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ARTICLE

Food challenges, technological changes and food geopolitics[1]

Desafios alimentares, mudanças tecnológicas e geopolítica alimentar

Georges Flexor[1]

[1] Instituto Multidisciplinar, Programa de Pós-graduação em Ciências Sociais: Desenvolvimento, Agricultura e Sociedade, Departamento de Ciências Econômicas, Universidade Federal Rural do Rio de Janeiro (UFRRJ), Rio de Janeiro (RJ), Brasil. E-mail: georges@ufrrj.br

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Abstract: In recent years, food insecurity has worsened despite decades of progress. Agrifood systems must evolve to address population expansion and climate change simultaneously. A problem of this magnitude necessitates the development of technologies that simultaneously increase (nutritious) food production and protect the environment. Based on an a diagram analysis of the economic model of technological change, this article explores various technological paths that can emerge in response to rising food prices and the need to preserve land. This article indicates, through the use of specialized literature, that the hypotheses derived from the analysis of the technological change model already exist. In addition, we investigate the potential geopolitical effects of these technological shifts on the global agri-food industry. Changes aimed at conserving land must encourage urban food production, systematic resource optimization on abundant high-quality land, and regenerative practices. In addition to rising food prices and population growth, the increasing significance of urban consumers and the internalization of environmental values should drive these various developments.

Keywords: food insecurity; sustainable development goals; technological change; geopolitics.

Resumo: A insegurança alimentar piorou nos últimos anos, apesar de décadas de progresso. Para lidar com a crescente população e as mudanças climáticas, os sistemas agroalimentares precisam mudar. Exige o desenvolvimento de tecnologias que, ao mesmo tempo, aumentem a produção de alimentos (nutritivos) e protejam o meio ambiente. Com base em uma análise de diagrama do modelo econômico de mudança tecnológica, este artigo examina vários caminhos tecnológicos que podem surgir em resposta ao aumento dos preços dos alimentos e à necessidade de preservar a terra. Este artigo indica, por meio do uso de literatura especializada, que as hipóteses derivadas da análise do modelo de mudança tecnológica já existem. Além disso, examinamos os potenciais impactos geopolíticos dessas mudanças no setor agroalimentar em todo o mundo. As mudanças que visam à conservação da terra devem incentivar a produção urbana de alimentos, a otimização sistemática de recursos em terras abundantes de alta qualidade e as práticas regenerativas. Esses desenvolvimentos devem ser impulsionados pela crescente importância dos consumidores urbanos e a internalização dos valores ambientais e o aumento dos preços dos alimentos.

Palavras-chave: segurança alimentar; objetivos de desenvolvimento sustentável; mudança tecnológica; geopolítica.

1. Introduction

The second goal addressed by the SDGs (Sustainable Development Goals) is the abolition of hunger. There was some hope at the start of the last decade that humanity could achieve this goal by 2030. Extreme poverty was rapidly declining, as was the proportion of people who

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were food insecure. However, since mid-2010s, the goal of achieving zero hunger has become more elusive. Food insecurity began to rise as a result of slower economic growth and rising food prices. Without affordable and nutritious food and adequate access to it, there is no hope to foster human capital development or promote productive transformation. Achieving the goal of zero hunger has become more distant.

While most analysts agree that rising food prices are the primary source of food insecurity in the short run, one fundamental challenge in the long run is to produce more food, particularly nutritious food, in a sustainable manner. What technological changes are likely going to happen in order to meet these challenges? Because land use is a major contributor to the production of greenhouse gases (Crippa et al., 2021; Poore & Nemecek, 2018), increasing food supply necessitates the development of solutions that minimize its use or enable it to generate positive rather than negative externalities. The paper introduces an analytical framework that can be used to examine various technological developments that may emerge as a result of these challenges. It not only provides a conceptual framework for analyzing the diversity of technological changes, but it also allows us to develop hypotheses about their potential effects on global food geopolitics, providing an analytical tool that policymakers can use to establish food scenarios and formulate policy agendas to address food security in the coming decades. The article is based on a review of relevant literature, a visual exploration of secondary data produced by the Food and Agriculture Organization (FAO), and a diagram analysis of technological change as developed by modern microeconomic analysis (Koutsoyiannis 1975).

In addition to the introduction, the paper is divided into four sections. The first section contains information on current agricultural markets behavior and global food security. This underscores the significance of current food challenges. The second section presents a conceptual framework for investigating how to improve food security in the face of fundamental environmental restrictions. The framework, which draws on basic microeconomics diagram analysis and is intended to be accessible to any social scientist or policymaker interested in the future of food security, indicates how different land-saving technological changes may develop and suggests hypotheses about their possible geopolitical consequences. The third section points out several emergent technological breakthroughs that highlight the analytical potential of the framework. In the last section, hypotheses regarding their possible spatial and geopolitical effects are explored.

