Institute for
Futures Studies

Working paper 2024:18

Backcasting the Future of Food: A Technology-Oriented Path to Sustainable Production in 2100[1]

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[1] This is a draft document, made available as a preprint. It can be cited as Jebari, Karim and Emma Engström, *Backcasting the Future of Food: A Technology-Oriented Path to Sustainable Production in 2100*, Institute for Futures Studies. Working paper 2024:10. It will be superseded by a final publication, which should be cited when available. The latest version will be available at https://mimircenter.org/publications

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Backcasting the Future of Food: A Technology-Oriented Path to Sustainable Production in 2100

Abstract

We stipulate a normatively desirable scenario for food production in 2100 and identify a technology-centered path to attain it. The target outcome is that the human population has increased following anticipated mainstream projections, and that the impacts on land systems, biosphere integrity, freshwater use, and eutrophying emissions are substantially reduced as compared to current levels. These reflect four planetary boundaries that are closely linked to agriculture. We consider the current average global diet and categorize the food into three groups: (1) fruits and vegetables, (2) grains, and (3) animal products, which together make up around nine-tenth (91%) of the human diet. In each group, we identify one disruptive technology with the potential to substantially contribute to achieve the desirable scenario: (1) vertical farming for fruits and vegetables; (2) genetically modified crops for improved photosynthesis of grains; and (3) realistic plant and microbe-based substitutes for animal products. Assuming widespread adoption of these technologies in 2100, we project that the area of farmland, the amount of freshwater, and the emissions of eutrophying substances would be reduced by 54%, 46%, and 32%, respectively, as compared to current levels. We discuss policies and adoption challenges related to their implementation, finding that some behavioral changes, mainly regarding acceptance of alternatives to animal food products and genetically modified organisms, are necessary to attain the target. Notably, abundant access to fossil-free energy is a crucial prerequisite for at least two of the proposed technologies. We conclude that the “electrify-everything” road to sustainability that is well-established in other sectors also holds for food.

1. Introduction

Our current agricultural system is unsustainable and there is a need to explore a variety of pathways to more sustainable food production. Humanity has overstepped a safe operating space in six of the environmental dimensions in the *Planetary Boundaries* (PB) framework (Richardson et al., 2023), and several of the critical boundaries are closely linked to food production. Gerten et al. (2020) showed that roughly half of global food production today is an effect of transgressions of planetary boundaries.

Agriculture implies the conversion of wild forests and wetlands to farmland and pasture, which particularly affects land systems change and biosphere integrity. It is the most important sector causing land use change, which, in turn, is the main driver behind biodiversity loss (Kok et al., 2018). Biotopes are transformed into agricultural land, which accounts for about 43% of the Earth's ice- and desert-free land, and of this, roughly 87% is used for food production (Poore & Nemecek, 2018). Agriculture is a threat to the vast majority of the species at the risk of extinction (86%), as it is the primary factor causing habitat loss, which happens when natural ecosystems are converted to areas for crop production or pasture (Benton et al., 2021). Preventing the conversion of forests and wetlands to farmland is thus of fundamental importance to reach sustainability goal (Garnett, 2014).

In terms of biogeochemical flows, Poore & Nemecek (2018) estimated that food production is responsible for approximately 78% of global eutrophication. The application of nitrogen, potassium and phosphate fertilizers are key drivers of the increased agricultural yields that have taken place in the last century (Fischer-Kowalski et al., 2014). Vitousek et al. (1997) estimated that annual total nitrogen fixation has been doubled by human activity. This process has fundamentally altered numerous natural habitats, as nitrogen, prior to the industrial fixation, was a crucial element governing the operation of many ecosystems. Nitrogen and phosphate runoff causes hypoxia in lakes, rivers, estuaries, and coastal waters and reduces biodiversity in aquatic ecosystems and low-nitrogen soils. Furthermore, domestic animals in industrial farms produce large amounts of manure that have become a serious contributor to eutrophication, as nearby agricultural land becomes overloaded with manure, causing runoff into streams (Won et al., 2017).

Long-term food security is another reason for concern in this domain (Garnett, 2014; Godfray et al., 2010; van Vuuren et al., 2015). More than two billion people experience micronutrient deficiencies, and 795 million suffer from hunger (FAO, 2017). This challenge is anticipated to increase in urgency considering that the world's population is predicted to reach 9.7 billion by 2050 and 10.4 billion by 2100, according to estimates by the UN Department of Economic and Social Affairs (DESA) (2022). FAO (2017) projected that 653 million people will remain undernourished without efforts to promote pro-poor development in 2030 and that around 50% more food will have to be produced by 2050 than in 2012. The demand for grains, including maize, wheat and rice, could increase by 70% by then (Donovan, 2020). Adding to this challenge, it has been estimated that one-fourth of current farmland is highly degraded (De Clercq et al., 2018).

Population growth is another factor affecting food security, given that the demand for agricultural products is relatively uniform across income levels (compared to consumption of fossil fuels). For example, the average per capita supply of food per day is relatively similar in North America and Africa, with 3.8 kcal in the former vs. 2.6 kcal in the latter (FAO 2020). Moreover, the increase in per capita consumption of calories in low-income regions is higher than in high-income regions, which suggests a converging trend globally (FAO 2020).

The global community has responded to these challenges with international treaties about shared goals, such as the Paris Agreement and Agenda 2030. An essential element of these treaties is the emphasis on global *goals* rather than on methods to achieve them. National roadmaps to reach the specified targets have thus not been fully articulated, which leaves a gap for national policy makers to fill. The current study intends to contribute decision-support in this context. Another key aspect of these global treaties is that they have transformative aspirations, which suggest that conventional forecasting techniques – identifying *likely* outcomes based on the continuation of dominant trends – may prove inadequate.

Backcasting (Robinson, 2003; Robinson, 1982) is an increasingly adopted approach in futures studies that addresses this limitation of forecasting. Backcasting assumes that the past is of limited importance when it comes to shaping the future, and that visions can guide decision-making and find adequate policies for *desirable* futures. Vergragt and Quist (2011) discussed the role of backcasting in the context of futures studies, denoting it "normative forecasting", which can involve both a backwards-looking conceptual analysis and a more operational approach. Backcasting can be used to develop different scenarios of alternative futures for opinion makers and the public; it explores their feasibility and provides better understanding of the society-wide transformations and implications that they entail (Neuvonen & Ache, 2017). As such, it is an appropriate method for analyzing complex problems that call for fundamental societal changes (Dreborg, 1996). The method allows for setting and ranking priorities, and the identification of steps needed to reach goals (Kanter et al., 2016).

While backcasting was originally developed for long-term energy policy analysis (Robinson, 1982), scholars have recently begun to use it for other purposes. For instance, Neuvonen and Ache (2017) applied backcasting to make visions for metropolitan futures for Helsinki in Finland in 2050. It has also been applied to global biodiversity objectives (Kok et al., 2018) and sustainable agriculture targets. Kanter et al. (2016) presented a backcasting approach and a methodological toolkit for countries to develop roadmaps to reach Agenda 2030, with the Uruguayan beef sector as a case study. Garnett (2011) examined existing methods to reduce GHG emissions in different parts of the food chain as well as their relation to other aspects of sustainability.

Van Vuuren et al. (2015), Kok et al. (2018) and Garnett (2014) discussed three distinct pathways for sustainable food production in the future, centered around technological development, consumer demand and systems changes, respectively. The first, which is the focus of the current study, is centered on innovations that alter the means of production, without changing the offer to consumers. It assumes neither great behavioral change in the form of consumer restraint, nor fundamental changes in the global food system. It is denoted the *Global Technology* pathway in Kok et al. (2018) and van Vuuren et al. (2015), and it relates strongly to the *Efficiency viewpoint* in Garnett (2014). The other two major pathways discussed in this literature is *Decentralized Solutions*, which implies system transformation towards local production and more equally distributed access to food, and *Consumption change*, which assumes that demand needs to change fundamentally to reach sustainability goals (van Vuuren et al., 2015).

