worldwide."[21] It is noteworthy that this conclusion was not reached in a report financed by a pesticide producer but by an in-depth intergovernmental research study. Due in large part to the oversimplified and one-sided messages circulating in the media, the public believes that chemical PPPs are, by definition, harmful to human health and the environment. Public opinion is similarly misinformed on organic farming and the overstated advantages of using natural PPPs. Poorly informed public opinion, in turn, has a strong influence on policymakers and can lead to poorly conceived strategies for addressing food demand.

PPPs undoubtedly increase crop yields and create more affordable food prices. Any restriction on their use will dramatically raise production costs and therefore food prices. This will cause people in lower income brackets to buy fewer fruits and vegetables and consume more food that is cheaper and has higher levels of sugar and fat. The risk of PPPs to human health is considerably lower than that of nutritional imbalance, i.e., higher sugar and fat and lower intake of the antioxidants, vitamins, and fibers that are found in fruits and vegetables.

To attract consumers who are sensitive to PPPs, a troubling practice is being applied at the retail level. Although already very stringent procedures are implemented to determine maximum residue limits (MRL) in the EU, some supermarkets, such as Coop, Aldi, and Lidl require extralegal standards, as low as 33% of MRL.[22] This is a pure marketing strategy with negative effects on food safety. Since supermarkets account for 70% of sales of fruits and vegetables, many farmers try to abide by these standards, which in turn prevents farmers from adequately treating their produce against storage diseases. In the case of apples, for instance, storage losses can exceed 50%.[23]

The problem with most pesticides and fertilizers lies not so much in their chemical

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[20] Dany Bylemans, Barbara De Coninck, and Wannes Keulemans, "Farming without plant protection products : Can we grow without using herbicides, fungicides and insecticides?," *Panel for the Future of Science and Technology* (March 2019). https://www.europarl.europa.eu/RegData/etudes/IDAN/2019/634416/EPRS_IDA(2019)634416_EN.pdf.

[21] Ibid.

[22] Katy Askew, "Danish supermarkets react to consumer concern over pesticide residues," Food Navigator, May 3, 2019, https://www.foodnavigator.com/Article/2019/05/03/Danish-supermarkets-react-to-consumer-concern-over-pesticide-residues.

[23] Bylemans, "Farming without plant protection products."

compositions but in how they are applied. Pesticides are lost to the environment due to runoffs and evaporation. Only a very small percentage of pesticides reach target insects. This value can be 0.03% or even lower for certain insecticides.[24] Overall, 99.9% of pesticides do not kill pests.[25] Moreover, up to 60% leach to a depth of 1 meter in the soil and groundwater, according to a more recent long-term study by the Danish Pesticide Leaching Assessment Programme.[26] Pesticide leaching depends on soil type and irrigation, such that loamy or other permeable soils and flood irrigation accelerate leaching; this is one of the main causes of underground water pollution. The most effective solution for mitigating the harmful effects of pesticides is to apply PPPs when and where needed, which is suitable for both chemical pesticides and their bio-alternatives. This is where integrated smart pest detection and application systems can play a vital role, thanks especially to advancements in sensing and communication technologies.

How to Reduce Chemical PPP Usage

One fruitful strategy for the reduction of PPP use is precision farming. In precision farming, remote sensing equipment is used to detect pests, artificial intelligence algorithms are developed to foresee potential threats to crops, and the farmer is advised to where to apply the necessary PPP and in what dose. This integrated strategy can allow farmers to combat pests in a much more effective way and significantly reduce the use of PPPs. Furthermore, moisture sensors, weather forecasts, and nutrient sensors can recommend an optimum irrigation and fertigation schedule for farmers. An ideal application of water and nutrients helps reduce the vulnerability of plants to pests and thus reduces the need for PPPs.

The use of resistant cultivars can also reduce PPP usage significantly. For most crops, there are many cultivars and varieties that are resistant to certain pests and diseases. A major reason why current crops are vulnerable to most pests lies in traditional domestication strategies. In these breeding programs, easy harvest, high yield, and low toxicity traits were selectively improved. Since PPPs became available to combat pests, traits that protect plants from biotic stress have been not been prioritized. Current breeding programs prioritize the identification and selection of resistance genes, which are mostly preserved in wild cultivars. For this strategy to be successful, traits important for food quality and yield need to be preserved, while original plant survival traits are re-introduced. Insect resistant crops (GMIR) have shown to be very successful in reducing PPP usage. For example, in 2016, GMIR cotton and maize respectively allowed for a 56% and 82% reduction in PPPs compared to their non-GMO versions.[27]

Although crop production without PPPs is unrealistic, reductions in usage are possible, some with acceptable yield losses. PPP reduction is currently possible for cases of high use, but not so much for those that are already low use. However, the major obstacle here is the financial risk for the grower, which can be subsidized by incentive programs.

