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OPPORTUNITIES AND CHALLENGES FOR FOOD SYSTEMS' TRANSFORMATION

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Meat Protein Alternatives: Opportunities and Challenges for Food Systems' Transformation

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Meat alternatives are attracting private investment and interest from the research community as possible solutions to meet the growing global demand for proteins in a sustainable, ethical, and healthy way. Using a food systems lens, this report investigates the opportunities and challenges associated with three meat alternatives: plant-based, insects and cultured meat. The analysis is based primarily on a literature review, which is complemented by an illustrative scenario using the OECD-FAO Aglink-Cosimo model. Results from the scenario analysis suggest that a shift from meat to meat alternatives in high and upper middle-income countries could result in a decline in global agricultural land use and GHG emissions from the agriculture, forestry, and other land use sector. Lower demand for meats in these countries would also lead to a decrease in international prices for meats, soybean and cereals, which would benefit consumers but place pressure on farmer incomes.

Key words: Plant-based, insect, cultured meat, economic scenario

JEL Codes Q19, Q55, O13, L66

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Key messages

This report looks at the potential implications of a growing market in meat alternatives for food systems' ability to tackle the triple challenge of providing food security and nutrition, contributing to environmental sustainability, and supporting livelihoods along the food supply chain.

Food security, nutrition and other consumer concerns

- At present, meat alternatives are generally more expensive than meats, thereby limiting consumer demand. However, their prices are expected to decline over the next decade as production scales up and production processes are optimised.
- The nutritional composition of plant- and insect-based alternatives presently available on the market is heterogeneous. Although these products are formulated to match or exceed the nutritional profile of meats, research on the nutritional impact of substituting meats with these alternatives is limited. Comprehensive nutritional data for cultured meat are not publicly available as it has not yet reached markets.
- By removing farm animals from the production process, meat alternatives can alleviate some of the associated negative externalities and ethical concerns. However, these new foods also raise concerns, leading in some cases to low consumer acceptance.

Environmental sustainability

- Life cycle analysis suggest that plant- and insect-based alternatives have a lower environmental footprint than meats.
- Cultured meat – under current technology and energy mix – is estimated to have a lower environmental footprint than beef, but higher than pigmeat and poultry due mainly to high energy requirements.

Livelihood

- Selected meat alternatives have higher production costs than do meats. For cultured meat, costs are estimated to be at least one hundred times higher than for meats, thus acting as the main barrier to its commercial viability.
- A growing market in meat alternatives could have negative economic consequences for actors along the livestock value chain, including on employment. However, it also creates opportunities for diversification and for collaboration between actors in the meat and meat alternative industries, particularly at the processing and distribution stages of the value chain.

Results from the scenario analysis suggest that a shift from meat to meat alternatives in high and upper middle-income countries could result in a decline in global agricultural land use and greenhouse gases emissions from the agriculture, forestry, and other land use sector. Lower demand for meats in these countries would also lead to a decrease in international prices for meats, soybean and cereals, which although would benefit consumers, would place pressure on farmer incomes. This analysis underscores the existence of synergies and trade-offs from a change in dietary patterns.

Introduction

Alternative proteins that aim to substitute traditional animal foods are attracting private investment, and interest from the media and research community as possible solutions for meeting the growing global demand for proteins in a sustainable, ethical, and healthy way (World Economic Forum, 2019[1]). While some of these alternatives, such as cultured meat, are in the early stages of development, they have the potential to radically transform food systems if they become market competitive (Treich, 2021[2]).

Some studies suggest that these innovations could deliver major environmental, health, and animal welfare benefits if they were to replace a substantial share of the world's meat production (World Economic Forum, 2019[1]). However, these benefits vary depending on the type of meat alternative and on the type of meat it replaces. Moreover, cost-efficiency, scalability, and consumer acceptance remain a challenge for the commercialisation and adoption of some of these alternatives, limiting their short-term impact on food systems (CE DELFT, 2021[3]) (Onwezen et al., 2021[4]).

Using a food systems lens, this report investigates the opportunities and challenges associated with three meat alternatives that aim to imitate meat: plant-based alternatives, insects and cultured meat. The analysis is based primarily on a literature review, which is complemented by an illustrative scenario analysis. This report does not aim to provide dietary, nor policy recommendations.

Trends in meat consumption and externalities associated with the production and consumption of meat are discussed in Section 1. With reference to the emerging literature on alternative proteins, Section 2 compares the performance of meats and meat alternatives across the three dimensions of the triple challenge faced by food systems (OECD, 2021[5]). The market growth potential of meat alternatives over the next decade is also explored in this section. Section 3 presents an illustrative scenario analysis that quantifies the medium-term impact on global agricultural markets of a shift in demand away from meats toward meat alternatives.