Of these three pathways, the first is the dominant one, as it has strong proponents among important food industry actors, such as farming unions, manufacturers, retailers, and governments (Garnett, 2014). In many ways, the global technology pathway seems more tangible than the other two, considering the complex nature of the system transformation pathway, and the radical challenges that consumer restraint implies. Among these is how to reverse the trend in low-income countries towards adopting the high-impact diets that are the norm in high-income countries (Garnett, 2014). Historical trends in consumption patterns and economic activity speak in favor of the technology-oriented solution. Technology-driven change has historically been the most important factor in increasing agricultural productivity.

Addressing this gap in the literature, this study deliberates on the technology-oriented solution by evaluating the social and environmental implications of specific emerging innovations in the long term. Its overall aim is to apply a backcasting approach to identify technologies with potential to substantially contribute to reach sustainability goals in 2100. Note that we focus on food production, which is a (significant) subset of the agriculture sector that excludes the production of, for example, cotton, biofuel, and leather. We focus on three categories of food: fruits and vegetables, grains, and animal-based protein foods (meat and dairy), based on the five groups categorized by the U.S. Department of Health and Human Services (HHS) and U.S. Department of Agriculture (USDA) (2015). Considering each of these three food groups, we ask three research questions (RQs):

> RQ1: Is there a disruptive technology that could substantially contribute to sustainable food production?
>
> RQ2: To what extent could this technology contribute to reduced environmental impacts in 2100?
>
> RQ3: What opportunities, challenges and trade-offs does this technology imply when it comes to widespread adoption?

By addressing these perspectives, the paper expands on the literature in two main ways. The first regards the time horizon, as we deliberate on a longer time frame than earlier literature by van Vuuren et al. (2015) and Kok et al. (2018). We focus on 2100 instead of 2050, in line with projections by the Intergovernmental Panel on Climate Change (IPCC) (2022). This long-term perspective allows us to consider technologies which currently can only be found in research laboratories, i.e., experimental, or niche innovations that may need time to get fully adopted and disrupt the food market. Thus, the study assumes that it will be inadequate to only rely on incremental improvements of mainstream practices, in agreement with previous studies that have concluded that such gradual changes will not be sufficient. For example, van Vuuren et al. (2015) argued that existing developments and policies were unlikely to ensure sufficient food supply while meeting environmental goals.

The second contribution regards our focus on specific technologies. Earlier backcasting studies on this topic have typically articulated the technology pathway in quite general terms, and few, if any, have thoroughly considered the potential of *individual* agricultural technologies. For example, Foley et al. (2011) considered a wider range of measures, also allowing for substantial behavioral change to address related sustainability challenges. Our focus on specific technologies is instructive because it improves understanding of the implications of the technology-focused pathway as compared to the other pathways that regard consumer demand and fundamental changes in the food production system (see Kok et al. (2018) and van Vuuren et al. (2015)). In examining specific food technologies, it further builds on Gerten et al. (2020), who reported that it is possible to support 10.2 billion people without transgressions of the planetary boundaries, given fundamental transformations of production and consumption patterns. We have a similar end goal as Gerten et al. (2020), but we limit our assessment to technological innovations, which makes our analysis more concrete.

2. Methodology

2.1. Stipulating a target scenario

The endpoint scenario in this study is sufficient and sustainable supply of food to nourish the global population in 2100. Consequently, we stipulate that 50% more food will be produced in 2100 than in 2020. This is based on FAO's (2017) assessment that food supply needs to increase by nearly 50% in 2050 as compared to 2012 to ensure food security, as well as the UN's (2022) medium projections which imply that the global population in 2100 (10.4 bn) will only grow slightly from the level in 2050 (9.7 bn). These forecasts together indicate that an increase in food supply of roughly 50% between today (2024) and 2100 will be needed.

To address sustainability in this context, we consider the planetary boundaries framework (Rockström et al., 2009; Richardson et al., 2023), which identifies nine critical processes to ensure the stability and resilience of the Earth system. Richardson et al. (2023) reported that six of these have already been transgressed. In the current study, we focus on four of these transgressed boundaries that are most closely linked to agriculture: biosphere integrity, biogeochemical flows, land system change, and freshwater change. This is the same set of dimensions as Gerten et al. (2020) accounted for in their study of sustainable food production.

Our end goal parallels four Sustainable Development Goals (SDGs): *Zero Hunger* (SDG 2), focusing on ensuring food security; *Responsible Consumption and Production* (SDG 12), limiting the material footprint such as land use; *Life Below Water* (SDG 14), reducing the eutrophication of oceans and seas; as well as *Life on Land* (SDG 15), sustaining forest ecosystems to limit biodiversity loss. Thus, we extend the global 2030 goals to 2100.

As it is not clear how to translate these interlinked planetary boundaries into specific boundary constraints in a 2100 scenario, we adopt proxies (Table 1). We consider land use for food production as a metric for both biosphere integrity and land-system change, since both of these boundaries are about stopping conversion of wildlife habitats, such as forests and wetlands, to farms and pastures (Gerten et al., 2020). Richardson et al. (2023) argued that human appropriation of the biosphere's net primary production is a relevant proxy for biosphere integrity. Our end scenario thus does not allow for expansion of the land area used for food production, which complies with FAO's (2017) assessment that there are few opportunities left for further development of agricultural areas. The other two metrics reflect the use of eutrophying emissions and freshwater in food production (Table 1).

Table 1: The desired target scenario for 2100.

Target	Specification	Metric
Sufficient food to feed the expected global population	A 50% increase in food consumption in 2100 vs now (2024)	The global population and average global daily food consumption
Reduced risks due to land systems change	Substantially reduced use of land for food production in 2100 vs now (2024)	Land use (m^2*year) from global daily food consumption
Reduced risks due to changes in biosphere integrity	Substantially reduced use of land for food production in 2100 vs now (2024)	Land use (m^2*year) from global daily food consumption
Reduced risks due to biogeochemical flows	Substantially reduced eutrophying emissions from food production in 2100 vs now (2024)	Eutrophying emissions (g PO_4^{3-}eq/g) from global daily food consumption
Reduced risks due to freshwater overuse	Substantially reduced use of freshwater for food production in 2100 vs now (2024)	Freshwater use (l) from global daily food consumption

2.2. Evaluating technologies

We searched for emerging agricultural technologies in the published academic literature and grey literature such as reports, newsletters, patents, press releases and business briefs. We used the following search terms: “agriculture”, “sustainability”, “intensification”, “emerging technology”, “technology impact”, “land use”, “food security”, “food system”, “mitigation”, “innovation”, and “farming”. We combined forward and backward snowballing of references and citations (Wee & Banister, 2016). In the academic literature, our emphasis was on two types of journals: those explicitly oriented towards futures studies, such as *Futures*, *Foresight*, and *Technological Forecasting and Social change*, as well as those that regard sustainable agriculture, such as *Biological Conservation*, *Journal of Cleaner Production*, and *Global Food Security*.

After listing a number of possible technologies in this literature, we evaluated each of them with respect to two aspects: yield increase and transformational impact. The former addressed whether the technology has the potential to generate substantially higher yields in relation to inputs of resources or environmental impacts, while the latter focused on whether the technology can be seen as *disruptive*, rather than as a gradual development of some established technology. The technologies that met these two criteria were subsequently examined in-depth, with a focus on social dimensions.

Specifically, each of the shortlisted technologies was evaluated with regard to the following criteria, adapted from Holmberg (1998): *function and contribution*, which addresses how the technology contributes to reduce environmental impacts and achieve sustainable agriculture; *enabling conditions*, which concerns whether there are natural or social conditions under which the technology will be particularly effective; *policies* *or circumstances* that would promote the technology, as well as *obstacles to its advancement* and widespread adoption; *tradeoffs and synergies*, which regards whether the technology's implementation involves tradeoffs or interactions vis-à-vis the different sustainability targets. We also considered scalability and adoption challenges, examining to what extent it will be possible to test and scale the technology, essentially asking whether it will contribute to targets *immediately*, or only after a lengthy transition phase.

