Essay

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From Dearth to Excess: The Rise of Obesity in an Ultra-Processed Food System

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From Dearth to Excess: The Rise of Obesity in an Ultra-Processed Food System

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Abstract: More people around the world now have obesity than suffer from starvation thanks to our modern food system. Agriculture was transformed over the 20th century by a variety of technological advancements that relied heavily on fossil fuels. In addition, government policies and economic incentives led to surplus production of cheap inputs to processed food industries that produced a wide variety of heavily marketed, convenient, rewarding, timesaving, and relatively inexpensive ultra-processed foods. The energy available in the food supply increased much more than population needs, albeit with large inequities in food distribution and nutrition security. While most of the rise in per capita food availability during the late 20th and early 21st centuries resulted in increased food waste, a variety of mechanisms have been proposed by which changes in the increasingly ultra-processed food environment resulted in excess energy intake disproportionately in people genetically susceptible to obesity. As populations continue to grow, substantial investments in coordinated nutrition and agricultural research are needed to transform our current food system to one that relies less on fossil fuels, preserves biodiversity, ensures environmental health, and provides equitable access to affordable, safe, and nutritious food that reduces the prevalence of chronic diseases like obesity.

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Introduction

Producing enough food has challenged humans for millennia. The 18th century English economist Thomas Malthus made dire predictions that population growth will outpace agriculture's ability to provide sufficient food thereby resulting in mass starvation [1]. Echoes of what has become known as the 'Malthusian trap' have reverberated for centuries since. For example, in the late 1960s and early 1970s the American biologist Paul Ehrlich predicted in that the USA would experience famines killing millions of mass starvation by the middle of the 1980s [2] – a period that was instead marked by a troubling increase in obesity prevalence [3]. Indeed, more people around the world now have obesity than suffer from hunger [4]. How did this happen? Here, I sketch how the development of our modern industrialized food system has thus far avoided the Malthusian trap and instead may have caused the increase in obesity prevalence.

The Rise of the Modern Industrialized Food System

Agriculture has relied on hard physical work of humans and draft animals for millennia. In the 18th century, seed drills mechanized planting and steel plows were introduced the 19th century, but it wasn't until the 20th century when agriculture was transformed by machines powered by fossil fuels replacing the vast majority of muscular farm work [5-8]. Mass mechanization of farming dramatically improved efficiency and more land could be farmed by fewer farm workers and without the need to also produce feed for draft animals.

Fossil fuels also transformed agriculture by indirectly increasing fertility of the soil. Specifically, soil nitrogen content sets a limit on the rate of protein synthesis and plant growth because nitrogen is an essential component of all amino acids. Atmospheric nitrogen is naturally fixed in the soil by bacteria that synthesize ammonia which is readily absorbed by plants, but increasing plant growth could be achieved by supplementing soil nitrogen with application of manure and guano.

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Unfortunately, the availability of sufficient natural fertilizers posed a limitation that was eliminated in the early 20th century when German chemists Fritz Haber and Carl Bosch invented a way to artificially synthesize ammonia from atmospheric nitrogen at industrial scale. Unfortunately, the Haber-Bosch process traditionally uses a substantial amount of fossil fuel [7, 8].

Twentieth century expansion of agricultural productivity and markets was facilitated by public investments in infrastructure, especially irrigation and transportation networks. Agricultural research resulted in the development of hybrid seeds for grains like corn, wheat, and soybeans that capitalized on the improved irrigation and fertilization of the soil to dramatically increase crop yields and select for varieties amenable to efficient mechanized harvesting. An industrial chemical revolution also produced new classes of pesticides, fungicides, and herbicides to further increase productivity [5-9].

These technological advancements have been collectively called the "Green Revolution" and are credited for avoiding the dire Malthusian predictions. In past several decades, advancements in molecular biology have resulted in the introduction of genetically modified organisms to agriculture in the hopes of further increasing productivity and improving nutritional quality of certain crops.

The grain commodity crops that have most benefited from the "Green Revolution" provided more than enough protein and calories to feed the growing population without substantial increases in land use. But food is more than protein and calories and the vast majority of these commodity crops are not directly consumed by humans. Rather, most are used as feed for cows, pigs, and chickens that are subsequently consumed by humans. Animal agriculture became increasingly dependent on grains, antibiotics, and confined feedlots to increase their growth efficiency. Furthermore, such practices allowed the animals to be located nearby slaughterhouses and transportation networks facilitated their efficient delivery to market [5, 6].