1. The special challenge of meat

1.1. Trends in meat consumption

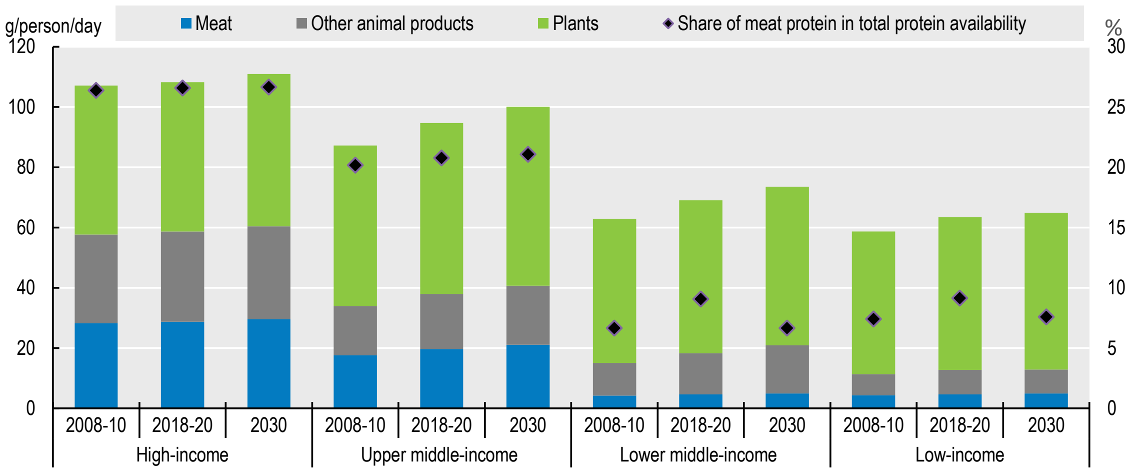
Meat provides 15% of available proteins and 8% of available calories at the global level (OECD/FAO, 2021[6]). However, its contribution to diets varies significantly between countries. Figure 1 shows the contribution of meat, other animal products (i.e. dairy products, fish and eggs), and plants to per capita protein availability by country income group. Meat consumption is also likely to vary widely within countries due to socio-economic (e.g. income, gender, level of education) and cultural differences.

Per capita meat availability is highest in high-income countries, at 30g of protein/person/day on average.[1] Meat provides 27% of available proteins in these countries, with dairy, fish and eggs accounting for an additional 28%. In upper middle-income countries, meat also accounts for over 20% of available protein, at 20g/person/day on average. This is projected to increase over the coming decade due to growth in per capita incomes, with the result that upper middle-income countries will gradually narrow the meat consumption gap with high-income countries.

[1] Figures presented for consumption are estimates of food availability and not of actual consumption. Quantities of food available for human consumption are higher than quantities consumed as some of food that is potentially available to consumers is lost or wasted along the supply chain.

In lower middle- and low-income countries, however, the contribution of meat to diets is relatively small (less than 10% of total proteins); plants provide over 70% of available proteins. Average per capita availability of meat is below 5g of protein/person/day, which is six times lower than in high-income countries. Although this low level of meat consumption is mainly due to income constraints, supply chain issues (e.g. lack of a cold chain infrastructure) remain a barrier in some areas, whereas dietary preferences for non-animal protein sources limit demand in others (OECD/FAO, 2021[6]).

Figure 1. Per capita protein availability, by country income group



Note: Meat includes beef and veal, pigmeat, poultry and sheep meat. Other animal products include dairy products, fish and eggs. Plants includes vegetable oil, pulses, roots and tubers and cereals (maize, wheat and rice).
Source: (OECD/FAO, 2021[6])

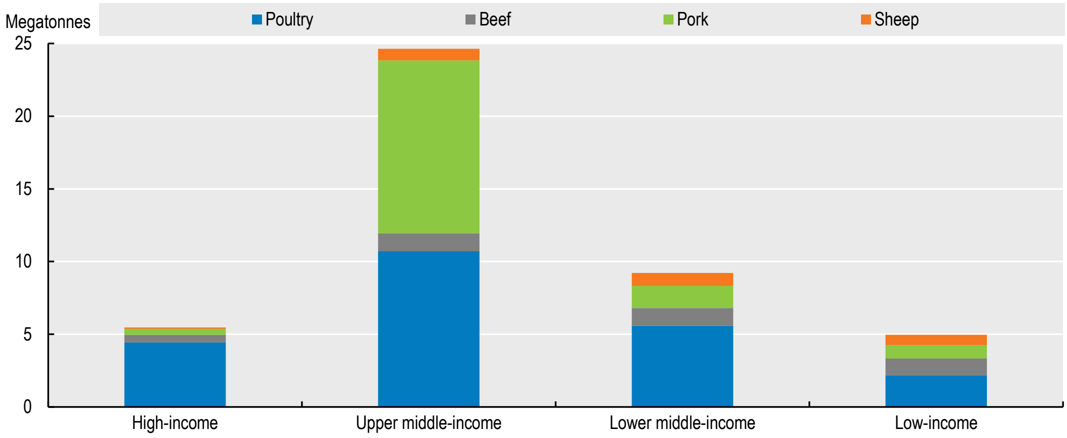
Global meat consumption is projected to increase by 14% (44 mega tonnes) over the next ten years due to growth in population and per capita incomes (Figure 2). This growth will translate into higher demand for different types of meat across countries and regions, depending on dietary preferences (OECD/FAO, 2021[6]).

Three-quarters of the global increase in meat consumption will occur in middle-income countries. In South East Asia and the People's Republic of China (hereafter "China"), for example, meat consumption is projected to increase by 20% and 17%, respectively, by 2030, mainly due to high income growth.

In high-income countries, meat consumption is expected to grow slowly over the next decade (+5%) due to slow population growth, near saturation levels in meat consumption, and growing health, environmental and animal welfare concerns. Most of the increase in meat consumption will be in poultry while pigmeat, beef and sheep meat consumption is projected to increase marginally, and to stagnate or decline on a per capita basis.

In low-income countries, growth in meat consumption will mainly be driven by population growth. Per capita consumption will be muted due to the lack of sufficient income growth, largely exacerbated by the COVID-19 pandemic.