2.3. Projecting impacts in 2100

We quantified the environmental benefits from the three recommended technologies in 2100, assuming widespread adoption. These projections should be seen as rough estimates of the potential of these technologies across environmental domains, not as predictions. For current estimates, we considered the global daily consumption of different food products (2009-2011 average), and the corresponding levels of land use and eutrophication per food type, using data from Poore & Nemecek (2018). Although slightly dated, this was the most detailed data set we could find in this literature, and it was adequate given that it is used to *compare* environmental impacts today vs. 2100. Specifically, we considered three food groups (fruits and vegetables, grains, and animal products), which make up 91% of the total retail weight in an average global diet, estimated based on Table S14 in Poore & Nemecek (2018). For comparison, we also calculated the impacts of the remaining foods (denoted "other"). The assumptions in the projections are fully accounted for in Appendix A.

Our projections assume that fossil-free energy will be readily available in 2100. This is grounded in the pledges made in the Paris Agreement, the legally binding international treaty that aims to limit global warning to well below a rise of 2°C as compared to pre-industrial levels. To reach this goal, the energy sector is central, because the consumption and production of energy reflect 86% of global carbon emissions (UNEP, 2023), and therefore a drastic increase in carbon-free power is a premise for stabilizing the concentration of GHG in the atmosphere (Jean-Baptiste & Ducroux, 2003). As reported by UNEP (2023), 97 parties, representing 81% of global GHG emissions, have adopted net-zero promises, and 37% of global emissions are covered by 2050 net-zero targets. Hence, it is not unreasonable to assume that abundant access to clean energy fifty years later will be possible, although we recognize that this is a key assumption in the study.

3. Results

3.1. Innovations identified

In the literature, a range of emerging techniques have been proposed to increase yields, including for example, connectivity technologies, such as smart-crop and smart-livestock monitoring, autonomous farming machinery, smart-building and equipment management, as well as AI imaging and monitoring of crops (Lutz et al., 2020). There is also great potential in other precision agriculture techniques, such as drip irrigation and fertilizing using drones, as well as anaerobic digestion by microbes that reuse agricultural waste (Garnett, 2014). Other promising methods include improving pastures with legumes instead of grass to reduce methane emissions, feed supplements to promote earlier first pregnancy in cattle, and tree planting to reduce heat stress (Kanter et al., 2016). However, while these innovations allow for gradual improvements in existing practices, they were not considered to be disruptive. In response to RQ1, we instead identified vertical farming, C4 photosynthesis and realistic substitutes for animal products as key innovations with great potential to transform food production and achieve the backcasting target scenario (Table 1), as detailed below.

3.1.1. Vertical farming for fruits and vegetables

Vertical farming is the practice of growing crops in vertically stacked layers in a controlled environment that has been optimized for plant growth using no-soil techniques, such as hydroponics (Van Gerrewey et al., 2021). It holds a lot of promise with regard to the use of water, land, and fertilizer. In hydroponic cultivation, a crop is planted in an inert medium (e.g., gravel) and nutrient-rich water, which is circulated, rather than allowed to evaporate, and this implies that water consumption is substantially reduced. It has been estimated that vertical farms can save as much as 99% of the water as compared to surface irrigation (Benke & Tomkins, 2017). For example, it has been estimated that 2–24 liters of water are needed to produce 1 kg of tomatoes in vertical farms, as compared to 60-200 liters in open-field farming in southern Europe (Economist Intelligence Unit, 2023). This corresponds to a reduction of freshwater use of up to 99%.

By stacking layers of crop plantations, vertical farms also substantively decrease the land used for cultivation, which is attractive from the perspective of biodiversity and land system change. They could be placed in areas of low value from a biodiversity perspective, such as industrial parks in depopulated towns, unused parking lots, or abandoned mines. For some crops, it has been estimated that the yield per acre can increase by 10 to 20 times as compared to open-field farming (Jiang, 2023). An especially promising example is lettuce, for which it has been estimated that the yield per square meter could be more than 80 times the yield of a traditional farm (Van Gerrewey et al., 2021). The U.S. Agricultural Research Service is investigating the potential of vertical farms for small fruits, such as strawberries and tomatoes, and it is also evaluating its potential for larger fruit tree crops, including apple and citrus (Jiang, 2023).

In addition, the recirculation of nutrients in the hydroponic system means that eutrophication can be reduced by 70–90% per unit of yield compared to traditional agriculture (Wildeman, 2020). Moreover, since the growing environment is controlled, this type of farming does not require pesticides and herbicides to the same extent as traditional agriculture. This also facilitates the prevention of pesticide and herbicide contamination in the natural environment and reduces harm to non-pest insects and aquatic animals. The reduced need for water compared to traditional agriculture implies that vertical farming is especially attractive in regions where water is scarce and expensive, yet electricity is affordable, for example in regions where desalinated water is used for irrigation (Allegaert, 2020). Additionally, vertical farming may be beneficial for countries with limited arable land to satisfy their population's needs, especially those striving for a level of food self-sufficiency. Vertical farming could be particularly attractive in regions that depend on costly imports for fresh food as it allows for locally grown food all year round (Jiang, 2023).

3.1.2. C4 photosynthesis for grains

C4 photosynthesis is a technology with large potential to contribute to environmental targets in this food group, which has particular consequence for land use. Cereal crops, such as wheat, rice, barley, and maize, are the backbone of global food production, and cover currently about 740 million hectares for rice and wheat, as well as 353 million hectares for coarse grains such as barley, corn, and oats (Hannah Ritchie & Rosado, 2023). Any technology that improves the yield per hectare of these crops would have a significant impact on land use (Leegood, 2013). Genetically modified crops have rapidly proliferated in the last two decades, and have, despite political opposition in some countries, been a considerable commercial, environmental and public health success, mostly in low and middle-income countries (Smyth, 2020). However, the full potential of agricultural biotechnology is still unfulfilled, and it could radically transform productivity and yields for cereal crops. One of the techniques with this potential involves improving the photosynthesis of plants.

Photosynthesis is the process by which crops convert light energy into chemical energy. This process involves converting carbon dioxide to sugars through the process of carbon fixation. There are two main types of carbon fixation in common agricultural crops, C3 and C4. C4 carbon fixation plants are superior at capturing energy from the sun, especially in sunnier climates. They also tend to have higher efficiency in water and nitrogen use (Osborne & Sack, 2012). Carbon fixation relies on an enzyme known as RuBisCO, which "catches" CO2 molecules, which are needed for photosynthesis, from the air. However, RuBisCO is not very good at this task in a low CO2 environment such as ours, and consequently it sometimes catches O2 (oxygen) molecules by mistake. O2 is a very reactive molecule, and it is harmful for the plant, which means that C3 plants need to spend much energy on containing and expelling oxygen. By contrast, C4 plants create an intermediary mechanism that provides the RuBisCO enzyme with a CO2 rich environment, where it is less likely to catch O2 by mistake.

While most cereal grains, including rice, wheat, barley, and oats, use C3 carbon fixation, some of the most productive crops, such as maize, sugar, and sorghum, are C4 plants. There is ongoing research to produce rice that can use C4 photosynthesis, an innovation that could increase yields, reduce nitrogen runoff, and reduce water needs. It has been estimated that the radiation use efficiency is 50% higher for C4 crops than C3 crops (Kajala et al., 2011; Wang et al., 2012). Ermakova et al. (2020, 2021) reported that C4 rice could double the yield per hectare as compared to C3 rice. Moreover, genes that could be used for creating C4 wheat have recently been identified, opening up the possibility for creating a strain of wheat and other cereal plants with much higher yield (Rangan et al., 2016). This research is still in the laboratory stage, and it has the potential to radically increase productivity.

3.1.3. Realistic substitutes for meat and dairy

With regard to protein foods from animals, alternatives from non-animal sources are needed to meet environmental targets in 2100. Producing food through animal rearing is in many cases very inefficient in terms of environmental impact per unit of calories. This is especially true for beef cattle, as every calorie of meat from cattle requires on average 326 m^2 of land to produce (Poore & Nemecek, 2018). As a rule, the larger the animal, the more energy is required as an input for a given amount of food calories from its meat. While some domestic animals eat food that cannot be consumed by humans (grass, for example), and some of that food grows on land that could not be used to grow food for human consumption, most livestock in modern agriculture that are reared for human consumption are fed significant quantities of human-type foods such as soybeans, corn, or wheat (Erickson & Kalscheur, 2020).