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[24] David Pimentel and Michael Burges, "Small amounts of pesticides reaching target insects," Environment, Development and Sustainability 14 (2012): 1-2. https://doi.org/10.1007/s10668-011-9325-5.

[25] David Pimentel and Lois Levitan, "Amounts Applied and Amounts Reaching Pests," BioScience 36, 2 (February 1986): 86-91. https://www.jstor.org/stable/1310108.

[26] Rosenbom et al., "Pesticide leaching through sandy and loamy fields e Long-term lessons learnt from the Danish Pesticide Leaching Assessment Programme," *Environmental Pollution* 201 (2015): 75-90. http://dx.doi.org/10.1016/j.envpol.2015.03.002.

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By their nature, PPPs have negative impacts on biodiversity since their aim is to kill unwanted plants and pests. From this perspective, one might think that organic farming with no synthetic PPPs would be better for biodiversity. Unfortunately, the solution is not that simple. Organic farming, on average, is 25% less productive than conventional farming.[28] Thus, to produce the same amount of food, more farmland is needed. Having more farmland requires deforestation, which is detrimental to biodiversity, greatly outweighing the negative effects of PPPs.

Using natural products for pest protection would only be meaningful with regards to sustainability if they can provide a similar reduction in yield losses compared to their chemical alternatives. This way, since the yield per area of land will be conserved, biodiversity will improve as there will be no increase in land use. Natural PPPs, or biopesticides, can be of plant, microbial, or mineral origin, or comprise living micro-organisms, such as nematodes that feed on pest insects. Unlike their chemical alternatives, biopesticides are harmless to non-target organisms. However, since these natural PPPs are more expensive than traditional PPPs, farmers would be hesitant to make the switch if they are not incentivized to use higher cost natural PPPs, and if they do not achieve crop yields similar to the levels obtained through traditional crop protection.

6. Regenerative Agriculture

As a proposed solution to achieve sustainable food production, regenerative agriculture (RA) is one of the most widely studied and implemented sustainable farming techniques. In fact, RA is an inclusive name, which encompasses different farming techniques that, in one way or another, aid in sustainability.

Although a clear scientific definition of RA is yet to be determined, some objectives and activities are present in most scientific studies. The main objectives of RA are: to (i) improve ecosystem health and biodiversity, (ii) improve water quality and availability, (iii) improve soil health, (iv) increase carbon sequestration, and (v) optimize resource management. To achieve these objectives, various farming activities are recommended: (i) reducing tillage, (ii) using cover crops, (iii) rotating crops, (iv) incorporating perennials and trees (intercropping), (v) restoring natural habitats, (vi) integrating livestock in farms, (vii) applying ecological and natural principles, and (viii) limiting external inputs and maximizing on-farm inputs.[29,30]

No-till is a cultivation technique that limits soil disturbance through tillage. No-till can reduce soil erosion, improve water infiltration, and increase organic matter retention and nutrient cycling. In this method, the soil is only disturbed along the slit or in the hole into which the seeds are planted, and debris from previous crops covers the seedbed. In organic farming, in which herbicides are not used, no-till is often complemented by crop rotation and cover crops to help suppress weeds.

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[28] Verena Seufert, Navin Ramankutty, and Jonathan A. Foley, "Comparing the yields of organic and conventional agriculture," *Nature* 485 (May 2012): 229-232. https://doi.org/10.1038/nature11069.

[29] L. Schreefel et al., "Regenerative agriculture – the soil is the base," *Global Food Security* 26 (August 2020): 100404. https://doi.org/10.1016/j.gfs.2020.100404.

[30] Peter Newton, Nicole Civita, Lee Frankel-Goldwater, Katharine Bartel, and Colleen Johns, "What Is Regenerative Agriculture? A Review of Scholar and Practitioner Definitions Based on Processes and Outcomes," *Frontiers in Sustainable Food Systems* 4 (October 2020): 577723. https://doi.org/10.3389/fsufs.2020.577723.