Figure 2. Absolute growth in meat consumption between 2018-20 and 2030, by country income group



Source: OECD/FAO (2021[6]).

1.2. Externalities associated with meat production and consumption

Meat production and consumption are associated with multiple externalities for public health, animal welfare, and the environment. With global meat demand set to increase and policies to internalise these externalities lagging, there are concerns these external costs will also mount as production expands.

Meats are a source of energy and a complete source of protein, as they contain all nine essential amino acids.[2] They also provide a variety of micronutrients, such as vitamin B12, other B-complex vitamins, and minerals (e.g. iron, zinc, copper) (Bender, 1992[7]). There is evidence, however, that the overconsumption of processed and red meats increases the risk of diet-related mortality (Afshin et al., 2019[8]) (Willett, 2019[9]) (Pan, 2012[10]) (Pan, 2013[11]).[3] Diets that are high in processed meats have been linked to cardiovascular diseases and type-2 diabetes. The evidence regarding red meats is less strong and mainly linked to risks associated with colorectal cancer. It is estimated that an individual should not consume more than 100g of red meat and 200g of poultry per week (Willett, 2019[9]). A high share of the population in high-income countries, and in some middle-income countries, consume more than this recommended amount. Dietary recommendations in several high-income countries advise limiting weekly intake of red meat (OECD, 2021[5]).[4] Excess meat consumption (processed meat in particular) has been associated with substantial health costs (Lieffers et al., 2018[12]) (Barnard, Nicholson and Howard, 1995[13]).[5]

Several illnesses can be transmitted from animal foods or farm animals to humans. A large share of food-borne pathogens – such as salmonella, campylobacter, and Escherichia coli – come from foods derived

[2] The nine essential amino acids are: histidine, isoleucine, leucine, lysine, methionine, phenylalanine, threonine, tryptophan, and valine.

[3] The mortality risks associated with diets high in processed and red meats are substantially lower than those that are high in sodium or low in whole grains and fruits (Afshin et al., 2019[8]).

[4] New Zealand's Eating and Activity Guidelines from 2015 recommend consuming less than 500g of cooked red meat per week. Ireland's 2017 Food Pyramid suggests that two to three servings of lean red meat can be consumed weekly. The EU's "Farm to Fork" strategy highlights the need to reduce red meat consumption and move towards a plant-based diet to meet health and environmental objectives (OECD, 2021[5]).

[5] Lieffers et al. (2018[12]) estimated that excess intake of processed meat is responsible for CAD 1.9 billion/year in health costs (both direct and indirect health costs) in Canada, and excess intake of red meat is responsible for CAD 397 million/year. Barnard, Nicholson and Howard (1995[13]) estimated that total direct medical costs attributable to meat consumption was USD 28.6-61.4 billion in the United-States.

from animals. Foodborne pathogens found in meat are responsible for millions of illnesses each year (Rubio, Xiang and Kaplan, 2020[14]). Animal farming is also at the origin of most infectious diseases, either directly through zoonotic transmission from wild to domestic animals or indirectly through agriculture expansion and intensification that increases the exposure of human and livestock to wild animals (Treich, 2021[2]). The World Organisation for Animal Health (OIE) estimates that 60% of all infectious diseases in humans are zoonotic. Finally, the excessive or inappropriate use of antibiotics in animal farming poses public health issues as they increase antimicrobial resistance, as witnessed in recent decades (World Organisation for Animal Health, 2021[15]). This threatens the effectiveness of antibiotics, one of the most important types of treatment in human medicine.

While not typically considered as an externality, meat production raises ethical concerns for some consumers due to the rearing and slaughtering conditions of farm animals. In high-income countries, a large share of animals are raised in intensive farming conditions, namely in cages or in confined environments with no outdoor access. Moreover, several painful practices continue to be used by the industry (e.g. castration without anaesthesia, dehorning, teeth clipping, slaughter without stunning) (Treich, 2021[2]) (Santo et al., 2020[16]). Overall, an estimated 50 billion chickens, 1.5 billion pigs, 600 million sheep, 500 million goats, and 300 million cattle are raised and killed for food every year (Thornton, 2019[17]) (FAO, 2022[18]). These animals are usually slaughtered very young, e.g. after 6 to 8 weeks for chickens, and about six months for pigs (Treich, 2021[2]).

Livestock production also has a large environmental footprint. Animal agriculture uses one-third of the world's land, consumes a fourth of all fresh water available, and, based on life cycle analysis, is responsible for 15% of global greenhouse gas (GHG) emissions (FAO, 2006[19]) (Mekonnen and Hoekstra, 2012[20]) (Gerber et al., 2013[21]). Land conversion for pasture and feed production is the main driver of deforestation, and contributes to biodiversity loss and CO_2 emissions (Tuomisto, Ellis and Haastrup, 2014[22]). Animal farming is also an important source of air and water pollution (Tschofen, Azevedo and Muller, 2019[23]) (Domingo et al., 2021[24]) (Gruère, Ashley and Cadilhon, 2018[25]).[6,7] However, the environmental impacts of livestock farming vary greatly between livestock types and production systems, with ruminant production contributing most to these environmental issues. Well-managed livestock production systems can also improve environmental outcomes, e.g. by maintaining soil carbon content and soil fertility (Chriki and Hocquette, 2020[26]). Several countries and industry actors have adopted, or are considering, measures to reduce the environmental footprint of livestock production, including through investments in research and development (R&D) and extension services, and industry initiatives (e.g. sustainability assessments, GHG reduction targets). To date the use of financial incentives, such as payments for abating emissions and for ecosystem services, has been very limited (OECD, 2022[27]) (Henderson, Frezal and Flynn, 2020[28]).