Consequently, producing agricultural goods in this way is a major contributor to human land-use change and the destruction of wild habitats, both for grazing and for the cultivation of crops to feed animals. Domesticated animals in agriculture also have a significant negative contribution to other concerns in the planetary boundaries framework, such as eutrophication, water use, and GHG emissions (Henry et al., 2019; Xu et al., 2021). The eutrophication problem is very difficult to avoid from animal rearing, as it is a consequence of concentrating many animals in a limited space and feeding them a nutrient-rich diet. The resulting manure is heavy and costly to transport over long distances, often leading to overuse and significant leakage to nearby fields.

We conclude that reducing the number of domestic animals in food production is a necessary requirement for reaching a safe operating space for humanity with respect to the boundaries of land use change, ecosystem integrity, and biogeochemical flows. This implies reducing the amount of animal products in our diets, especially from ruminants (mostly cattle and sheep).

Broadly acceptable substitutes for animal products are therefore promising technologies. For example, plant-based milk products imply less use of land and water than conventional milk (Berardy et al., 2022). The mean land use per liter has been found to be 8.9 m^{2}*year for milk and 0.7 m^{2}*year for soymilk (Poore & Nemecek, 2018). In the dairy-substitute market, several wheat, soy, and almond based products are already available at prices that are somewhat more expensive than traditional milk, but still in the competitive range. Over the last decade, these products have also seen improvements in taste and texture; for example, milk substitute products designed for coffee drinkers no longer curdle at high temperatures (Brown et al., 2019).

Another possibility involves creating protein-rich food from hydrogen-metabolizing bacteria. While using bacteria to produce or alter food is as old as the agricultural revolution (e.g., yoghurt), novel experimental developments offer the prospect of creating food without the use of plant or animal-based products (Jolly, 2024). Some food companies are developing methods to use bacteria to produce edible proteins from hydrogen, water, nitrogen, and carbon dioxide. Rather than using plant-based sugar as the energy source (such as in the production of Quorn), some companies have adopted a type of bacteria with an unusual metabolic process: oxidizing hydrogen. Since hydrogen can extracted be from water with electricity and/or heat, these bacteria enable the production of food without the otherwise inefficient process of photosynthesis, seeing that the most effective plants convert about 4% of light energy to biomass energy (Blankenship et al., 2011).

By not requiring plant-based products to produce food, this method could not only outmatch animal-based protein, but also plant-based protein in terms of land use efficiency. Even when using solar PV, which is one of the least effective methods of producing electricity in Finland in terms of land use, the Finnish company Solar Foods maintains that their method, which uses the bacterium *Xanthobacter* VTT-E-193585, can produce proteins with only 10% of the land required to produce an equivalent amount with soybeans. This technology is still experimental, and it has yet to prove that it can be scaled up. However, even if it was an order of magnitude less efficient than claimed, it would constitute a significant achievement.

Prima facie, using bacteria to create proteins seems more viable than using animal cell cultures to produce meat for human consumption, as some companies hope to do. An animal muscle cell divides every 24 hours, while a bacterium typically divides every 20 minutes. A typical bacterium, such as *E. coli*, can under optimal conditions produce about 10^72 bacteria in 24 hours, while the number of muscle cells will only be 2-4. The stark differences in reproductive rate between bacteria and muscle cells mean that the requirements for keeping cell cultures free from contaminants are daunting, as a single microbe can quickly destroy an entire batch of cells. Moreover, animal muscle cells are adapted for growing inside bodies, protected by skin and the immune system, and fed by blood vessels, adding to the relative complexity and cost of cultured meat relative to bacteria-based alternatives for producing protein.

3.2. Projections

This section quantifies environmental effects assuming worldwide use of the three disruptive technologies (RQ2). We found that the per-capita annual land use impacts from daily food consumption would decrease by 71%, from 5.61 m^{2*}years (current level) to 1.72 m^{2*}years (2100) (Figure 1). Most of this reduction could be attributed to substitutes for animal products, projected to decrease by 76%, from current levels of 3.58 m^{2*}years to 0.86 m^{2*}years in 2100.

Further, the total per-capita annual eutrophying emissions would decrease by 64%, from 17.53 g PO43-equivalents (current level) to 6.28 g PO43-eq in 2100 (Figure 2). Again, substitutes for animal products would account for the largest share of this reduction, since they would imply a decrease in eutrophying emissions of around 90%, from current levels of 9.82 g PO43-eq per person per year to 1.0 PO43-eq in 2100.

Lastly, we projected that freshwater use would decline by 50%, from 488.9 l (current level) to 220.7 l in 2100 (Figure 3). Following the other environmental dimensions, the largest share of this reduction related to substitutes for animal products. The decrease was also massive for vertical farming, as freshwater use is reduced by 95%. Note that an unusually large share of current impacts can be attributed to grains, mainly rice production, which demands as much as 1,575 liters per person per day (Poore & Nemecek 2018).

As the pre-defined end-goal was a 50% increase in food consumption in 2100, we multiplied these environmental effects with 1.5. This generated land use impacts that were 54% lower than current levels (2.58 m^{2*}year), eutrophying emissions that were reduced by 46% (9.41 g PO43-eq), and freshwater use that decreased by 32% (331.1 l). Hence, these projections implied that impacts would decrease substantially, meeting the target scenario (Table 1).

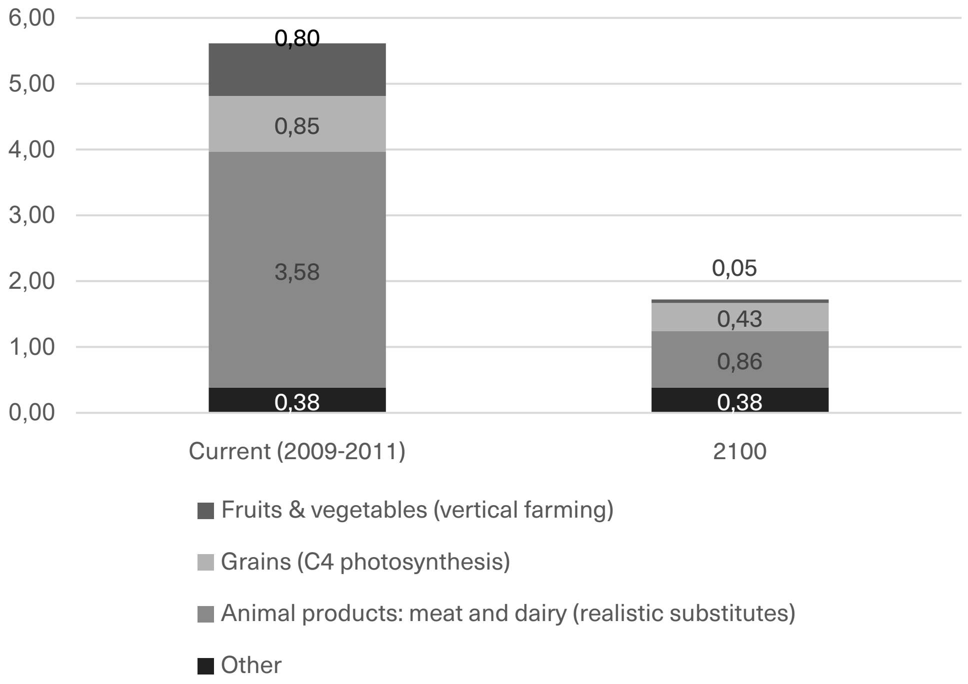

Figure 1. Estimated land use impacts (m^2*year) from current global average daily food consumption and projections for 2100. This current level is based on Poore & Nemecek (2018), and the 2100 projections are grounded in the assumption of all-encompassing adoption of the three technologies (Appendix A).