2. Analytical Background

Food question at the beginning of the 21st century

Food insecurity and hunger, after showing a significant decrease in the first decade of the 21st century, have increased in recent years. In 2001, 13.2% of the world's population was undernourished. In 2015, this proportion had decreased to 8.3% and remained stable until 2019. In 2020, however, it grew to 9.3% and in 2021 it reached 9.8%. According to the United Nations (World Food Programm, 2022), in 2021, between 702 and 828 million people suffered from hunger and about 2.3 billion people were food insecure.

The increase in food insecurity is particularly worrying because it occurs in a food context marked by intense social and geographic inequalities. The proportion of undernourished people is concentrated in low-income countries and, to a lesser extent, in middle-income countries. Most of these countries are on the African continent, the worst case being found in Somalia, where 59.5% of the population is estimated to be undernourished, according to data previous to the Covid-19 pandemic.

In addition to geographical inequality, food insecurity greatly affects women and children. In 2019, globally, almost 30% of women of reproductive age (i.e., 15 to 49 years old) suffered from anemia, which is particularly severe in South Asia (49.35%) and Sub-Saharan Africa (40.55%) countries. Because of malnutrition, an estimated 149 million children under five years old were considered stunted in 2020. In countries such as Mozambique, Niger, Central African Republic, Madagascar or the Democratic Republic of Congo, the proportion of children under five years of age who were more than two standard deviations below the average height for age was over 40%.

Access issues to a healthy diet – that is, one made up of a variety of foods such fruits and vegetables, meat and dairy products, as well as cereals and other starchy foods – are another manifestation of food insecurity and associated inequities. In 2020, more than three billion people could not afford to purchase the whole spectrum of foods that are essential to a balanced diet. Most of them live in low-income countries in South Asia and Sub-Saharan Africa. In middle-income countries, particularly in the Middle East, North Africa and Latin America, the high cost of a healthy diet contributes to the increase in the number of overweight individuals, many of whom can only afford calorie-dense but nutrient-poor foods such as rice, pasta, potatoes, cereals, bread and sugar.

These problems with food security make it hard to reach the SDG 2030 goals. And, as we will see below, recent food market trends are one of the factors that make this challenge even more serious.

Food prices

Food high inflation has been a major contributor to the rise in food insecurity in recent years. The FAO food price index increased by 39.92% between January 2015 and July 2022. Although the index remained stable between 2015 and 2020 due to low economic growth (global GDP grew on average 1.75% per year between 2012 and 2019) and normal supply conditions, food prices have risen dramatically since the beginning of 2021. Rising production costs due to rising energy prices, logistics disruption caused by Covid-19 and unfavorable weather conditions in several food commodity producing regions have put pressure on food supply and trade. The problems affecting food supply led prices of food commodities to increase rapidly in a context of renewed demand following vaccination against Covid-19 and the subsequent gradual normalization of economic activity. The conflict between Russia and Ukraine, two major producers of wheat, sunflowers, and fertilizers, which started at the beginning of 2022, leads to the acceleration of food price inflation.

Beyond short-term tensions that drive food price behavior, some medium-term trends shaping the broader context must be highlighted in order to analyze the challenges to be addressed, aiming to reduce long-term food insecurity and achieve SDG goals. The upward trend in prices that has characterized the behavior of food markets over the last two decades is one of the most critical aspects for long-term food security. As shown in Figure 1, price indices of the major food commodities have been rising since the beginning of the new millennium, indicating a context of long-term change in food markets.[2]

[2] The linear relationship between the FAO food price index and time, measured in months, was positive from January 2000 to July 2022, with the coefficient of the linear regression between time and index being 0.2.

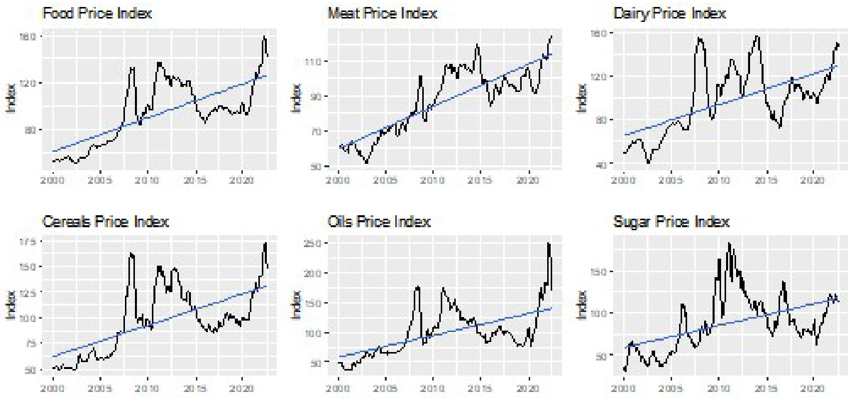

Figure 1. Trends in the major food price index from 2000 to 2020
Source: FAOSTAT (Food and Agriculture Organization of the United Nations, 2023)