Over the past decades, public awareness of health, environmental sustainability and animal welfare issues has been growing, particularly in high-income countries and among the younger generation. These concerns are fostering interest in alternative sources of protein, which hold the promise of being nutritionally sound while alleviating some of the negative externalities and ethical concerns associated with the production and consumption of meat.

Section 2 gives an overview of the main types of meat protein alternatives currently available on the market or in the process of development. The main opportunities and challenges associated with these alternatives are then reviewed with regard to their potential impact the triple challenge faced by food systems.

[6] Domingo et al. (2021[24]) found that 80% of the 15 900 annual deaths in the United States resulting from food-related fine particulate matter (PM2.5) pollution were attributable to animal-based foods.

[7] The overall costs across OECD countries of water pollution due to agriculture, both in terms of treatment for consumption and damage to ecosystems, are likely to exceed billions of euros annually (Gruère, Ashley and Cadilhon, 2018[25]).

2. Meat protein alternatives: Opportunities and challenges

2.1. Meat protein alternatives: An overview

Alternatives to meat – such as tofu, tempeh or seitan – have existed for centuries. However, a new generation of alternatives that more closely mimic meat in terms of taste, texture, appearance, and nutritional properties has appeared on the market in recent years, enabled by advances in food sciences and manufacturing (Rubio, Xiang and Kaplan, 2020[14]) (King and Lawrence, 2019[29]).

Although some consumers are willing to reduce their meat consumption for various reasons,[8] many still desire the specific flavour, texture, and mouthfeel associated with meats. This has underpinned the development of a range of new products using plant proteins, new animal sources, and biotechnological innovations which are formulated to mimic the taste and consuming experience of meats (McDermott, 2021[30]) (McKinsey & Company, 2019[31]).

For the purpose of this report, we focus on three types of meat protein alternatives that aim to mimic meat in terms of organoleptic (i.e. taste, appearance, texture) and nutritional properties (Figure 3). The following are generally considered as key groups of alternatives to meat in the literature (Lahteenmaki-Uutela et al., 2021[32]):

- *Plant-based alternatives*: We mainly focus on plant-based alternatives such as burger patties, meatballs, nuggets and sausages, which are made from plant proteins and marketed as nearly equivalent to meats.
- *Insect-based alternatives*: These include edible insects and insect-based ingredients (e.g. insect powder and flour) that are used as a source of protein in the formulation of meat alternatives. Insects can also be used as a source of protein in animal feed, but this is beyond the scope of this report.
- *Cultured meat*: Cultured meat, also referred to as lab-grown meat or in-vitro meat, involves producing meat from animal cells, not from slaughtered animals. This breakthrough innovation is at an early stage of development and is, so far, only commercialised in one restaurant in Singapore.

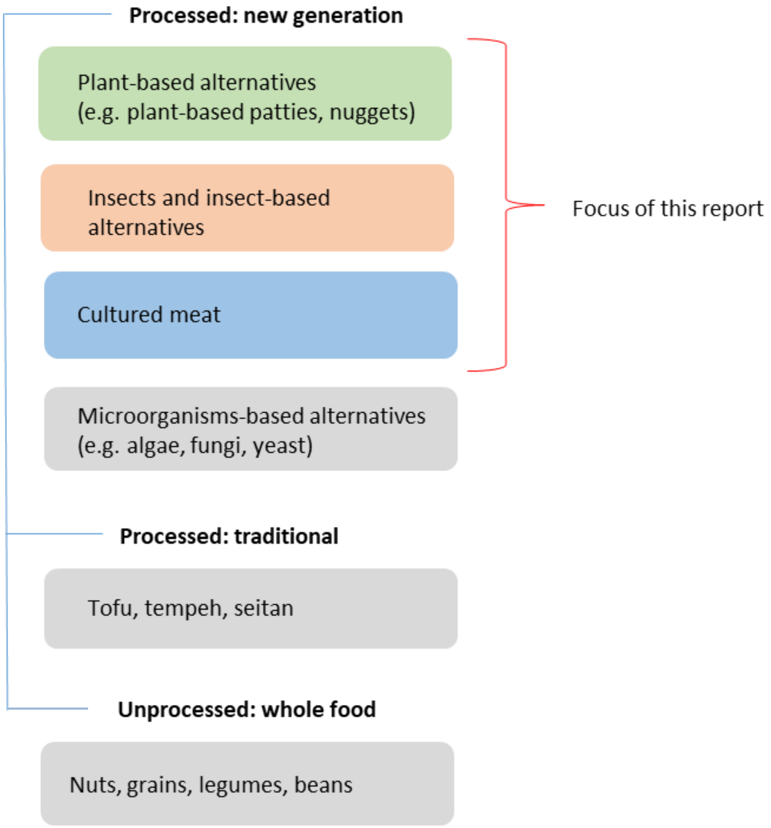
Hybrid products, which are either a blend of meat and meat alternatives (e.g. meat with plant proteins) or a blend of different meat alternatives (e.g. insect and plant proteins, cultured meat and plant proteins) are briefly discussed in this report.

Other types of meat alternatives (e.g. those based on microorganisms-based protein such as bacteria, yeasts, algae, and fungi) as well as dairy, egg and seafood alternatives also exist and are developing rapidly, but are not examined in order to keep the scope of this report manageable.