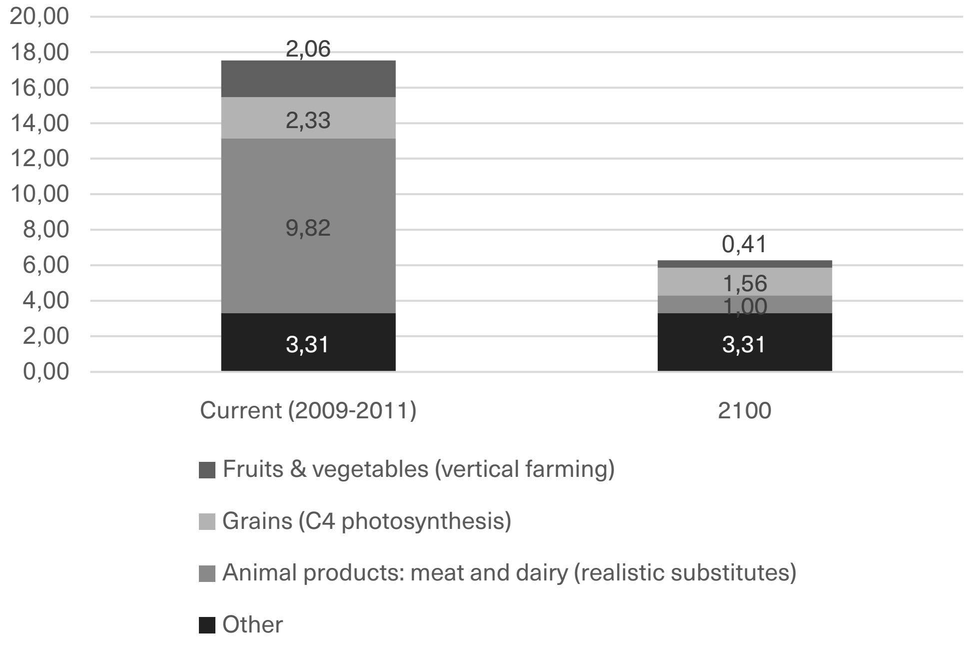

Figure 2. Eutrophying emissions (g PO$_4^{3-}$eq/g) from current global average daily food consumption and projections for 2100. This current level is based on Poore & Nemecek (2018), and the 2100 projections are grounded in the assumption of all-encompassing adoption of the three technologies (Appendix A).

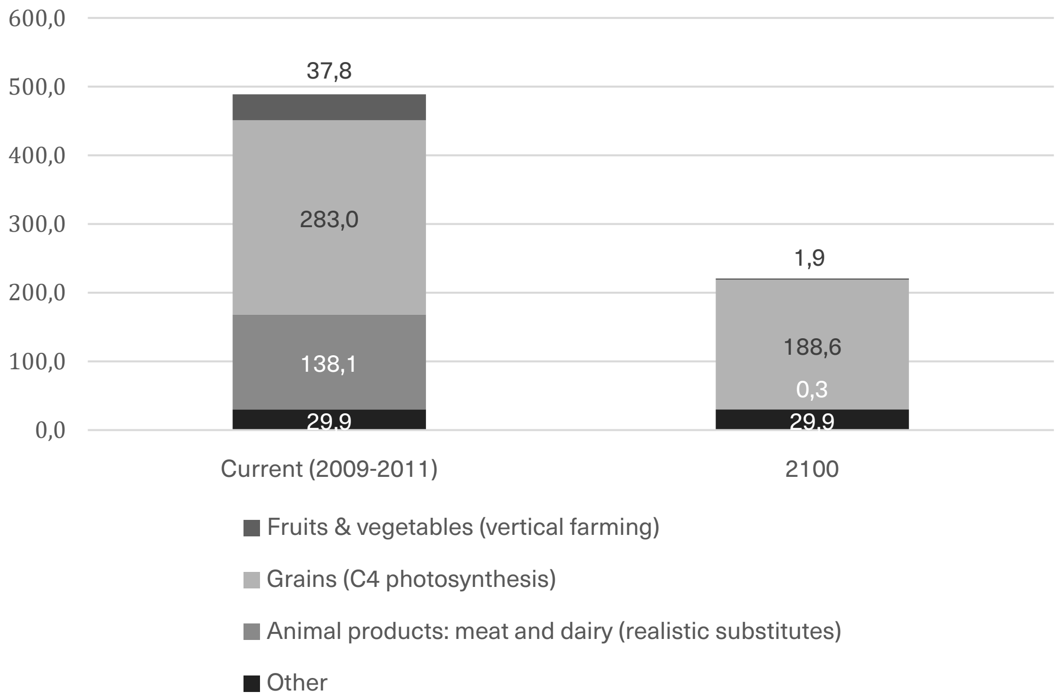

Figure 3. Freshwater use (liters) from current global average daily food consumption and projections for 2100. This current level is based on Poore & Nemecek (2018), and the 2100 projections are grounded in the assumption of all-encompassing adoption of the three technologies (Appendix A).

3.3. Implementation potential and challenges

This section addresses the opportunities, enabling policies, and trade-offs involved in the development and adoption of the identified technologies (RQ3).

3.3.1. Energy supply for vertical farming

Vertical farming has several implementation challenges. The main one is high energy costs, because the main drawback of vertical farming is that it requires artificial light, given that only the top layer in a stack of plants can be exposed to the sun. Vertical farms also require a significant amount of electricity for ventilation and cooling per kg of produce (Asseng et al., 2020). The prospects for a reduction of these costs are positive from a twenty-first century perspective. LED lamps have in the last two decades followed a forecast articulated by Roland Haitz (2007), becoming increasingly energy efficient. However, while this trend is likely to continue, artificial light will never be as cheap as natural sunlight. Moreover, due to the heat generated by artificial light, most vertical farms will need to be cooled, which is energy intensive. Increased energy efficiency in cooling is also a necessary condition for vertical farms to be practical.

The second implementation challenge relates to the fact that vertical farming is currently relatively labor intensive, requiring a highly skilled and hence expensive workforce (Kabir et al., 2023). Vertical farming will not be able to compete with traditional farming for most crops as long as this is the case. Technologies to make the harvesting and tending of crops more efficient are therefore needed to reach price parity for medium-value crops such as legumes and fruits. Here, future developments in robotics could make a significant difference, in particular improvements in machine vision and robotic manual dexterity would be important. This is an area of research and development that has the potential to make substantial progress over the next few decades. Moreover, improvements in algorithmic evaluation of humidity, temperature, chemical composition of the nutrient solution are also needed, as many of these systems are currently monitored and fine-tuned by humans.

Hence, the most important variable to make vertical farming viable is inexpensive and abundant fossil-free electricity; the cheaper the electricity, the more crop types would be relevant for vertical farming (Lubna et al., 2022). This technology essentially trades many negative environmental impacts of traditional agriculture (water use, land use, eutrophication, chemical contamination) for substantively increased electricity needs, mainly for artificial lighting, ventilation, and cooling systems. This means that the total environmental impact of vertical farming will be determined by the energy mix that is being used to generate electricity. In other words, if electricity is supplied by coal, the environmental impact of vertical farming would be largely negative, relative to traditional agriculture.

Moreover, if vertical farms use the energy from diffused renewable energy sources, such as solar photovoltaic (PV) panels or wind turbines, some of the land-use benefits of vertical farms would be negated, depending on where the renewable energy source is placed. Since solar PV has about 20% conversion efficiency, using land to produce electricity that is then used to illuminate crops implies a considerable efficiency loss in terms of land use, relative to using that land to produce crops directly (Kobayashi et al., 2022). This *can* still be worthwhile if mostly marginal or low value land (from a biodiversity perspective) is used for renewable installations, such as rooftops, parking lots, etc. However, if such land is not available, and vertical farming is to reduce human land-use, this technology only makes sense if it can be powered with a concentrated form of low-carbon energy such as hydroelectricity, geothermal or nuclear power. It should nonetheless be noted that vertical farms powered by solar PV might still be superior to traditional farms with regards to water use, eutrophication, and pesticide/herbicide contamination.

Another potential advantage is that vertical farms could be used to balance energy demands, which will be increasingly important as variable renewable energy becomes a larger fraction of the energy mix, as most crops require light for about 16 hours per day (Blom et al., 2024). For example, vertical farms could be used when electricity demand is low or when energy production is high, thus balancing the demand curve in the electricity system. Lastly, vertical farms produce significant amounts of waste heat, which could synergize well with residential areas, if connected to district heating networks. They could also be used in combination with ordinary greenhouses, since these often require heating, especially in cold climates.