The primary drivers of this trend are, according to most analysts, on the demand side, population growth, rising incomes and the institutionalization of biofuel policies; and, on the supply side, declining investments in agricultural research and development, rising production costs and climate change. The rapid economic development of China and India over the past two decades has had both direct and indirect effects on the behavior of food prices (Baffes & Dennis, 2013; Mitchell, 2008; Timmer, 2008). The growth in affluence of hundreds of millions of people has directly led to a substantial rise in demand for meats and vegetable oils. As Bennett (1941) noted eight decades ago, as earnings increase, intake of grains and starchy foods is replaced by protein-rich and more nutrient-dense foods. Between 2000 and 2020, China's economic growth of around 8.5% per year led to an average increase in meat consumption per capita of 48.16 percent. Even in India, where animal protein intake is extremely low, demand has increased in tandem with economic growth: the average supply of animal proteins per resident has climbed from 9 grams per person per day in 2000/2002 to 15 grams per person per day in 2019/2017, a 66.66% increase. As an increase in consumption of animal proteins implies a substantial increase in demand for soy or corn, and given the demographic weight of China and India, any increase, even if marginal, in consumption of meat in these two countries ends up generating a substantial increase in demand for grains, thereby exerting upward pressure on their prices.

The interaction between agricultural commodities and energy markets fostered by the institutionalization of biofuel production and use policies in the 2000s is another factor influencing the behavior of food prices. In the United States, the amount of energy generated by biofuels, such as ethanol and biodiesel, increased by 858.33% between 2000 and 2011. Zhang et al. (2010) found a positive correlation between the effects of biofuel production and food costs when analyzing the relationship between the two. However, they note that this effect diminishes over time. In addition, this link varies from crop to crop, with the increasing demand for energy influencing the price of maize but having essentially little effect on the pricing of other grains (Zilberman et al., 2013). After being criticized for contributing to rising food costs (Von Braun, 2008a; Ziegler, 2008), biofuel production has lost much of its political attractiveness, and its growth rate is decelerating substantially. From 2011 to 2021, global production increased by 45.89%. In the preceding decade, its growth was 581.65%.

Several supply-side factors contribute to the upward trend in food commodity prices. The rapid growth of China, India, and the developing world in general has increased demand for energy and minerals, raising agricultural production costs and thus prices (Alexandratos, 2008; Radetzki & Wårell, 2020). China's case is once again unique. China's economic growth in recent decades has been primarily driven by the expansion of industry and infrastructure in energy and mineral-intensive sectors. The country has turned to international markets to meet some of its requirements, increasing imports of key energy and mineral commodities. Because food production is becoming more energy and mineral commodity intensive – whether for transportation, machine use, or fertilizer production –, commodity prices have risen as a result of increased import demand, particularly from China, resulting in higher agricultural production costs and, thus, higher food prices (Baffes & Haniotis, 2010; Mitchell, 2008; Piesse & Thirtle, 2009).

Furthermore, insufficient public investments in agricultural research and development over the last two decades have resulted in a decrease in the growth rate of agricultural productivity, as seen in rice, which dropped from an average of +2.3% kg/ha per year between 1970 and 1990 to +0.89% in the following two decades; wheat, which decreased from +2.81% kg/ha per year to +1.08%; and corn, which decreased from +2.0% kg/ha per year to +1.48%. Private investments and the adoption of a highly mechanized production method on a broad scale in Brazil and Argentina helped preserve soybean productivity (at a rate of +1.27% kg/ha per year). In other words, agricultural productivity has increased slowly since the 1990s, and in the absence of increased public investment in research and development, food supply stagnates and prices continue to rise (Pardey et al., 2006; Timmer, 2008, 2015; Von Braun, 2008b).

In addition to rising production costs and lack of public investment in agricultural research, climate change is wreaking havoc with food supply. Droughts have become more common in recent decades, affecting both the major grains producing regions – the midwestern and western United States, southern Australia and a portion of the Southern Cone – and the densely populated food importing regions – the Mediterranean, the Middle East, and East Asia (Chiang et al., 2021). If this pattern continues and no significant technological changes occur, agricultural productivity will stagnate while import demand will rise. Food prices are likely to continue rising under these conditions.