Cover crops are used as animal feed, but they are also critical for improving water availability and soil health. For example, at the beginning of summer, when winter wheat is harvested, cover crops such as alfalfa can be planted on that land until the next sowing season, rather than exposing the soil directly to the sun. Since cover crops minimize direct sun exposure, the soil can retain more water during a dry summer season. After cover crops are harvested, the land is in a better condition to take on water from subsequent rainfalls. Water runoff on empty farmland that has been exposed to long hot and dry periods is common after the first heavy rainfall, and these situations can often result in flooding.

A natural way to limit external inputs for soil nutrition is to make use of compost and animal manure, rather than relying mostly on mineral fertilizers. To incorporate such practices, the integration of livestock in farms is crucial. Other natural materials such as volcanic rock can be used to incorporate micronutrients, which cannot be replenished by manure or compost alone. Using compost also aids in carbon sequestering.

7. Data Use in Agriculture

Data collection and deployment are becoming more important parts of any field or technology. Artificial intelligence systems need significant amounts of data to be trained and recurrent new data to operate on. Data use is also becoming a large part of novel agricultural technologies. Analyzing on-site data such as precipitation, humidity, and temperature allows AI systems to learn from and recommend irrigation and fertigation schedules. Through these recommendations, AI programs operate on-site irrigation/fertigation systems. In this way, farmers can use water and other inputs much more efficiently and increase their yields. The need for manual labor is likewise reduced.

Data and the Internet of Things (IoT) are also being used to craft more precise pest-management systems. Conventionally, various pesticides are applied to the entire farm to prevent yield loss due to potential pests. To be precise, the insect trap stations of pest-management systems are set up at regular intervals. These stations attract and confine insects by releasing pheromones and are equipped with an image sensor that can track the number of trapped insects and send this information to the main computer or cloud. Hence, the real-time insect population is estimated throughout the farm. Through this insect population map, farmers can decide where to apply the necessary insecticide to protect their crops.

AI systems and farmers can learn from the inputs, actions, and resultant outcomes of AI's decisions. Hence, as these systems get more experience in the field, their efficiency will further improve. In a similar logic, AI systems can also be fed real data from other farms, including humidity, irrigation, fertigation, temperature, sowing and harvest times, and crop yields, run these inputs through algorithms, and compare them to real-life scenarios, in a cycle of self-improvement.

Lastly, satellite imagery is being used to map humidity and temperature levels in fields, eliminating the need for on-site sensors. High-resolution versions can even detect single trees. This data can then be used to advise farmers on irrigation schedules, especially for vineyards and orchards.

8. Food Waste

Every year, almost one-third of global food production, approximately 1 billion tons, is wasted. In this regard, measures to prevent food loss alone greatly improve our chances of feeding the growing population. Food waste occurs in three main stages: food service, retail, and households. Globally, 61% of food waste comes from households, 26% from food service, and 13% from retail. One of the EU's 2030 sustainable development goals is to halve food waste per capita both at the retail and consumer levels.[31] Achieving this goal alone would be equivalent to increasing global food production by 25%.

Unpredictable weather conditions or a sharp drop in prices can oblige farmers to discard their crops, which are the main causes of early food waste. Meanwhile, inadequate infrastructure and poor planning and logistics cause food spoilage during the transportation stage. During processing and packaging, unnecessary trimming for aesthetic or technical reasons also result in significant food loss. At the retail and restaurant level, incorrect packaging, overstocking, and insufficient consumer demand also result in waste. However, especially in developed countries, most food waste occurs in households due to overbuying, overcooking, or forgetting to eat. Annual household food waste in Europe, Unites States, Canada, Turkey, and China are approximately 75, 59, 79, 93, and 64 kg per capita, respectively.[32]

What Can We Do to Reduce Food Waste?

We can reduce our food waste through the implementation of innovative technologies and social initiatives. Turning waste back into food is possibly the best option to mitigate food waste. In this regard, there are initiatives to transform unwanted bread and ugly fruit and vegetables into a puree and 3D printing them into baked snacks.[33] Another example is to use the waste pulp from beer breweries and juicer manufacturers and press it into granola bars, veggie burgers, or vegetable crisps.[34]

Unwanted food can also be used as animal feed. For example, more than half of Japan's food waste is converted into eco-friendly animal feed, mostly for pigs.[35] This strategy not only reduced Japan's environmental impact but also created a new market for eco-friendly Japanese pork. Edible insects are also perfect to feed on food waste.