The following sub-sections describe the input requirements, production processes, and technologies used for the production of selected meat alternatives. While these products aim to resemble meats as closely as possible in terms of organoleptic properties, their production methods differ significantly from the one of meats.

[8] ING (2017[127]) found that around one quarter of Europeans anticipate a reduction of their meat consumption mainly due to health, animal welfare, environmental or financial reasons. (Weinrich, 2018[126]) found, using a focus group study, that motivating factors for not eating meat ranked differently in Germany (e.g., animal welfare, health, environmental impacts), the Netherlands (e.g. animal welfare, poor meat quality, health), and France (e.g. health, animal welfare, sustainability) (Weinrich, 2018[126]).

Figure 3. Meat alternatives studied in this report



2.1.1. Plant-based alternatives

Processed meat alternatives made of plants (e.g. veggie burgers) have been on the market since the late 1970s (Vox Media, 2019[33]). Over the last ten years, however, a new class of plant-based alternatives that more closely mimic meats in terms of organoleptic and nutritional properties has emerged (Section 2.3). These meat alternatives, commercialised by companies such as Beyond Meat and Impossible Foods, are marketed as near-equivalent to meats and are sometimes placed on meat shelves (Ministère de l'Agriculture et de l'Alimentation, 2021[34]).[9] This newer type of plant-based alternative is the focus of this report (Figure 3).

Inputs used for the production of plant-based alternatives to meats are similar to those of conventional agriculture. These inputs include arable crops, energy and water (Kearney, n.d.[35]). The main plants used in plant-based meat formulation are plants with high protein content, such as soybean and peas. Plant-based meat recipes also typically include cereals (e.g. wheat, rice), potatoes starch, and vegetable oils (e.g. coconut, canola, and sunflower oils).[10]

[9] Beyond Meat first products were launched in the United States in 2012.

[10] Ingredients of the Beyond burger are: water, pea protein, expeller-pressed canola oil, refined coconut oil, rice protein, natural flavours, dried yeast, cocoa butter, methylcellulose, potato starch, salt, potassium chloride, beet juice colour, apple extract, pomegranate concentrate, sunflower lecithin, vinegar, lemon juice concentrate, vitamins and minerals.

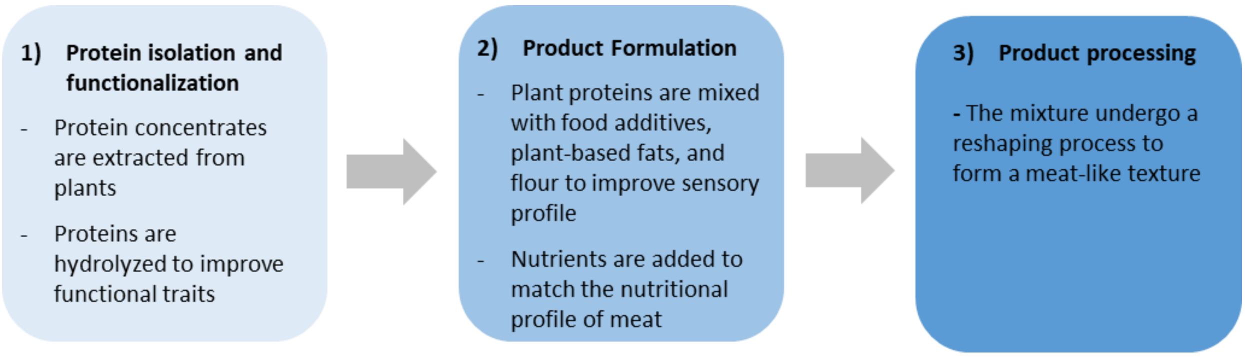
Ingredients of the Impossible Burger are: water, soy protein concentrate, coconut oil, sunflower oil, natural flavours, 2% or less of: potato protein, methylcellulose, yeast extract, cultured dextrose, food starch modified, soy leghemoglobin, salt, mixed tocopherols (antioxidant), soy protein isolate.

A key advantage of plant-based protein is that it avoids the feed-to-food conversion loss typically associated with animal protein. It is estimated that 1.3 kg of arable crops are needed to produce 1 kg of plant-based meat (i.e. a conversion rate of about 75%) (Kearney, n.d.[35]), compared with 7-10 kg of feed per kg of live weight for beef, 4-5 kg for pigmeat, and 2-2.5 kg for poultry (Van Huis, 2013[36]) (CE DELFT, 2021[37]) (Kearney, n.d.[35]).

The production process of plant-based alternatives involves three main steps (Figure 4). First, protein concentrates or isolates are extracted from plants. Plant proteins are then subject to hydrolysis to improve their functionalities, such as solubility and cross-linking capacity (*Step 1*). Plant-based proteins are then mixed with flavour additives to reproduce the taste and smell of meat.[11] Heat-stable fruit and vegetable extracts (e.g. apple extract, beet juice) or recombinant heme proteins[12] are added to recreate the colour of fresh meat, that will change to brown upon cooking, together with plant-based fats (e.g. coconut oil, cocoa butter) to mimic animal fat marbling. Carbohydrates, such as potato starch and methylcellulose, are then added as binders to bring all the ingredients together (*Step 2*). Finally, this mixture undergoes a reshaping process to form a meat-like texture. Innovative technologies such as shear cell technology, mycelium cultivation, or 3D printing are sometimes used by plant-based companies to mimic more closely the texture of meat (*Step 3*) (Rubio, Xiang and Kaplan, 2020[14]) (Kearney, n.d.[35]).