Aside from signaling a potential structural change, the dynamics of food markets have become increasingly volatile. As shown in Figure 2, which depicts the square of the variation of monthly growth rate of price indices, agricultural commodity markets behavior over the last two decades has been marked by two intense peaks and frequent volatility. The two peaks correspond to events that shook the global economy as a whole, namely the 2008 financial crisis and the Covid-19 pandemic, which was followed by the conflict between Russia and Ukraine in early 2022, affecting primarily the grain and vegetable oil markets.

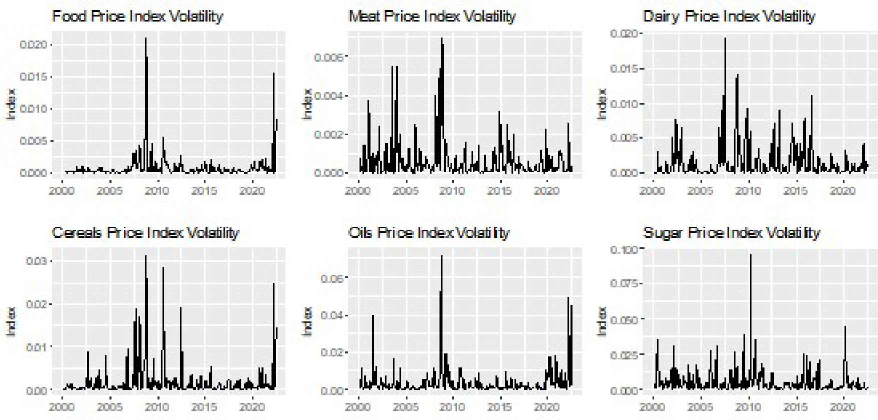

Figure 2. Volatility of the major food price index from 2000 to 2020.
Source: FAOSTAT (Food and Agriculture Organization of the United Nations, 2023)

According to Gilbert & Mugera (2014), the integration between energy markets and food markets is the primary cause of food market's increased volatility. By influencing production factors prices, energy markets affect the course of food prices. The institutionalization of policies for production and use of biofuels strengthens the integration of the energy market into agricultural commodity markets. Thus, as volatility in the former increases, the latter tends to follow suit. As a result of the rising financialization of energy markets, these markets have become more volatile, and this instability is ultimately transmitted to the wheat, corn, and soybean markets.

The financialization of agricultural commodity markets is frequently cited as contributing to rising market volatility (Field, 2016). Bruno et al. (2017) demonstrate the existence of a serial correlation between peak grain prices and financial activity. Through speculative operations on the futures markets, financial players attempt to profit from a situation in which the inelasticity of supply acts as a Damocles' sword for buyers of agricultural commodities at these critical junctures. In a scenario in which food stocks are relatively low (Piesse & Thirtle, 2009) and in which certain exporting countries impose export bans in response to potential social pressure induced by rising food prices, the presence of financial actors ends up further disrupting the behavior of prices. However, as Bruno et al. (ibid.) point out, the effect of financial operations on futures markets is short-lived and, to a certain extent, contributes to mitigate panic movements insofar as they provide purchasing options, even if they are extremely expensive.

More volatile and structurally rising food prices are indications that the fight against hunger is not nearly finished and that achieving the goals of social and sustainable development will require substantial investments for, simultaneously, increasing food supply, ensuring access to nutritious food, and promoting a significant reduction in greenhouse gas emissions. The following are some emerging technology avenues for addressing these difficulties.

3. A methodological framework to analyze food supply and technological changes: a diagram analysis

A diagram analysis is presented in this section to help understand what technological paths can be developed to sustainably increase food supply in the face of rising food prices. It is far too simplistic to account for the complexities of technological, organizational and institutional arrangements that characterize technological change. It does, however, provide a useful analytical framework for comprehending the technological options that may emerge in the context of structural change in food markets and fight against climate change.

Before illustrating how rising food prices drive the development of new technology, it is necessary to make some preliminary generalizations. We assume that food production – or calories – depends on two production factors: capital (k), which can be physical, human, or financial, or a mix thereof, and land (L). Various configurations of these factors can be used for production. In this sense, land and capital are substitutes. However, because they are imperfect substitutes, the amount of capital required to compensate for the loss of one unit of land, such as a hectare, while maintaining the same amount of food (or calories) varies. When production needs a great deal of capital, only a little amount of land is required to replace one unit of capital. However, as more land is used for production, less and less capital is required. This relationship is graphically depicted by the Q1 curve, which describes the various combinations of capital and land required to produce a particular quantity of food (or calories): Q1 is an isoquant, which is a simplified representation of the various production factors combinations that result in the same produced quantity. To make the analysis as easy as possible without sacrificing generality, we consider that the isoquant is continuous and convex, as neoclassical economic theory suggests.