Government policies have incentivized farm specialization, increased commodity crop production, and promoted larger farm sizes. Indeed, the number of farms and people working on farms has decreased substantially over the past several decades, and draft animals are now practically nonexistent [6]. As a result, much of the rural population moved to cities and suburbs whose residents rely on others to produce their food.

Improvements in transportation networks, manufacturing methods, food packaging and preservation technologies enabled the rise of large national and multi-national food brands. These processed food and beverage manufactures relied on inexpensive agricultural inputs of protein and calories and their food scientists invented ingenious processing methods to "add value" to their products [9]. Products were fortified with vitamins and minerals, flavors were enhanced with additives, textures were engineered to improve "mouth feel", and other technologies were applied to increase the overall appeal of their products that were sold for a considerable profit [10, 11].

Processed food companies grew at an astonishing rate in the 20th century. Investments in research and development resulted in an ever-expanding range of new products that were more convenient, time-saving, and tasty. When a sufficient market of consumers objected to certain products on offer, industry responded by offering a new line of "gluten free", "low fat", "low carb", or other products in addition to the existing products thereby capturing additional market share.

Food and beverage industries have a guaranteed market because we all need to eat. However, these industries are faced with a fundamental limitation when it comes to their growth: Engle's law states that a person's spending on food decreases as a percentage of their increasing income, in part, because food requirements are physiologically limited. Thus, even in a growing economy, profit growth of food and beverage companies is reliant on increasing the size of their market to a greater extent than other industries. Shareholders of individual food and beverage companies demand increased profits which incentivizes aggressive marketing campaigns to replace traditional foods and incentivizes development of a wide variety products that can be easily consumed above physiological needs. Increasing portion sizes appeal to the consumer's sense of value for money and promotion of snacking behavior alters social norms of eating and further increases opportunities for consumption [12].

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Beyond increasing food and beverage consumption in existing markets, another way for processed food companies to increase profits is to enter new markets and displace traditional foods. For example, in 2010 the world's largest food manufacturer Nestlé issued a press release announcing the launch of a "floating supermarket" stocked with Nestlé products on the Amazon River touting the project as an "Unprecedented Business Model [that] will extend the company's presence in Brazilian households" [13].

Ultra-Processed Foods

Even before the launch of Nestlé's "floating supermarket", Carlos Monteiro documented an alarming increase in processed food products entering the Brazilian market and displacing more traditional foods [14]. To better document and measure this shift in the food market, in 2010 Monteiro introduced a new food categorization system called NOVA that largely ignored nutrient content and instead classified foods based on the extent and purpose of processing [14]. Originally containing only three categories, the NOVA system was later modified [15]to include four categories: 1. Unprocessed or minimally processed foods such as whole foods that have been washed, chopped, frozen, dried, or fermented; 2. Processed culinary ingredients such as sugar, butter, cooking oils, and salt; 3. Processed foods that are combinations of category 1 and 2 foods for purposes of preservation or to increase palatability; and 4. Ultra-processed foods that are "industrial formulations manufactured by deconstructing foods into their component parts, modifying them and recombining them with a myriad of additives and little, if any, whole foods. Importantly, ultra-processed foods are distinct not only in terms of their ingredient composition, but also in terms of the purpose for which they are produced. The purpose underlying the manufacture of ultra-processed foods is to create convenient (durable, ready-to-consume), tasteful (often hyper-palatable) and highly profitable (cheap ingredients, value adding) products that are liable to displace all other NOVA food groups" [16].

The fact that NOVA downplays the importance of nutrients is antithetical to the long history of successful reductionistic approaches in nutrition science [17]. It is therefore not surprising that the NOVA food classification system has been met with substantial criticism [18-22]. Some critics have argued that the NOVA system offers no meaningful benefits over traditional nutrient-based classification systems because diets high in ultra-processed foods also tend to have greater amounts of salt, sugar, and fat while being lower in protein and fiber [18]. Another criticism is that the NOVA system is unclearly defined and difficult to implement, with substantial discrepancies between different people asked to rate the same foods according to the NOVA system [23]. However, other studies have found more consistent NOVA ratings between people [24, 25].