Transforming food waste into new, compostable materials is also a promising approach. For example, MarinaTex converts fish scales, algae, and crustacean shells into a bioplastic, which composts in a few weeks.[36] Similarly, coffee grounds are used in the production of bioplastics.[37]

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[31] Natalie Marchant, "The world's food waste problem is bigger than we thought - here's what we can do about it," World Economic Forum, March 26, 2021, https://www.weforum.org/agenda/2021/03/global-food-waste-solutions/#:~:text=Around%20931%20million%20tonnes%20of,halve%20food%20waste%20by%202030.

[32] Hamish Forbes, Tom Quested, and Clementine O'Connor, *Food Waste Index Report* 2021 (Nairobi: United Nations Environment Programme, 2021), 58-65.

[33] Hanna Watkin, "Cape Town Designers Reduce Waste by 3D Printing "Ugly" Fruit and Veg," *All3DP*, June 11, 2018, https://all3dp.com/cape-town-designers-reduce-waste-3d-printing-ugly-fruit-veg/.

[34] Leanna Garfield, "We tried granola bars made from beer waste — and they were surprisingly delicious," *Business Insider*, June 27, 2016, https://www.businessinsider.com/we-tried-these-new-granola-bars-made-from-beer-waste-and-they-were-surprisingly-delicious-2016-6.

[35] Risa Maeda, "Japan feeds animals recycled leftovers," ***Reuters***, July 23, 2008, https://www.reuters.com/article/lifestyle-japan-food-recycled-col-idCAT21465920080723.

[36] "Marinatex - a home compostable alternative to plastic film," Marinatex, accessed October 20, 2022, https://www.marinatex.co.uk.

[37] "Wastespresso," Wastespresso, accessed October 21, 2022, https://www.wastespresso.com/.

Converting food waste to energy is another option. Biogas can be used directly for energy or purified into biomethane, which can be used as vehicle fuel. Burning food waste can also be used for heating water and generating electricity. In Sweden, public buses partially run on biomethane, and the country imports waste to supply hot water to local homes.[38]

If the above strategies are not applicable or feasible, we should compost food waste, such that it is transformed into natural fertilizers. Sending food waste to landfills should be avoided, since food degrades into methane, a potent greenhouse gas.

Social initiatives can also be efficient in fighting food waste. Food redistribution organizations collect surplus food and deliver it to underprivileged communities. An organized marketplace that connects food outlets and food suppliers can also be effective in lowering post-harvest losses. For example, Twiga Food reduced food harvest losses in Kenya from 30% to 4%.[39] In 2016, France became the first country to ban large grocery shops from wasting food by passing the Garot Law.[40] This legislation requires supermarkets to donate unsold food to partner charities, with the goal of halving retail food waste by 2025. Meanwhile, in Argentina, the Wiolit initiative established a software that allowed users to choose their dish in advance from canteen menus and gathered data about food preferences, which resulted in a 51% reduction in food waste.[41,42] In the United Kingdom, the bread discarded by bakeries is used to brew a beer named Toast Ale, which is known as the "planet saving beer".[43]

Packaging

Packaging is critical for food security, as it allows for extended periods of storage of fresh produce. Achieving sustainable packaging, however, is not as simple as switching from plastic to paper, as many people might assume.

A technique called life-cycle analysis (LCA) is used to assess the totality of environmental impacts of packaging materials: (i) resources (ii) emissions related to its life cycle, including manufacturing and transport, (iii) the use, and (iv) end of its life cycle. Glass, for example, is indefinitely recyclable, whereas transport and remelting stages have high associated carbon emissions. Garçon Wines launched a new flat-bottom wine bottle made from recycled polyethylene terephthalate (PET), which allows for much more efficient packing – 91% more wine can be placed on the same pellet with 50% lower carbon emissions due to its lighter weight.[44] Glass bottles are also beneficial for deposit-return systems, but their carbon footprint only becomes lower than PET after being reused 20 times.[45]

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[38] Arfan et al., "Biogas as a Transport Fuel—A System Analysis of Value Chain Development in a Swedish Context," *Sustainability* 13 (2021): 4560. https://doi.org/10.3390/su13084560.

[39] Justin Norman, "How Twiga Foods reduces the price of food in Nairobi using technology," How we made it in Africa, July 12, 2020, https://www.howwemadeitinafrica.com/how-twiga-foods-reduces-the-price-of-food-in-nairobi-using-technology/68379/.

[40] Angelique Chrisafis, "French law forbids food waste by supermarkets," The Guardian, February 4, 2016, https://www.theguardian.com/world/2016/feb/04/french-law-forbids-food-waste-by-supermarkets.