There are two distinct types of technology, denoted by the letters A and B (Figure 3). A is relatively land intensive and B is relatively capital intensive. That is, to produce a quantity Q1 of food, technology A uses a lower capital-land ratio, i.e., K/L, than technology B. The latter is said to be relatively capital-intensive. In this framework, the relative cost of the various factors determines whether technology A or B should be used. Land is relatively inexpensive and technology A predominates in places and nations with a relative abundance of land (low K/L). Point 1 serves as a visual representation of it. In contrast, technology B is dominant in nations where land is relatively scarce, and capital is abundant – high K/L (point 2).

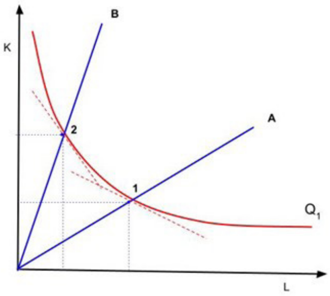

Figure 3. Diagram of Technological Choice

To increase food (calories) production from Q1 to Q2, both technology A and B require more land and capital (Figure 4). Producing Q2 units of food with technology A, shown at point 3 in the diagram, is only conceivable with a (substantial) increase in the amount of land and capital committed to agricultural output. If a country has an abundance of unexplored land and food prices rise, as they have in recent decades, then technology A can flourish. With technology B, food production needs additional capital and land inputs to produce Q2 (point 4). This technological path is expected to expand mostly in nations with relative capital abundance.

However, because allocating more land for agricultural production is one of the drivers of global warming, technology A faces restrictions in its ability to expand. In other words, land supply is rather inelastic, and the option of using technology A to increase output (from Q1 to Q2) is limited and environmentally hazardous. As a result, increased food supply is likely to come from more capital-intensive technologies. This process encourages the gradual adoption of more capital-intensive technologies in countries with a relative abundance of land, as graphically illustrated by the shift from technology A to AB, which is characterized by a 3b factor proportion at the Q2 production level. Food production growth faces fewer constraints in countries with a relative abundance of capital and a proclivity to adopt technology B.

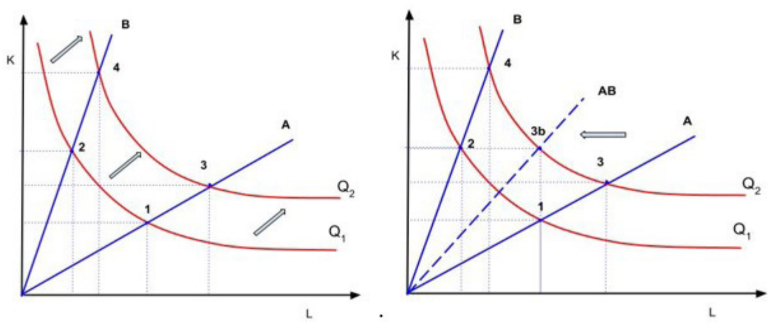

Figure 4. Diagram of increasing food production from Q_1 to Q_2

Food prices growth not only attract capital but also provides incentives for innovations. In a context where land is the primary constraint to production expansion, search for new products, processes, and markets tends to focus on the development of land-saving technologies. The search process can be time-consuming. However, with the expectation of long-term profits, innovation effort has plenty of incentives and ends up discovering a variety of technically and economically viable options. Innovative firms started to explore these options once they have been chosen. During this period, new technological paths begin to take shape and emerge as potential solutions. Exploration of these technological paths, driven by the inflow of capital attracted by the prospect of profits, promotes a biased productive change that allows the same amount of food (or calories) to be produced with fewer resources. This technological change is represented in Figure 5 by the shift to the left of the isoquant Q2. It can be seen that, for a given amount of capital, technological change needs less land, removing the main constraint to food supply growth.

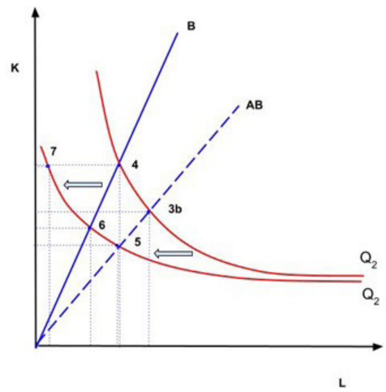

Figure 5. Diagram of Technological Changes

Based on this conceptual framework, we can formulate the following hypotheses regarding the technological paths encouraged by agricultural market behavior and the need to produce more food with less environmental impact:

- The rising trend of food prices and the implementation of environmental regulations should serve as catalysts for 1) the advancement of capital-intensive technologies and 2) the optimization and enhancement of the land factor's quality.
- In places with an abundance of land and easy access to capital, food production grows owing to solutions that make the best use of land. Adding capital improves food production, without the need to add new areas.
- In places where land is scarce and capital is abundant, technical change tends to favor more extreme methods to save land and take advantage of capital.