These sophisticated production processes have enabled these newer types of plant-based products to mimic meats more closely compared to their predecessors (Kearney, n.d.[35]). However, plant-based meat producers continue to face several technical challenges. First, improvements in organoleptic properties may come at the cost of certain nutritional aspects, as some nutrients can be lost during product processing (Section 2.2.1). Moreover, the current technology does not enable to reproduce whole cuts of meat (ING, 2020[38]). At present, plant-based alternatives available on the market only mimic minced meat (mainly burger meat, sausage, and nuggets) (Good Food Institute, 2022[39]).

Figure 4. Main steps of the production process of plant-based meat



Sources: (Rubio, Xiang and Kaplan, 2020[14]), (Kearney, n.d.[35])

2.1.2. *Insect-based alternatives*

According to recent estimates, approximately 2 111 species of insects are consumed in about 140 countries. While insects have been part of the human diet in different regions of the world for centuries, insect consumption is not widespread in most high-income countries (FAO, 2021[40]). However, there is a

[11] Flavour additives generally compose 3-10% of the final product (Rubio, Xiang and Kaplan, 2020[14])

[12] Heme protein, or ''leghaemoglobin'', is an iron-containing molecule found in the nitrogen-fixing root nodules of leguminous plants.

growing interest in these countries to use insects as a source of nutrition, and several edible insect-based products have recently appeared on the market (Section 2.3).

Edible insects are mainly collected from the wild but farming insects for food and feed consumption is increasing. It is estimated that 92% of known edible insect species are wild-harvested, 6% semi-domesticated, and 2% are farmed (FAO, 2021[40]). Some insect species, such as crickets, mealworms, and black soldier flies, are farmed intensively around the world. Several industrial-scale farms, in China and Thailand in particular, produce insects for human consumption. Major companies in the European Union, the United States and Canada, however, mainly focus on insect farming for pet food and animal feed (mainly as fishmeal replacement) (Rowe, 2020[41]).[13]

The main inputs for insect production are feed, energy, and water. Some insect species can be reared on organic side streams (e.g. manure, pig slurry, compost), which appears as an attractive way to reuse food waste and contribute to a circular economy (Elleby et al., 2022[42]). However, for food safety reasons, most legislations prevent the use of organic side streams as insect feed for insects meant as food (e.g. the European Union Novel Food regulation). Other species, such as crickets, are mainly raised on insect farms and fed with grain-based feed such as chicken feed (FAO, 2013[43]).

Insects have one of the highest feed conversion ratios among animal proteins. It is estimated that about 1.7-2.3 kg of feed are needed to produce 1 kg of live weight, which is substantially lower than what is needed to produce 1 kg of beef and pigmeat, and lower or equivalent to what is needed to produce 1 kg of poultry (Van Huis, 2013[36]) (Oonincx, Van Broekhoven and Van Huis, 2019[44]) (FAO, 2021[40]).

Insects also have higher fertility rates than conventional livestock and can reach maturity within days, allowing farmers to harvest them multiples times a year (Alexander et al., 2017[45]).

Insects can be processed in several ways. In traditional cultures, insects are often steamed, roasted, smoked, fried, stewed, or cured to improve their sensory and nutritional qualities as well as their shelf-life (Melgar-Lalanne, Hernandez-Alvarez and Salinas-Castro, 2019[46]). To increase consumer acceptance in high-income countries, various technologies have been developed that primarily aim to use insects as ingredients in a non-recognizable form, such as powders or flour. These technologies include drying[14] and new processing methods – such as ultrasound-assisted extraction, cold atmospheric pressure plasma, and dry fractionation – that are mainly designed for protein, fat, and/or chitin extraction. Insect powder/flour can then be used as a source of protein in the formulation of meat alternatives (e.g. insect burgers). However, insect powder/flour has a distinct texture, appearance, and aroma that can create challenges in product formulation. Insect-based ingredients are also sold for the production of cookies, chocolates, tortilla-style chips, and other snacks (Melgar-Lalanne, Hernandez-Alvarez and Salinas-Castro, 2019[46]).

2.1.3. Cultured meat

Cultured meat involves the production of meat outside of the animal and in vitro. Cultured meat is produced from animal cells, rather than from slaughtered animals. Its technology is based on advances in stem cell biology and tissue engineering originally purposed for medical applications (Rubio, Xiang and Kaplan, 2020[14]).

Scientists have been working on cultured meat since the 1990s. Wilem van Eeln, a Dutch scientist, filed the first patent for a cultured meat production method in 1994. Cultured meat gained public visibility in

[13] There are about 90 insect farms in North America and Europe (Cohen and Duchemin, 2020[130]). The International Platform of Insects for Food and Feed (IPIFF) estimates that, in 2020, several thousand tonnes of insect-processed animal proteins were produced in the European Union (IPIFF, 2021[120]). In 2019, 500 tonnes of edible insect-based products (whole insects, insect ingredients, and products incorporated with edible insects) were placed on the European market (IPIFF, 2020[129]).

[14] For example, sun-drying, freeze-drying, oven-drying, fluidized bed drying, and microwave-drying.

2013 when a medical researcher, Mark Post, and two journalists tasted Post's cultured-meat burger on a TV show in London and declared that "it was close to meat'' (Treich, 2021[2]).

At present, there are about 100 start-ups working on cultured meat and associated technologies (e.g. scaffolding, growth medium) (Good Food Institute, 2021[47]), mostly located in the United States and the European Union, but also in Israel and Asia. A dozen of these companies are working to develop and bring their products on the market in the coming years. To date, however, only the US start-up "Eat Just'' is selling his cultured meat product to a restaurant in Singapore (since December 2020). The production of cultured meat has yet to be scaled up to an industrial level (Treich, 2021[2]).