With regards to scalability and adoption, vertical farming is already used for certain high-value crops, such as lettuce, chili fruits and herbs, although it is currently not an economically viable alternative to traditional farming for most crops (Benke & Tomkins, 2017). However, many of the negative externalities associated with traditional farming are not included in the price of agricultural products. For example, farmers rarely pay market prices for the environmental harm to wild animals and plants caused by pesticides. Neither is the impact on local biodiversity and land use change included in the price of food. If such costs were internalized with an environmental tax, vertical farming might become much more attractive, especially in water and land scarce regions with access to relatively cheap energy. In a scenario in which energy producers are constrained to internalize the costs of environmental degradation, while food producers are not, there is little prospect for competitive vertical farming for most crops, as electricity makes up such a significant part of the cost of this practice.

Nevertheless, there is great potential to develop the right technological mix that would allow more crop types to be grown in vertical farming over the next decades. It has been argued that basically *any* crop can be cultivated in such farms (Benke & Tomkins, 2017; Despommier, 2010). Even though there are currently practical obstacles to growing some larger crops, its use to grow peach, citrus and apple trees is already being developed by USDA researchers (Jiang, 2023). As the main bottleneck for this technology is related to the amount of light that can be used for photosynthesis, the potential for vertical farming is related to the dry weight of crops. Generally, the larger the fraction of a crop that is non-water, the more light is needed to produce a certain amount of that crop (Taiz et al., 2014). Consequently, we expect vertical farming to mainly be relevant for non-cereal crops such as pulses, fruits, vegetables, herbs, roots, tubers, and legumes. If vertical farming could be used for this wide array of crops, it would be a highly disruptive innovation.

3.3.2. Acceptance of GMOs

As a rule, C4 plants can be deployed in regions where their C3 counterparts are. Moreover, since C4 plants are better at retaining water, they are more resistant to conditions of drought and high temperatures. Since the C4 mechanism is metabolically expensive for the plant to sustain, it has the greatest potential to increase yields in regions with abundant sunlight, for example the lands in the Ganges, Indus, and Mekong River valleys. The largest potential for C4 crops is in tropical and subtropical regions. Today these include some of the most productive agricultural regions in the world. Even if C4 variants were limited to these regions, and even if it would be limited to rice, it could make a very large contribution to increased yields per hectare. However, we find it likely that C4 carbon fixation can be expanded to cover most of the cereals over the coming decades, making a major contribution to increasing yields.

With respect to political and socio-cultural factors, a large-scale deployment of this technology requires broad public acceptance for the use of genetic engineering in food crops. Notably, several of the major countries in the global south, especially in Asia and South America, where this technology is most likely to have a major impact, have in the last decade increased their acceptance of GM technology (Singh et al., 2020). In terms of synergies, this technology is likely to synergize well with efforts at increasing yields and reducing nitrogen leakage and climate impact from food production. It is particularly helpful for rice plantations, where nitrogen use efficiency is generally low (Alam et al., 2023).

3.3.3. Development of realistic alternatives to animal products

Substitutes for animal foods based on plants, fungi or bacteria face several obstacles to widespread use. First, financial incentives in high-income countries favor traditional means of producing animal-based foods. For example, the EU subsidizes cattle rearing with about 30 billion €, an estimate that amounts to up to 20% of the EU budget (Greenpeace European Unit, 2019). Second, to reduce prices, the manufacturing of plant-based products needs to attain much larger scales, something which has yet to be.

Third, there is still need for significant investment in research and development for this technology to better mimic the taste and texture of animal food.

These products could, if producers of animal food were forced to internalize the cost of their negative environmental externalities, displace some animal products, most notably dairy milk, in the next decade (Adamczyk et al., 2022; Laila et al., 2021). Plant-based substitutes for other dairy products (e.g., cheese, yoghurt) have also entered the market and could also win a significant market share if provided with a favorable legal environment and financial incentives. Thus, this is a technology sector that is able to benefit from market-based incentives and regulatory support. For example, the EU could facilitate the approval of novel food technologies that use genetically modified organisms. Plant-based products are also more resilient to conditions of drought and natural disasters than their animal-based equivalents. For example, oat grains are easy to transport and store in comparison to milk and other dairy products. They would be even more affordable if prices of staple crops were reduced, as the bioengineering techniques described above could bring about.

However, current trends in the adoption of alternatives to animal products are not favorable (Parlasca & Qaim, 2022); while the share of vegetarians has increased in high-income countries, meat consumption has also increased in almost every country in the last 20 years (Parlasca & Qaim, 2022). The consumption of animal protein is often part of complex cultural, economic, and political systems, as well as social identity. Thus, dietary shifts to reduce overconsumption are unlikely to happen quickly (Rust et al., 2020; Valli et al., 2019). Hence, while for example, a tax on the negative externalities of animal products could reduce demand, such pricing would also likely be rather unpopular (Fesenfeld, 2023). Carbon taxes are an instructive example of the political costs of taxing products that are in high demand (Grimsrud et al., 2020; Mrchkovska et al., 2023). As many people feel that eating meat is a morally acceptable, and even culturally valuable activity, taxes that penalize meat-eating are often seen as assaults on certain lifestyles and cultural traditions. This makes the political economy of taxes on animal products even more vexed than that of some other goods with negative externalities.

Plant-based products are often perceived to be inferior in terms of taste and quality (Giacalone et al., 2022) (Giacalone et al., 2022). These issues can over time be addressed by further research and development, but they may not be fully eliminated. While previous generations of plant-based substitutes for animal food products were acceptable to some consumers, they did not taste like "the real thing" and did little to attract people who enjoyed the taste of animal-based food. In the last decade, there has been significant innovation in this space, and novel plant-based substitutes for animal products have entered the market. These novel products aim, to a greater extent than previous generations, to mimic the flavor and texture of the original, and thus have the potential to disrupt the traditional animal food market. Products include Beyond burger and Impossible foods (minced beef), and products that mimic tuna (BettaF!sh), caviar (CaviArt), chicken (Tindle) etc. The common denominator of these products is that they are not primarily aimed at the vegetarian/vegan consumer segment, but at the animal-consuming mainstream market. These products are already (to some extent) commercially viable and could, on a level playing field, become truly disruptive. This is an area where both venture funds and philanthropic capital have made major investments, and where we are likely to see major improvements over the next decades. Plant (or fungi) based animal products could conceivably replace a significant fraction of animal-based products well before 2050.

However, there are considerable adoption challenges for non-animal alternatives to meat and dairy products. Meat and dairy are integral parts of many human cultures, and people seem to be more unwilling to change food consumption habits relative to other habits (Hansen & Syse, 2021). Moreover, meat is in many contexts a symbol of wealth and affluence, and therefore highly desired (Milford et al., 2019). This is why we believe that only when non-animal alternatives are sufficiently similar will there be a significant shift in behavior. But similarity in the experience does not guarantee universal adoption. Consider the resistance of EU consumers against genetically modified and irradiated food, even when this food does not differ in taste or appearance (Castell-Perez & Moreira, 2021). As such, non-animal alternatives will likely need to be promoted in various ways, even when competitive in terms of price and indistinguishable in taste. Such political promotion could in some countries become a controversial political issue, especially as farmers sometimes have disproportional political influence.

4. Discussion

4.1. Disruptive technologies vs. behavioral change

This study has focused on technologies that involve a fundamental change in how food is produced but which require only limited changes in consumer behavior. In this context, it must be recognized that the development of future technologies is one of the greatest sources of uncertainty ahead and a focus of considerable disagreement. Many economists are quite optimistic about human ingenuity and technological advances to overcome global challenges. In the 1970s, one of the key advocates of this point of view, Solow (1973) (p. 45) stated: "There really is no reason why we should not think of the productivity of natural resources as increasing more or less exponentially over time". In a relatively recent book on this topic, Brynjolfsson and McAfee (2014) asserted that GDP growth is *limitless* thanks to *recombinant innovation*, the combination of existing ideas.