It is important to note that places with land and capital issues are more likely to import more food. It should also be observed that an increase in land endowments as a result of regeneration of degraded areas or improvement in soil quality resulting from increase in biodiversity, coupled with an increase in income that enables consumption of higher quality and more expensive food, represents an important technological alternative. This option tends to be an intriguing technology in places with a high standard of living or in regions and countries with fragile ecosystems and significant capital scarcity.

In the next section, we highlight some of the most promising new technological alternatives currently emerging to address the issue of food scarcity.

4. Results and discussions

Emerging technological paths

The first path is sustainable intensification (SI), which can be summarized as 'doing more with less'. Sustainable intensification is a process that aims to increase agricultural yields while decreasing the environmental impact of production (Garnett et al., 2013; Pretty et al., 2018). According to Pretty & Bharucha (2014), SI is not associated with a particular technology standard. Rather, it covers a variety of technological choices that share the goal of enhancing agricultural productivity without negatively impacting the environment or requiring the use of new land. Cassman & Grassini (2020) propose that environmental performance measures must be incorporated into the IS process at all stages of food production and marketing, from farm to fork. This allows for more accurate identification of the complex relationships between production and its social and environmental costs. With more and better information and increasingly complex algorithms to process it, agri-food chain management can achieve significant gains in efficiency and sustainability: soil moisture can be controlled, fertilizer use optimized, pest control significantly improved and so on. If applied in the world's major breadbasket, i.e., countries with favorable climates and fertile soils, SI can considerably reduce environmental impacts and production costs while increasing the yield of staple commodities. For low-income countries with relatively low agricultural earnings, SI focuses more on adopting best practices and narrowing the yield gap. With access to improved seeds, modern fertilizers, effective irrigation systems, and cutting-edge agronomic expertise, numerous nations can enhance food production without increasing land use. In this sense, there would be no need for a substantial change in agricultural methods, but its adoption would demand a larger capital investment. It corresponds to the set of possibilities indicated by the area between points 3b, 4, 5, and 6 in Figure 5.

The second alternative has no direct effect on agricultural production. It intends to lessen environmental impact by substituting animal protein with plant-based protein or laboratory-made meat. In response to a shift in consumer preferences away from animal protein consumption, new alternatives are being created. These innovations in the agrifood industry are currently mostly driven by plant-based meats. Incorporating modern technologies that aim to mimic the texture and juiciness of animal proteins through precise fermentation and cellular engineering, these breakthroughs have advanced fast since the beginning of the 2010s. According to many experts and corporate slogan-makers, the potential environmental effects of the spread of these food technologies are substantial. To understand why, it is essential to recall that meat production, particularly beef and sheep, is an inefficient method of creating protein. According to a study by Poore & Nemecek (2018), it takes 163.6 square meters of land to produce 100 grams of beef protein. The same quantity of protein may be obtained with only 3.4 square meters of land if peas, a fundamental ingredient in "plant-based" alternatives, are grown. In a paper published in Nature, Mazac et al. (2022) estimate that the potential savings in water and land use if animal-based foods were replaced with new or plant-based foods would reduce the environmental implications of food production by 80 percent in Europe. Even though the production of these alternatives does not yet present a diversified product offering, providing mostly hamburgers, chicken nuggets, sausages, and milk derivatives (Wilkinson, 2022), sales have already surpassed $7 billion. According to the Good Food Institute (2023), investments are increasing, precision fermentation is advancing, and new protein-rich products are being developed. This form of change, which is capital-intensive (human capital in particular) and land-saving, corresponds to the technology range between points 6 and 7 in Figure 5.

Growing meat from animal muscle cells is one of the food industry's most revolutionary technological frontiers. This technology does not aim to replace animal proteins with plant-based substitutes that mimic their taste and texture; rather, it aims to produce 'real' meats in laboratories. As it requires no land and its production process can, in theory, be decarbonized, this technology offers the possibility of producing a perfect substitute for animal protein at no cost to the environment. This possibility has sparked hopes that it could be one of the solutions for the future of food, which has encouraged increased investment. According to a report by the Good Food Institute on the state of the 'lab meats' industry, total investments in this technology reached $1.38 billion in 2021, a 336% increase over 2020 (Good Food Institute, 2022). Even though more than half of the companies that have invested in this new technology are in the life sciences industry, it should be noted that JBS, the world's largest animal protein company, is taking 'lab meats' seriously, announcing an investment of more than $100 million that includes the acquisition of the Spanish startup Biotech Food and the establishment of a research center in Brazil. This technology, which promises a 95% reduction in land utilization and carbon footprint compared to conventional beef production, corresponds to point 7 in Graph 6. Currently, however, it is more of a gamble than a reality, and according to skeptics, the technical problems of moving from laboratory to industrial-scale production are extremely complex and difficult (Sergelidis, 2019), if not insurmountable (Fassler, 2021).