Inputs for cultured meat production mainly include nutrients and other ingredients required for the formulation of the growth medium, i.e. the solution that provides the energy requirements for cells to grow. Energy and water are also needed, both in upstream production of the growth medium and during the production process.

The growth medium is composed of basic nutrients such as amino acids, glucose, vitamins, and inorganic salts (CE DELFT, 2021[37]) (Good Food Institute, 2021[48]). Amino acids and glucose can be extracted via hydrolization from a large variety of biomass, including livestock by-products and several types of plants such as soy, pea, maize and red sugar beets. It is estimated that about 1.5 kg of arable crops are needed to produce 1 kg of cultured meat (i.e. conversion rate of about 70%) (Kearney, n.d.[35]). Thus, cultured meat is expected to have a higher feed conversion ratio than all meat types. The basic nutrients in the growth medium are then supplemented with recombinant protein, growth factors or hormones and other ingredients such as lipids and antioxidants (Good Food Institute, 2021[48]).

The production of cultured meat involves four main steps (Figure 5). It is important to note, however, that the production technique of cultured meat is in development and might change when moved from laboratory- to industrial-scale (Ministère de l'Agriculture et de l'Alimentation, 2021[34]).

First, a few cells are taken from a living animal via a biopsy. Stem cells are generally taken from muscle tissue or from an embryo (*Step 1*). The stem cells are then grown in a bioreactor, which controls the temperature and oxygen levels, and deliver the growth medium that allow cells to proliferate (*Step 2*). When the desired number of cells is achieved, cells are induced to differentiate into skeletal muscle, fat, and connective tissues via changes in the growth medium composition, often in tandem with cues from a scaffolding structure (*Step 3*).[15] The differentiated cells are then harvested, prepared, and packaged into final products (*Step 4*) (Good Food Institute, 2021[48]). The entire production process is expected to take between 2 to 8 weeks, depending on the kind of meat being cultivated (Good Food Institute, 2021[48]). This is shorter than the production time of all meat types, which ranges between 7 and 112 weeks from birth to slaughter.

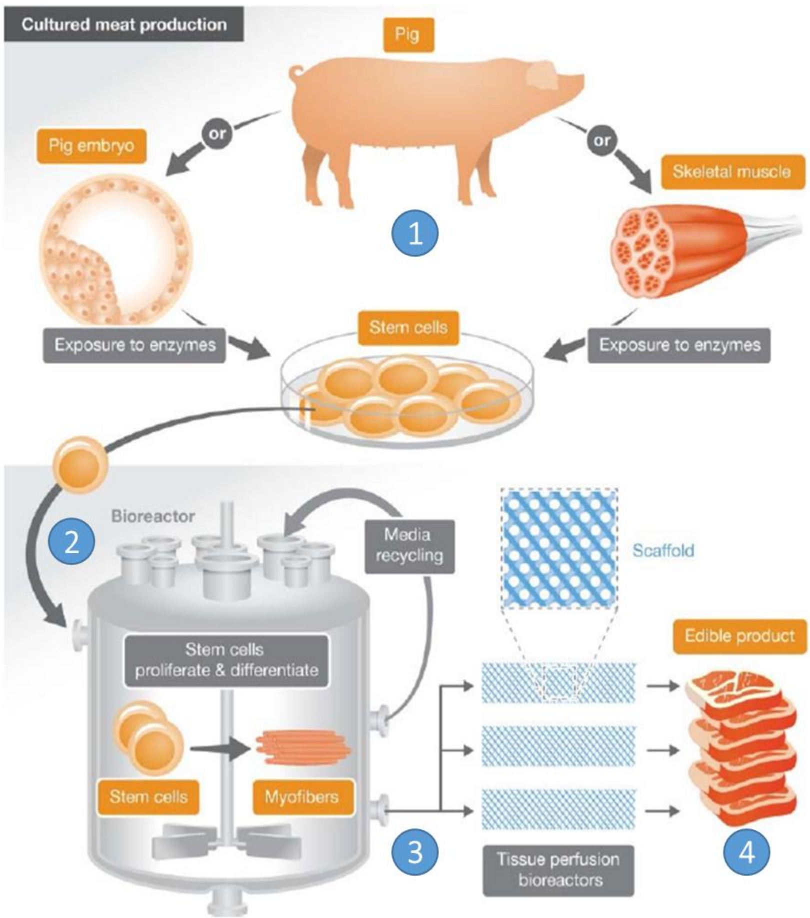
As cultured meat is intended to be molecularly extremely close to meat, it could be an almost perfect substitute in terms of taste, texture and appearance. There remain, however, several technical challenges associated with cultured meat production. First, replicating all the features of meat using cultured meat processes is challenging. For instance, proteins and metabolites that give meat products their colour, smell, and cooking properties may be expressed differently in cultured meats. Additionally, it is not known whether the post-mortem enzymatic events that can influence meat texture occur similarly in cultured meat products. There may be a need to add ingredients to aid in the colour, binding and texture of cultured meat, as is presently the case for plant-based meats (Good Food Institute, 2021[48]).

[15] The scaffold is the structure on which animal cells are grown to make them form muscle tissue that resembles the structured cuts of meat. The scaffold can be made from many materials, including plant polymers and extruded soy protein.