The NOVA definition of ultra-processed foods is sometimes misunderstood to merely consider the nature and extent of food processing, but the "purpose of processing" criterion of the NOVA 4 is important to the definition of ultra-processed foods. All food producers intend to increase profits, so this is not a unique motivation of ultra-processed food manufacturers. However, ultra-processed foods have a uniquely wide scope for extensive reformulation to meet market demands and displace foods from other NOVA categories. Thus, some have argued that ultra-processed foods would be better describes as "ultra-formulated" foods [26].

Despite the scientific debate about the NOVA system, many consumers understand the basic advice to minimizing ultra-processed food intake more readily than recommendations to moderate consumption of precisely defined nutrients such as sodium, saturated fat or sugar – nutrients that are particularly prevalent in ultra-processed foods. As such, official dietary guidelines of health organizations and nations have included statements to limit consumption ultra-processed foods [27] because they have been linked to a variety of poor health outcomes, including obesity [28-30]. However, the NOVA 4 definition currently represents such a wide variety of products that there is a risk of enacting ineffective and regressive policies without a better mechanistic understanding of how ultra-processed foods cause adverse health outcomes [31].

One thing seems clear, the processed food industry is especially concerned about widespread adoption of the NOVA system. Reformulating products out of the NOVA 4 category will be very

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difficult if recommendations to decrease consumption of ultra-processed food are heeded. However, by subcategorizing NOVA category 4 foods based on a better understanding of mechanisms it may be possible to help reformulate ultra-processed foods and provide effective consumer advice on the basis of their individual risk of a disease or health condition such as obesity [31].

Increasing Obesity Prevalence and the Changing Food Environment

Within a given food environment, individual susceptibility to obesity is largely explained by genetic differences, particularly genes preferentially expressed in the brain and likely involved in appetite control [32]. The changing food environment is thought to explain the increasing prevalence of obesity in the population [33], and our modern industrialized food system has provided excess calories in the form of increased availability and marketing of inexpensive and convenient ultra-processed foods.

There is much debate about the most important factors in our changing food environment that are responsible for the increase in obesity prevalence. Associations between ultra-processed food intake and obesity observed in epidemiological studies [28-30] do not necessarily imply that ultra-processed foods causes excess intake and weight gain. We recently conducted controlled randomized crossover trial to investigate this issue and found that a diet high in ultra-processed foods caused an increase in ad libitum energy intake of ~500 kcal/d and weight gain in adults as compared to an unprocessed diet matched for overall presented calories, carbohydrate, sugar, fat, sodium, energy density, glycemic load, and fiber that resulted in spontaneous weight loss [34]. There are a variety of mechanism that may have been responsible for these results.

Mechanisms by Which Ultra-Processed Foods Promote Excess Energy Intake and Obesity

A wide variety of mechanisms have been proposed to explain why diets high in ultra-processed foods are consumed in caloric excess and may lead to obesity. One mechanism involves the typically high energy density of ultra-processed food which is a property that is well-known to positively affect ad libitum energy intake, at least acutely [35]. While the overall energy densities of the ultra-processed and minimally processed diets in our study were matched, this was achieved primarily by including more low-calorie beverages with the ultra-processed meals to deliver soluble fiber supplements to match the overall fiber content of the minimally processed diet [34]. Non-beverage energy density differed substantially between the ultra-processed and minimally processed diets, primarily because of decreased water content in the ultra-processed foods. In a secondary analysis of the meal intake data, non-beverage energy density was an important variable positively predicting meal energy intake and mediating a substantial fraction of the effect of ultra-processed versus minimally processed meal energy intake in our trial [36].

Eating rate has been implicated as a mechanism that positively promotes energy intake and is related to the sensory properties and structure of the foods [37-39]. Ultra-processed meals in our study were consumed more quickly than the minimally processed meals when including the masses of the beverages but non-beverage items in the ultra-processed meals were eaten more slowly than in the minimally processed meals [36]. In a secondary analysis, non-beverage eating rate was a positive predictor of individual meal energy intake [36].

While the overall diets were matched each day for sodium, sugar, carbohydrates, and fat in our trial, the individual meals differed in the proportion of calories presented as hyper-palatable foods defined as having high amounts of both sodium and fat, sodium and carbohydrates, and sugar and fat [40]. Indeed, neuroimaging studies have suggested that hyperpalatable foods high in sugar and fat are particularly reinforcing [41]. In a secondary analysis of our ultra-processed versus minimally processed diet study, we found that meal energy intake was positively influenced by hyper-palatable foods as a proportion of calories presented [36]. We also found an interesting interaction between non-beverage meal energy density and hyper-palatable foods such that the effect of hyper-palatable foods was greater for meals with lower energy density and vice versa.