Vertical farms are an additional technology that requires almost no land to produce food; thus, they correspond to point 7 in Figure 5. According to Pinstrup-Andersen (2018), an early skeptic about the technology, they represent a technological shift that has the advantages of producing nutrient-rich foods such as vegetables, fruits, and legumes in a controlled environment that avoids the use of fertilizers and pesticides and is highly water efficient.[3] As they are typically located in large urban centers, transportation costs and the significant losses that characterize their production can be minimized.[4] In contrast to 'laboratory meats,' this is no longer a bet. With several vertical farms already in operation, it is a reality by now. However, the widespread adoption of this technology faces significant challenges. Because it is capital-intensive, it tends to develop in wealthier urban areas, and there are many concerns about its spread to areas and countries where capital is less abundant. Furthermore, because it is also energy-intensive, a decrease in the relative price of energy is required to make it a broad technological change. The rapid decrease in renewable energy production costs, particularly solar, and the development of increasingly efficient lighting systems are factors that should encourage the spread of this food production system. However, to position itself as a viable and widespread alternative, its economic and environmental costs must be significantly reduced (Armanda et al., 2019).

Agroecology represents a perspective that is radically distinct from the technological pathways highlighted previously. According to some authors, agroecology is fundamentally distinct from other sustainable food production strategies (Altieri, 2018; Food and Agriculture Organization of the United Nations, 2018; Wezel et al., 2020). It does not seek to 'do more with less' as sustainable intensification does, nor does it seek to replace a portion of animal protein production with plant-based or laboratory alternatives. Neither does it seek to provide a 'high-tech' or urban solution to the problem of producing nutritious food. It is more appropriate to view agroecology as a paradigm shift for the agrifood system than as a technological change. It is based on the diversification of production to enhance biodiversity, the diversity of nutrient sources, and the resilience of production systems, as stated in the paper 'First International Symposium on

[3] It allows a 95% reduction in water use (Armanda et al., 2019).

[4] Food losses from farm to market account for 25.3% of root and tuber and 21.6% of fruit and vegetables (Food and Agriculture Organization of the United Nations, 2023).

Agroecology for Food Security and Nutrition' (Food and Agriculture Organization of the United Nations, 2018). In order to accomplish this, it adopts an epistemology that combines modern science with traditional knowledge. The goal is to develop knowledge that can shed light on local issues and stimulate the development of contextually appropriate technologies. In this sense, it calls for institutional innovations that encourage stakeholder (producers, communities, scientific organizations, political actors, companies, consumers) participation and foster trust. These institutional innovations are critical components in the search for product, actor, and scale synergies. In this paradigm, efficiency gains result from synergies that stimulate greater ecological, social, and economic diversity. In agroecological systems, efficiency is more of an emergent property than a process of resource optimization. By promoting recycling, ecological and cultural diversity of food systems, the development of locally adapted and socially inclusive solutions, trust among actors, and multi-scale forms of governance, agroecology positions itself as a set of ideas and practices aimed at reorganizing the relationships between society and food. It would be the equivalent of shifting out an isoquant that, rather than measuring food production in terms of quantities or calories, would provide a graphical representation of nutritional quality. This shift would not be the result of technological advancement or an increase in the use of resources, but rather the consequence of synergies resulting from the adoption of this new agri-food paradigm. Such a transformation of the agrifood system takes time, and without changes in consumer preferences and improved access to food diversity – such as higher and more secure earnings – it risks becoming socially and geographically limited.

Technological changes and food geopolitics

At this point, it is not possible to make an accurate prediction regarding the development of these various technological paths. On the other hand, hypotheses might be made with regard to their most likely distributional consequences on agrifood systems and its geopolitics. As was mentioned before, sustainable intensification should be beneficial to the most capital-intensive farmers in large grain producing regions, such as the Midwest of the United States, Ukraine, Russia, Argentina, Brazil, or a portion of Australia. Besides being land-abundant, these nations possess the financial and human resources required to invest in precision agriculture, big data, effective irrigation systems, or enhanced seeds. In low-income countries with abundant arable land and water but limited money, such as several sub-Saharan African nations, international community must fund the necessary investments for the spread of sustainable intensification technology. Lastly, for SI to be effectively sustainable, it needs institutional frameworks that can internalize the negative externalities of food production, monitor compliance with environmental standards, and manage land conflicts when they inevitably emerge.