Nevertheless, this study finds that sustainable food production in 2100 cannot take place without *some* element of behavioral change; this becomes obvious in terms of substitutes for animal food products, the category which has, by far, the most fundamental impact across the domains considered (Figure 1-3). Eating realistic alternatives to animal products *does* involve (slight) changes in consumer behavior, although it can be assumed that such products would taste *almost* like conventional products, thanks to technological developments before 2100. This assumption is supported by current trends, as the taste of plant-based dairy and meat have converged towards that of animal products. We conclude that it will not be feasible to reach the stipulated goals only by changing the means of production; in this way, this study has contributed to articulate why it may not be possible to fully rely on technological innovation. Note however that all disruptive innovations require *some* change in consumer behavior, so this finding is not unique for the solutions that we have promoted here.

The in-depth assessment of the technology-focused pathway in this study is instructive because it implied a clearer articulation of the challenges that this perspective entails; concretely discussing *specific* technologies allowed us to better assess the feasibility of this pathway in comparison to the other two conceptually different approaches, addressing changes in demand and the food system as a whole, respectively (Garnett, 2014; van Vuuren et al., 2015). The aim of this study forced us to look for technological solutions with the smallest behavioral impacts, and in a way, it allowed us to pinpoint the *minimum* level of change in consumer behavior required for sustainable food.

4.2. Main realization challenges

Adoption of innovations is a known challenge in the agriculture sector, as it is complicated by the large heterogeneity of actors, technologies, capital, education, experiences, environments, and systems (Kassie et al., 2013; OECD, 2001). Agriculture is different from other sectors, such as energy or transportation, given the wide range of small-scale actors, who are faced with large uncertainties about the effects that new technologies might have throughout the food chain (OECD, 2001). When interpreting the results in this study it is thus important to recognize that farming is deeply engrained in local cultures. Therefore, the solutions proposed may seem unrealistic in many communities today, for social, economic or cultural reasons given that the proposed innovations are technology-centered, which means that small-scale farmers may not be able to adopt them. Many communities may not be willing or able to adopt vertical framing technology, for example. However, given the fast economic growth in the last 75 years, with many newly industrialized countries, it is possible that the coming 75 years will see a similar development, implying that small-scale farming is likely to make up a much smaller share of food production in 2100.

With regards to other central implementation challenges, this study suggests that access to climate-neutral electricity in 2100 is essential. A premise for vertical farming and some forms of microbe-based protein to meet global goals is access to emission-free and affordable electricity. These technologies can hence only be adopted assuming that there are significant investments in fossil-free energy production, which implies large-scale adoption of solar, wind or geothermal energy in areas where impacts in terms of biodiversity loss and lands systems change are small. Alternatively, nuclear power could be used to produce large quantities of electricity with a relatively small land-use impact.

Technologies that shift diets away from meat have the greatest impact, but they also face considerable resistance. Hence solutions may be a *combination* of the three technologies, as not all meat will be replaced by plant-based alternatives. Further, alternatives to animal products and vertical farming also struggle with the fact that they are still relatively expensive alternatives to conventional products. These limitations are in part due to the significant subsidies and regulatory support that traditional food producers receive. A level playing field, and pricing that reflects negative externalities is likely to be necessary for these technologies to be competitive.

C4 photosynthesis and substitutes for animal products face considerable adoption challenges among consumers. Widespread adoption of these technologies is controversial. While this study found that GMOs could contribute substantially to meet sustainability targets in food production, they are for example part of the dimension of "novel entities" in the planetary boundaries framework, and as such they are considered to impose a risk on the Earth system, as we read Richardson et al. (2023). Richardson et al. (2023) reasoned that novel entities are unstudied, noting that it is a scientific challenge to assess how much the Earth system can tolerate in this domain. The role of GMOs in future food production remains contested in public debates. We have not found any empirical evidence to the effect that they are harmful, although we recognize that more research in this domain is imperative.

4.3. Assumptions

A key merit of this study is that it adopts an interdisciplinary approach that interprets the backcasting method in a new way, with a global and long-term focus. We have considered a broad literature within food innovations, environmental science as well as futures studies. Nevertheless, the study is based on several important assumptions, which have been necessary given the long-term scope. In particular, the quantitative projections should be interpreted with regard to the many assumptions involved. We have aimed to find numbers that indicate the *order of magnitude* of the potential effects of each technology. However, since we are estimating impacts more than half a century from now, all accounts will be very approximate.

We adopt a relatively long-time perspective, aiming at 2100 instead of 2050 as the target year. Such a long period has the limitation that the evaluation will be less precise, and that estimates of environmental impacts at the end year will be rougher. However, it has the advantage that it allows for more fundamental technological changes as compared to how food production takes place today. Notably, the study assumes that food production would be climate neutral by 2100, assuming that net zero carbon energy will be available by then. We recognize that the assumption of readily available carbon-free energy in 2100 is challenging, and that huge global efforts are needed to reach this goal.

The end target was formulated based on global goals and earlier studies within sustainability research, which was motivated by the focus on long-term food supply – a global concern, with millions of stakeholders. Nevertheless, our approach is distinct from earlier backcasting studies, in which targets are specified by the stakeholders themselves, which in this case would entail industry associations, policymakers, academics, community organizations, and the public, for example (e.g., Kanter et al. (2016)). Such participatory approaches come with several advantages, as they account for local knowledge, promote a policy debate as well as commitment, stakeholder engagement and buy-in by the actors involved (Kanter et al., 2016). Given the long-term and global scope, it was reasonable to base the target on published academic literature in the current analysis, however.

This study has aimed to assess global challenges for agriculture in the twenty-first century, a scope of obvious relevance for people alive today and their children. This time span allows for an evaluation taking emerging and relatively immature technology into account. While we understand that this exercise has its limitations, we believe it is instructive because it makes the technology pathway more tangible. It illustrates what it could mean to attain global food security goals while not overstepping the planetary boundaries. By identifying the most *promising* technologies to reach global goals, we show how far a technology-centered approach can go. Such an assessment allows for better articulation of the trade-offs involved.

We have identified three technologies that have large potential in this domain, but clearly, other innovations might be equally relevant. Focusing in depth on a few is instructive because it shows that it is possible to reach goals. An underlying assumption is however that the technologies that may be relevant to achieve sustainability targets in agriculture in 2100 are known to the research community today.

5. Concluding remarks

This paper explores a technology-oriented pathway towards food security in 2100, given the assumption that the global population, on average, will not fundamentally change its food habits until then. While non-technological solutions may be part of the solution ahead, this study has focused on how much of the transition burden can be placed on adoption of innovations. We considered an end goal in which the food supply has increased by 50% as compared to current levels. We found that three technologies may enable more sustainable agriculture in terms of four critical planetary boundaries: land systems change, biosphere integrity, biogeochemical flows, and freshwater use. The most important technology type is alternatives to animal-based food products, which assumes technological development for better mimicking of conventional alternatives, as well as consumer acceptance. The main political challenges involve changes in taxation and regulation to make GM crops and non-animal-based food alternatives commercially viable. Two key technologies, bacteria-based proteins and vertical farms, imply enhanced electrification of agriculture as they require abundant cheap fossil-free electricity. We conclude that the “electrify-everything” pathway to sustainability also applies to the food sector.

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Appendix A. Projection of the effects of widespread technology adoption in 2100

The evaluation of the environmental impact of current diets (Table A1) was based on data presented by Poore & Nemecek (2018), who accounted for 53 food products from FAO's food balance sheets (www.fao.org/faostat). Specifically, we considered the 43 food products listed in Supplementary Material Data S2 in Poore & Nemecek (2018). For each of these products, we used data about the current global per capita consumption (2009-2011 average) in terms of retail weight functional units (g/day) using Supplementary Material: Table S14 (Poore & Nemecek 2018). The food products that we considered excluded 10 food products that were short of data on environmental impacts in Data S2 (Poore & Nemecek 2018). Therefore, our analysis covered 91% of the total retail weight in the average global diet in Poore & Nemecek (2018): Supplementary Material: Table S14.