[41] Wiolit," accessed July 20, 2022, https://www.wiolit.com.

[42] Inés Oort Alonso, "Fighting Food Waste With Social Initiatives," *Foodunfolded*, September 29, 2021, https://www.foodunfolded.com/article/fighting-food-waste-with-social-initiatives.

[43] Toast – Here's to Change," Toast Ale, accessed October 20, 2022, https://www.toastale.com.

[44] Rima Sabina Aouf, "Garçon Wines create flat wine-bottle case that's greener to ship," *dezeen*, March 7, 2019, https://www.dezeen.com/2019/03/07/10-flat-bottle-case-garcon-wines-design/.

[45] Fabiano Sordo, "Deposit-Refund System: Save Money, Reduce Waste and Save the Planet," *ecobnb* (blog), March 12, 2020,

Biodegradable and Active Packaging

Single-use containers skyrocketed during the Covid-19 pandemic. To reduce plastic accumulation and the formation of microplastics, bio-based, compostable materials are being developed that can be made from numerous sources of biomass. Recent examples include plastics made from fish,[46] bacteria,[47] seaweed,[48] starch,[49] and milk protein.[50]

In addition to biodegradable packaging to combat plastic waste, active packaging techniques are used to further prolong the shelf life of food products. With regard to active packaging, a special attention should be paid to nanotechnology. At the nanoscale, materials have very high specific surface areas, which allow them to have extraordinary properties, such as optimum material absorption. Nanofillers, such as halloysite nanotubes, can absorb unwanted gases, or be pre-loaded with various active agents, such as antimicrobials. These nanofillers can then be integrated in the production of the packaging materials.

Active packages enable improved food safety through different mechanisms, including gas scavenging and barrier, antimicrobial, antioxidation, and moisture and temperature control.[51] For example, certain nanofillers that are added to packaging films can absorb the naturally produced ethylene gas, which is responsible for the softening and aging of fruits and vegetables. Furthermore, these films perform better than neat polymeric films in limiting the transmission of spoilage-inducing gas molecules and moisture.[52] Meanwhile, antimicrobial packaging can be produced by incorporating essential thyme oil in polymeric films.[53] As a result, such active packages slow down the ripening process and hinder bacterial growth. By using these technologies, we can extend the best-before dates of many food products, including fruits, vegetables, and meat, and drastically reduce food waste. This will have the same positive effect on sustainability as increasing crop yields per hectare.

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https://ecobnb.com/blog/2020/03/deposit-refund-system/.

46 Marinatex, "Compostable alternative to plastic film."

47 Patricia Cazón and Manuel Vázquez, "Bacterial cellulose as a biodegradable food packaging material: A review," *Food Hydrocolloids* 113 (2021): 106530. https://doi.org/10.1016/j.foodhyd.2020.106530.

48 Dietz Carina et al., "Seaweeds polysaccharides in active food packaging: A review of recent progress," *Trends in Food Science & Technology* 110 (2021): 559-572. https://doi.org/10.1016/j.tifs.2021.02.022.

49 Helen Onyeaka et al., "Current Research and Applications of Starch-Based Biodegradable Films for Food Packaging," *Polymers* 14 (2022): 1126. https://doi.org/10.3390/polym14061126.

50 Viviane Machado Azevedo et al., "Effect of replacement of corn starch by whey protein isolate in biodegradable film blends obtained by extrusion," Carbohydrate Polymers 157 (2017): 971-980. http://dx.doi.org/10.1016/j.carbpol.2016.10.046.

51 Selçuk Yildirim, "Active Packaging Applications for Food," *Comprehensive Reviews in Food Science and Food Safety* 17, 1 (January 2018): 165-199. https://doi.org/10.1111/1541-4337.12322.

52 Cüneyt Erdinç Taş et al., "Halloysite Nanotubes/Polyethylene Nanocomposites for Active Food Packaging Materials with Ethylene Scavenging and Gas Barrier Properties," *Food and Bioprocess Technology* 10 (2017): 789-798. https://doi.org/10.1007/s11947-017-1860-0.

53 Sara Casalini and Marco Giacinti Baschetti, "The use of essential oils in chitosan or cellulose-based materials for the production of active food packaging solutions: a review," *Journal of the Science of Food and Agriculture* (2022). https://doi.org/10.1002/jsfa.11918.