Interestingly, the participants in our trial did not report significant differences in palatability between the ultra-processed versus minimally processed meals [34]. However, palatability is only a

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single dimension of the multifaceted concept of food reward [42] and ultra-processed meals may have increased incentive salience, wanting, and motivation to eat that may have driven excess energy intake [43].

Some investigators have hypothesized that ultra-processed foods contain highly processed carbohydrates that are quickly absorbed causing rapid increases in circulating glucose thereby enhancing reward related brain activity via mechanisms similar addictive substances [44, 45]. The subsequent fall in in circulating glucose may also result in late-postprandial glucose dips that induce hunger [46]. While the ultra-processed and minimally processed diets used in our trial varied in added sugars, the diets were similar in glycemic load and resulted in no significant differences in mean glucose or glucose variability as measured using continuous glucose monitors [34, 47].

Ultra-processed foods tend to have lower protein content [48] and the protein leverage model of obesity suggests that diets with diluted dietary protein result in excess energy intake to achieve a given protein target [49, 50]. While our ultra-processed and minimally processed diets differed slightly in the proportion of presented calories as protein (14% versus 15.6%, respectively) we calculated that protein leverage could not fully explain the observed differences in mean energy intake [34, 51]. Indeed, in a secondary analysis of our ultra-processed and minimally processed meal data we found that more protein offered with meals significantly increased energy intake [36].

A variety of gut signals are modulated in response to food ingestion and are believed to play important roles in appetite control [52]. The production of ultra-processed foods disrupts the natural food matrix of the whole food ingredients and may result in altered intestinal digestion and absorption of nutrients [53]. For example, if nutrients from ultra-processed foods are absorbed more proximally in the gut they may instigate a different pattern of gut-brain signals as compared to the same nutrients ingested in the form of minimally processed whole foods. These gut-brain signals include vagal afferents, hormones derived from enteroendocrine cells, or signals from the intestinal microbiota. Enteroendocrine cells and microbiota may also be negatively influenced by low amounts of insoluble fiber or various emulsifiers or additives in ultra-processed foods. Another ingredient of ultra-processed food involves the materials used in packaging which may alter the endocrine system and act as obesogens [54, 55]. Finally, the increasing prevalence of ultra-processed foods in the food supply has gone along with an increase in fats derived from processed seed oils which have a high proportion of omega 6 to omega 3 unsaturated fatty acids that have been suggested to promote obesity through various mechanisms, including influencing the endocannabinoid system to increase appetite [56-58].

Conclusions

Through a variety of technological advancements, government policies, and economic incentives, the modern food system relies heavily on fossil fuels to generate a huge surplus of calories available in a wide variety of heavily marketed foods that are inexpensive, convenient, ubiquitous, energy dense, and often hyperpalatable. This flow of matter and energy through the industrialized food system has increased over the past half century on a per capita basis in correspondence with the rise in obesity prevalence [3] and an even larger increase in food waste [59].

We find ourselves in a unique position in human history where food is produced in excess by relatively small numbers of people and is relatively affordable. Whereas food purchases represented ~60% of disposable income at the beginning of the 20th century in the USA, now, food costs <10% of disposable income [12]. The benefits of these changes include the fact that more food is prepared outside the home and cooking meals at home is more convenient thereby freeing up time and money for other pursuits.

It is intriguing to speculate that increasing obesity prevalence has been an inevitable result of striving to create a food system that avoids Malthus' predictions. In other words, society has incentivized surplus agricultural production (relying on cheap fossil fuels) to provide low-cost inputs to food and beverage industries that produce heavily marketed, convenient, rewarding, timesaving, and relatively inexpensive ultra-processed foods in great excess of consumption needs of the population, albeit with large inequities in food distribution and nutrition security [4].

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We are now faced with a huge challenge and opportunity. As populations continue to grow and agriculture faces the added pressures of tackling climate change and loss of biodiversity, substantial investments in coordinated nutrition and agricultural research are urgently needed to transform our current food system to one that relies less on fossil fuels, ensures environmental health, and provides equitable access to affordable, safe, and nutritious food that reduces the prevalence of chronic diseases like obesity.

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