We listed the median environmental impact for each food product: median GHG emissions (kg CO_2eq/FU, IPCC (2013), including climate-carbon feedbacks: CO_2, CH_4, N_2O to air), median Land Use (land use * occupation time), median eutrophying emissions (NH3, NOx to air, NO3−, NH4+, P, N to water), and median freshwater withdrawals (liters), using Poore & Nemecek (2018): Table S2 and Data S2. We then calculated the total impact for each food product by multiplying the average global retail weight with the median environmental impacts per unit of weight (Table A1). We grouped each of the 43 food products into one of four categories: 1) fruits and vegetables; 2) grains; 3) animal products; and 4) other (Table A2). We then assessed whether each food product could be produced in 2100 with one of the three proposed technologies.

Regarding the 2100 projections, we postulated that all the food products in each of the three categories (1-3) would be produced with one of the three proposed technologies, unless there were obvious exceptions (e.g., maize is already a C4 crop). We projected that all foods categorized as fruits or vegetables would be produced in vertical farms, which includes foods that are currently grown in such farms only under laboratory conditions. We further assumed that all food products that were categorized as grains, such as rice, would be produced by C4 photosynthesis, except those that are already C4. For animal products meat and dairy, we considered that the environmental impact would correspond to that of the crops that are currently used for products that replace meat and dairy products. We assumed the weight from animal products in the current average global diet and postulated that this would be replaced by plant-based substitutes, specifically soybeans, peas, and pulses. The assumptions per food group as related to land use, eutrophying emissions and freshwater use are summarized in Table A3.

Table A1. Global per capita diet and environmental impact per food product, using data from Poore & Nemecek (2018): Table S14 for global diets and Data S2 for retail weight (2009-2011 average), as well as land use (median), eutrophying emissions (median), and water use (median).

Food product	**Global consumption (2009-2011 average grams per day retail weight)**	**Land use impact (median m^2*year per gram retail weight)**	**Eutrophying emissions (median grams PO_4^{3-}e per gram retail weight)**	**Freshwater per gram retail weight (median liters)**
Apples	22	0.001	0.002	0.115
Bananas	29	0.001	0.002	0.001
Barley (Beer)	63	0.001	0.002	0.007
Beet Sugar	7.9	0.002	0.004	0.012
Berries & Grapes	7.5	0.003	0.001	0.404
Bovine Meat (beef herd)	10	0.170	0.321	0.740
Bovine Meat (dairy herd)	8.6	0.026	0.141	2.614
Brassicas	25	0.000	0.006	0.055
Cane Sugar	41	0.002	0.011	0.008
Cassava	45	0.001	0.001	0.000
Cheese	8	0.020	0.100	1.559
Citrus Fruit	40	0.001	0.002	0.037
Coffee	1.7	0.012	0.050	0.033
Crustaceans (farmed)	2.1	0.001	0.141	1.208
Dark Chocolate	0.6	0.054	0.067	0.025
Eggs	24	0.006	0.021	0.633
Fish (farmed)	7.4	0.006	0.244	1.581
Groundnuts	3.5	0.008	0.017	0.900
Lamb & Mutton	3.7	0.127	0.102	0.461
Maize (Meal)	28	0.002	0.002	0.044
Milk	171	0.002	0.011	0.197
Nuts	2.7	0.009	0.014	1.823
Oatmeal	1	0.008	0.010	0.670
Olive Oil	1.3	0.017	0.039	0.318
Onions & Leeks	23	0.000	0.002	0.002
Other Fruit	58	0.001	0.002	0.004
Other Pulses	15	0.012	0.014	0.000

Other Vegetables	213	0.000	0.002	0.081
Palm Oil	6.7	0.002	0.010	0.006
Peas	2.1	0.007	0.002	0.000
Pig Meat	28	0.013	0.054	1.810
Potatoes	90	0.001	0.004	0.003
Poultry Meat	26	0.011	0.035	0.370
Rapeseed Oil	4.1	0.009	0.016	0.001
Rice	134	0.002	0.009	1.575
Root Vegetables	11	0.000	0.001	0.010
Soybean Oil	10	0.010	0.014	0.002
Soymilk	9.1	0.001	0.001	0.001
Sunflower Oil	3.8	0.016	0.019	0.010
Tofu	3.2	0.003	0.007	0.007
Tomatoes	37	0.000	0.002	0.077
Wheat & Rye (Bread)	166	0.003	0.005	0.419
Wine	8	0.002	0.004	0.005

Table A2. Categorization of food products and the disruptive technologies.

Food product, as listed in Poore & Nemecek (2018): Data S2 and Table S14	**Category (our grouping)**	**Technology**
Apples	Fruits & vegetables	Vertical farming
Bananas	Fruits & vegetables	Vertical farming
Barley (Beer)	Grains	C4 photosynthesis
Beet Sugar	Other	-
Berries & Grapes	Fruits & vegetables	Vertical farming
Bovine Meat (beef herd)	Animal products (meat & dairy)	Realistic substitutes
Bovine Meat (dairy herd)	Animal products (meat & dairy)	Realistic substitutes
Brassicas	Fruits & vegetables	Vertical farming
Cane Sugar	Other	(Already C4)
Cassava	Fruits & vegetables	Vertical farming
Cheese	Animal products (meat & dairy)	Yes-fake-dairy
Citrus Fruit	Fruits & vegetables	Vertical farming
Coffee	Fruits & vegetables	Vertical farming
Crustaceans (farmed)	Other	-
Dark Chocolate	Fruits & vegetables	Vertical farming
Eggs	Other	-
Fish (farmed)	Other	-
Groundnuts	Fruits & vegetables	Vertical farming
Lamb & Mutton	Animal products (meat & dairy)	Realistic substitutes
Maize (Meal)	Grains	(Already C4)
Milk	Animal products (meat & dairy)	Yes-fake-dairy
Nuts	Fruits & vegetables	Vertical farming
Oatmeal	Grains	C4 photosynthesis
Olive Oil	Fruits & vegetables	Vertical farming
Onions & Leeks	Fruits & vegetables	Vertical farming
Other Fruit	Fruits & vegetables	Vertical farming
Other Pulses	Fruits & vegetables	Vertical farming
Other Vegetables	Fruits & vegetables	Vertical farming
Palm Oil	Other	-
Peas	Fruits & vegetables	Vertical farming
Pig Meat	Animal products (meat & dairy)	Realistic substitutes
Potatoes	Fruits & vegetables	Vertical farming
Poultry Meat	Animal products (meat & dairy)	Realistic substitutes
Rapeseed Oil	Other	-
Rice	Grains	C4 photosynthesis
Root Vegetables	Fruits & vegetables	Vertical farming
Soybean Oil	Fruits & vegetables	-
Soymilk	Fruits & vegetables	Vertical farming

Sunflower Oil	Other	-
Tofu	Fruits & vegetables	Vertical farming
Tomatoes	Fruits & vegetables	Vertical farming
Wheat & Rye (Bread)	Grains	C4 photosynthesis
Wine	Fruits & vegetables	Vertical farming

– No applicable technology found in this study.

Table A3. Assumptions in the projections of environmental impacts in 2100.

Food group	**Disruptive technology**	**Land use**	**Eutrophying emissions**	**Freshwater withdrawals**
Fruits and vegetables	Vertical farming	15 times higher yield per acre as compared to open fields (average of 10 and 20) (Jiang, 2023)	A reduction by 80% per unit of yield, based on Van Gerrewey et al. (2021) and Wildeman (2020)	A reduction by 95%, based on the Economist Intelligence Unit (2023)
Grains	C4 photosynthesis	A reduction of land use per unit of yield by 50% based on Ermakova et al. (2020, 2021)	Impacts per unit of production will be two-thirds of current levels, given that the photosynthesis efficiency has been estimated to be 50% higher for C4 than C3 crops (Kajala et al., 2011; Wang et al., 2012)	
Animal products (meat and dairy)	Realistic substitutes	The impact per unit of weight is assumed to be the same as for crops that are currently used in products that replace meat and dairy: pulses, peas, soymilk, and soybean oil		
Other	N/A	Other foods are assumed to have the same environmental impact as currently		

The Institute for Futures Studies is an independent research foundation financed by contributions from the Swedish Government and through external research grants. The institute conducts interdisciplinary research on future issues and acts as a forum for a public debate on the future through publications, seminars and conferences.

This working paper has been produced by the Mimir Center for Long Term Futures Research at the Institute for Futures Studies.