9. Policy Recommendations

Considering the findings presented above, there are many actions that governments or international organizations can take. However, coming up with the optimum solution is not as straightforward as determining the shortcomings of the current situation. Also, a one-size-fits-all solution is often not possible. So, to supplement the views presented in this paper, people from different backgrounds were interviewed about sustainable food production. Their insight was used to help form the policy recommendations provided below.

Interviewees include a manager at a leading agriculture firm in Turkey, an academician working on biological plant protection, an agricultural start-up founder, and university students. A total of 14 interviewees answered four multiple-choice and seven open-ended questions. I first aimed to understand which topics are regarded as the greatest challenges for agriculture, but the majority of the survey was intended to ascertain the interviewees' policy recommendations.

Interviewees regard drought, excessive fertilizer and pesticide use, development of pesticide resistance, inadequate use of technology, lack of education, and decrease of agricultural land as the major challenges for food production. Extreme weather events due to climate change, lack of genetic diversity of crops, biodiversity loss due to deforestation, genetically modified crops, and soil erosion were viewed as other challenges that should be tackled.

Solutions to these challenges do not usually comprise one simple method, but rather require an interplay of complementing approaches along with adequate incentives for methods that require time to be economically feasible. The average farmer will almost always choose the more economical method, ignoring its possible negative effect on the environment. Therefore, switching from unsustainable technologies that are more economically feasible than their sustainable alternatives requires a mixture of restrictions and incentives.

Interviewees were also asked to elaborate on the prospective effects of climate change on food production, policy suggestions on the use of chemical pesticides, and non-degradable PE mulch film, which causes microplastic accumulation. They were asked to explain their perspectives on hybrid/ancestral seeds from a lawmaker's viewpoint. Finally, they provided their thoughts on agriculture 4.0 and the challenges of incorporating novel technologies into farmers' current practices.

Irrigation

Agriculture's primary input is water. We may consume only 2 liters of it per day, but 3,496 liters are required to produce the daily food of only one person. This means our water footprint due to food production is roughly 100 million liters in an average lifetime.[54,55] Daily domestic water consumption per person, including showering, flushing, laundry, cooking, and cleaning is negligible at 137 liters compared to agricultural water use.[56] All

[54] Max Roser, Esteban Ortiz-Ospina and Hannah Ritchie, "Life Expectancy," Our World in Data, last modified October 2019. https://ourworldindata.org/life-expectancy.

[55] Angela Morelli, "The Water We Eat," thewaterweeat, accessed October 25, 2022, https://thewaterweeat.com.

[56] Ibid.

interviewees agreed that, in an ideal world, agriculture should account for at most 40% of global water usage, wherein this ratio is currently around 70% and even exceeds 90-95% in underdeveloped countries.[57] Even a minimal increase in water use efficiency in agriculture is translated into major water savings and is considerably more effective than striving to save water in our homes. Therefore, any governmental incentive to encourage farmers to assume the financial burden of transitioning to water-efficient irrigation systems is highly valuable in terms of sustainability.

Helping farmers switch from flood irrigation to sprinkler or drip irrigation is a common suggestion. Terminating the cultivation of water-hungry plants, such as corn and sugar beet, in water-scarce regions is yet another proposition that is part of better general cultivation planning – each year, a new agricultural production plan should be devised and implemented, stating which major crops are to be produced by whom according to the needs of the population and suitability of each region. A large portion of our farming land is used to grow crops for animal feed including corn and alfalfa, which are water-hungry and generally cultivated from hybrid seeds that do not produce fertile seeds. In this case, switching back to free-range animal husbandry in pastureland is regarded as a more sustainable solution for utilizing more arable land for human nourishment with a lower water footprint.

Plant Protection, Plastic Pollution, Ancestral Seeds

Although the public has negative view of pesticides, no interviewee found a complete ban on chemical pesticides to be realistic. Instead, most agreed that further limitations on chemical pesticides combined with the incentivization of biological pest management systems present a more sensible approach.

When asked about non-degradable PE mulch films, unlike chemical pesticides, some suggested a complete ban on them and a thorough transition to biodegradable alternatives. However, most found recycling mandates and further incentives for bio-degradable films to be a more reasonable approach.

Although there were ambivalent views on hybrid and ancestral seeds, there was a consensus on the need for the incentivization of the utilization of ancestral seeds, at least to a certain extent. This incentive should be supported by a guarantee of purchase by the government and corporate firms to provide assurance to farmers. According to plant protection academicians, ancestral seeds are genetically resistant to regional pests from an evolutionary point of view. However, their main drawback is that their yield is generally inferior. One shared expert suggestion was to incentivize the hybridization of ancestral seeds with high-yielding variety seeds.