If grain producers and production chains into which they are integrated have everything to gain from the aforementioned emerging technological changes, the same cannot be said for the meat industry, particularly beef. Meat production and consumption are impacted by a shift in consumer preferences. Meat is considered an environmental 'villain' due to its contribution to deforestation, inefficient protein and calorie production, and excessive methane emissions. The number of individuals who identify as vegetarian, vegan, or flexitarian[5] is increasing, particularly among young adults. This transition is facilitated by the emergence of near-perfect substitutes derived from plant alternatives, precise fermentation, or laboratory meats. Significantly unfavorable economic repercussions may result for large meat producers in Brazil, Argentina, the United States, Australia and Europe as a result of these developments.

[5] That is, a diet with reduced meat consumption.

The decline in demand for animal protein as a result of shifting consumer preferences and the development of substitutes should also have a detrimental impact on major producers of corn and soybeans used for animal feed. In contrast, it presents great opportunity for innovative entrepreneurs and businesses able to mobilize financial and human resources to industrially manufacture ever-more-perfect substitutes. This technological path tends to spread in large urban centers, particularly in North America and the European Union, where these resources are abundant and the demand for meat alternatives is increasing.

The development of vertical farms is particularly well-suited to large urban centers because of their advantageous location. In addition, because it consumes a lot of energy and requires a significant amount of both financial and human capital, it is likely to be more successful in nations and regions that have a high per capita income, are highly urbanized, and have a limited amount of available land. The Persian Gulf, the major cities of East Asia, Europe, and the United States of America are the ideal locations for the expansion of this technology on a larger scale. Since most of the world's population growth over the next few decades is anticipated to take place in urban areas of developing countries, vertical farms may flourish in these areas as their use becomes more widespread, their costs decrease, and cheaper and more standardized solutions are developed.

The spread of agroecology should be facilitated in two types of locations and countries. First, countries where customers value their food traditions and have the financial means to pay a premium to maintain them. In this sense, it tends to be adopted in wealthy nations as well as in great metropolitan centers of emerging nations, where a growing upper-middle class is ready to pay a larger amount of its income for a nutritious diet and is morally committed to preserving the environment. Another vector that promotes the spread of agroecological practices, particularly in developing countries, is the fragile ecological conditions found in many places. With its ability to improve biodiversity, soil quality, and the resilience of agricultural production systems, agroecology provides a more suitable path for many nations and regions afflicted by desertification, soil erosion, excessive evaporation and a lack of nutrient-rich food. Furthermore, because it is labor intensive, agroecology provides a way to smooth out the rapid urbanization that is occurring in the majority of these countries, gaining valuable time to better manage this fundamental demographic transition.

5. Conclusion

After decades of improvement, food insecurity has deteriorated in recent years. Food prices behavior indicates a structural shift in food markets. If we assume that the mechanisms driving food prices to increase will persist throughout the next decade, achieving the goals of sustainable development will become increasingly challenging. This paper aimed to demonstrate why the current food environment needs either technological changes or a food system paradigm that can simultaneously enhance supply and decrease the environmental implications of food production. The most likely distributional consequences of these technologies on agrifood geopolitics are highlighted, along with the principal technological paths that try to provide solutions to the food dilemma.

Countries with ample capital and high-quality land, as well as cities and their surrounding regions, are possible 'winners' of these developments. The former can greatly benefit from technological advances that promote sustainable intensification. By optimizing their resources, they can increase staple food production without increasing land use. The technical developments described above could benefit urban food producers as well, by partially altering the conventional relationship between food production and rural areas. Theoretically, the proximity between food consumption and production should enable greater incorporation of urban consumer preferences, facilitate access to capital markets, and stimulate product and process innovation. However, it may make rural populations that suffer the most from food insecurity even more politically invisible.

Attaining sustainable development goals would likely necessitate a combination of these many technology strategies. Public and private actors must respond immediately. Governments must engage with innovative land and water use planning policies, encourage financing of investments in green technologies, support the institutionalization of mechanisms to effectively internalize negative externalities (pollution, biodiversity loss, etc.), promote payment for ecosystem services, and lead the transition to a healthier diet. It is vital to institutionalize policies that can ensure access to nutritious foods for the most disadvantaged populations, particularly for the poorest mothers and children. Without these mechanisms, achieving sustainable development goals such as eradicating poverty and hunger or enhancing health, equitable opportunity and gender equality will be impossible. The status quo cannot be defended by private actors. They need to assume the risks associated with the transition, which includes providing large amounts of capital, investing in environmentally friendly technologies and nutrient-dense products, and enhancing the management of agrifood chains to reduce waste, food loss, water pollution, and energy consumption. The adoption of more open and socially inclusive modes of governance is also required to reduce monitoring costs, encourage technological advancement and bolster consumer rights. International markets that work properly are also critical for minimizing price volatility and assuring access to food imports. The agenda and efforts are not small, but they are necessary right now because there is no time to waste.

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