Agriculture 4.0

Finally, the interviewees provided their insights on agriculture 4.0 and the challenges of transitioning farmers' current practices to incorporate novel technologies.

Regarding agriculture 4.0, most interviewees thought that current farmers were not ready to implement novel technologies, with one stating that most farmers still employ conventional techniques. For this reason, incentivization and restriction mechanisms

[57] The World Bank, "Annual freshwater withdrawals, agriculture."

are essential to changing farmers' practices. In addition, a more prevalent agricultural cooperative network is critical for influencing farmers. Agriculture engineers in cooperatives can guide farmers in (i) determining crops that are needed and are suitable for their land, (ii) selecting appropriate irrigation methods for their land, (iii) devising fertilizer and plant protection product application schemes, and (iv) evaluating novel technologies and facilitating their implementation. Additionally, farmers can be required to get permission from their cooperatives for every practice. Agriculture engineers in these cooperatives should follow technological developments around the world and be required to complete training every one or two years. Moreover, some interviewees proposed mandating the proper education of farmers and restricting those from farming who are untrained.

Stocking

Due to high inflation in some countries, some farmers who have the economic freedom to do so prefer to stock their harvest to sell at a higher price in the near future. However, stocking requires a warehouse investment, which would not be feasible for single farmers. Managing the stock of many farmers at a common warehouse, on the other hand, may not only provide economic benefits to farmers of all sizes but also solve more general market problems related to supply-demand imbalances.

Governmental incentives for licensed stocking can provide farmers with stable, foreseeable revenues. Licensed stocking in agriculture is a system that sets the rules for and regulates such warehouses. Universalizing this system would: (i) ensure the safety and quality of the harvest, (ii) enable the classification of produce by quality and size by a competent legal authority, (iii) overcome price surges by maintaining stocks and prevent sudden price drops during harvest periods, (iv) enable simple registration of agriculture commerce, and (v) provide financing to farmers through electronic production notes.[58,59,60,61]

Selecting the appropriate crop is vital both from agricultural and economic perspective. Wheat, the profit from which can be as low as 1-2%, can be grown in many countries, prompting some eligible countries to buy it from others and grow crops with higher returns. However, to have this freedom, having sufficient stocks is crucial to compensate for unexpected delays in shipment. This freedom allows countries to include more revenue-generating crops in their cropping patterns. Private licensed and government warehouses can be a major driving force behind a shift towards economically more feasible cropping patterns.

Data Use in Agriculture

Data-driven AI or other automated systems are used by certain farmers, who do not necessarily share their intellectual property with each other. These technologies are becoming more widespread every day, and will soon cover a significant area of our

[58] "Lisanslı Depoculuk ve Ürün İhtisas Borsası," Türkiye Cumhuriyeti Ticaret Bakanlığı, December 31, 2020, https://ticaret.gov.tr/ic-ticaret/sikca-sorulan-sorular/lisansli-depoculuk-ve-urun-ihtisas-borsasi.

[59] "Lisanlı Depoculuk Sistemi Nedir?", Köseoğlu Agro, accessed on January 11, 2023, https://www.koseogluagro.com.tr/tanimi.html.

[60] Tarım ve Orman Bakanlığı, "LİSANSLI DEPOLARDA MUHAFAZA EDİLEN TARIMSAL ÜRÜNLER İÇİN DESTEKLEME ÖDEMESİ YAPILMASI HAKKINDA TEBLİĞ (TEBLİĞ NO: 2021/30)," Resmi Gazete, November 14, 2021, https://www.resmigazete.gov.tr/eskiler/2021/11/20211114-6.htm.

[61] "Elektronik Ürün Senedi (ELÜS) Karşılığı Kredi," Ziraat Bankası, accessed January 11, 2023, https://www.ziraatbank.com.tr/tr/kurumsal/tarim/diger-kredilerimiz/elektronik-urun-senedi-elus-karsiligi-kredi

farmlands. Sharing agricultural data will benefit collective food production. Farmers who do not have the necessary equipment can nevertheless get insights from neighboring farmers who do. Moreover, tracking and recording water use, crop yields and types, fertigation, and pesticide use can help compile a larger agricultural record from which governments can benefit. More favorable cropping patterns can be devised, and irrigation can be better controlled. In Europe, a guideline is proposed for such use of data, under the name of EU Code of Conduct on agricultural data sharing by contractual agreement.

10. Conclusion

Feeding people within the sustainable limits of our planet is an intricate task. It requires the cooperation of many stakeholders, including even consumers to manage food waste. Unfortunately, climate change makes this task even more difficult because it creates erratic precipitation regimes that result in droughts and flooding, increases pest populations in some regions, and allows new pest species to emerge.

The following should be the leading items of a global action plan:

- Reducing water usage in agriculture by improving irrigation canals and infrastructure, switching to more efficient irrigation systems, and using cultivation planning.
- Educating farmers through cooperatives and other organizations and making training certification for farmers a requirement.
- Organizing campaigns to prevent the spread of false information on farming techniques and pesticide residues among the public, and to combat general information pollution.
- Harnessing cultivation planning according to the conditions of each region to limit surpluses or deficits of food production and use natural resources more efficiently.
- Subsidizing farmers for high-cost input items, such as gasoline, seed, pesticide, and fertilizer.
- Integrating data use through on-site sensors and satellite imagery to enable more efficient use of resources and smart crop protection.

Agriculture has many inputs, which are not independent of each other. Numerous methods have been proposed to address a particular problem with current, traditional practices. Yet, almost always, any altered method or new technique in turn affects other mechanisms and methods, thereby influencing the overall outcomes in terms of sustainability, crop yields, and environmental impact. Thus, similarly, the methods we utilize in agriculture, conventional or novel, are not independent of each other. I believe this school of thought is most important when evaluating the potential impact of alterations or additions to current agricultural practices.

Bearing this in mind, it can be understood why a single major change in any aspect of agriculture cannot serve as a magic formula for sustainable food production. For example, while organic farming eliminates chemical pesticides, its yield efficiency is, on average, 25% lower than that of conventional agriculture.[62] Thus, by itself, it cannot be a comprehensive sustainable solution unless it addresses the crop yield losses through additional techniques.

[62] Bylemans, "Farming without plant protection products," II

Solutions for sustainable food production are complicated, and we do not have definitive answers. In fact, the ideal strategy should be one that is flexible and can adapt. Meanwhile, climate change and other factors are altering rainfall regimes, temperatures, pest types, and populations, among others. Thus, we must constantly revise our strategy to suit current and projected environmental conditions, incorporating ideal agricultural practices and striving towards sustainable food production for all.

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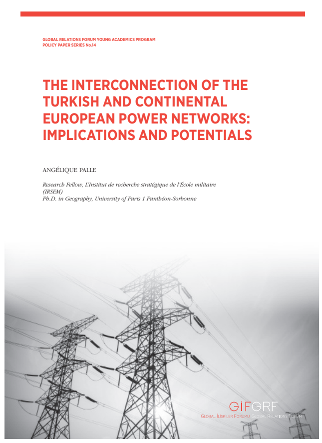

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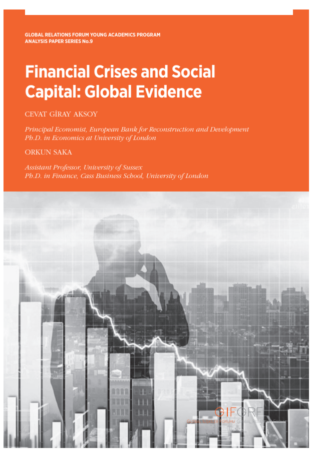

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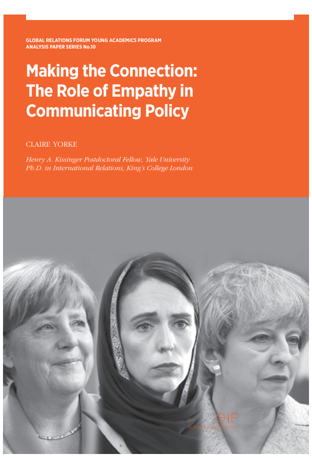

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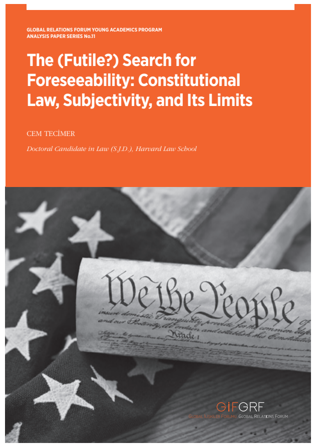

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