From a technical standpoint, unstructured minced products (e.g. burger meat, nuggets, sausages) are easier to create, and will likely represent the first generation of products on the market. Fully structured products will depend on advances in scaffold technologies and are likely to arrive later as it is more difficult to emulate the appearance and texture of whole cuts of meat (Good Food Institute, 2021[48]).[16] Moreover, it is unclear whether cultured meat techniques will be able to reproduce the diversity of flavours and textures that exist across species (pigmeat, poultry, ovines, bovines, etc.) and within species, between breeds, genders, animal types, and farming conditions (Chriki and Hocquette, 2020[26])

Finally, several technical challenges remain to ensure a cost-efficient cultured meat production (Section 2.2.3) and at scale for food supply. These challenges concern all key components of the cultivation system, i.e. the cell lines, the growth medium, the bioreactor process, and the scaffolding structure (Post et al., 2020[49]) (Good Food Institute, 2021[48]) (Ministère de l'Agriculture et de l'Alimentation, 2021[34])

Figure 5. Main steps of the production process of cultured meat (simplified)



1) Cell isolation: stem cells are extracted from an animal by biopsy. Cells are taken from muscle tissue or embryos.
2) Cell proliferation: Cells are placed in a bioreactor in a growth medium, causing them to proliferate.
3) Cell maturation and differentiation: Change in the medium composition, in combination with a scaffolding structure, pushes the cell to differentiate into muscle, fat and connective tissue
4) Cell harvesting and processing: differentiated cells are harvested, prepared, and packaged into final products.
Source: Tuomisto (2018[50]).

[16] The cultured meat start-up Aleph Farms, however, announced it had successfully replicated a ribeye steak using a 3-D cell printing process (Aleph Farms, 2021[123]) (Ministère de l'Agriculture et de l'Alimentation, 2021[34]).

2.2. Performance across the food systems' triple challenge

The literature on meat protein alternatives is relatively recent, but has been expanding rapidly. In reference to this emerging literature, we discuss the opportunities and challenges associated with selected meat alternatives using a food systems lens.

This assessment is mainly based on available evidence, including data on the price, nutritional composition, environmental footprint, and production costs of meat alternatives. For some meat alternatives such as cultured meat, however, most available estimates are preliminary as the technology is still in the early stages of development. Priority has been given to peer-reviewed academic publications in this assessment, which were complemented with data from consulting firms and the industry.

This report discusses the potential implications for animal welfare, and other issues that could impact consumer acceptance of these new foods and technologies. How these considerations will influence demand for meat alternatives will depend on the preferences and values that consumers and other stakeholders hold with respect to the attributes of food products. Understanding key values at stake with regards to meat alternatives will require further research.

This report also touches upon the potential wider economic impacts of a growing market in meat alternatives, such as effects on employment along the livestock value chain. Any disruptive technology can create winners and losers among producers, consumers and other interest groups. Anticipated distributional impacts could pose challenges for the development of meat alternatives if interest groups can influence the policy and regulatory environment. The interests at stake in the context of meat alternative development could be further explored in future work.

The following sections discuss the potential implications of a growing market in meat alternatives for food security, nutrition, and other consumer concerns (Section 2.2.1), for environmental sustainability (Section 2.2.2), and for the livelihood of the producers of meat and meat alternatives (Section 2.2.3).

2.2.1. Food security, nutrition, and other consumer concerns

This section compares meat alternatives with meats in terms of price and nutritional composition using available information and data from academic publications, research institutes, and the industry. These factors, together with products technical and sensorial properties (Section 2.1), are likely to be important determinants of consumer demand for meat alternatives.

Other potential drivers of consumer demand such as animal welfare and other ethical considerations that could have implications for consumer acceptance of meat alternatives are also discussed in this section.

Consumer price

Price is a key factor in determining consumer purchasing decisions. At present, selected meat alternatives are more expensive than meats, which limits consumer demand. However, the price of these alternatives is expected to fall in the coming decade as production scales up and production processes are optimised. The price paid by consumers depends on several factors, including production costs, which are discussed in details in section 2.2.3.

a) Plant-based alternatives

Plant-based alternatives are the most affordable of the three selected alternatives, but their price remains higher than those of meats (Cohen, 2021[51]) (Santo et al., 2020[16]). In 2021, for instance, the US retail price for 1 kg of ground beef was USD 9.5 (USDA, 2022[52]), compared to USD 21.3 and USD 17.5, respectively, for 1 kg of Beyond and Impossible burger patties.[17] In the European Union and the United Kingdom, the price of plant-based burgers and nuggets is also higher than that of beef burgers and chicken nuggets, respectively, although the price gap varies between countries (ING, 2020[38]). Despite the recent decline in the retail and food service prices of plant-based alternatives, these products continue to be sold at a premium price (Cohen, 2021[51]). Witte et al. (2021[53]) estimate that plant-based burgers could reach price parity with beef burgers by 2023, but that it will likely take longer for plant-based poultry pieces to compete with conventionally-raised poultry meat.

b) Insect-based alternatives

The price of edible insects is relatively high. The retail price for edible yellow mealworms and crickets in the United States and the European Union, for instance, range between USD 30-50/kg (Niyonsaba et al., 2021[54]). Insect burger patties, which are made of insect flour and plant mixture, are more expensive than both beef and plant-based patties. Coop (a Swiss start-up) and Bug Foundation (a German start-up) burger patties, for example, are sold at USD 46/kg and USD 35/kg, respectively (Coop, 2022[55]).

c) Cultured meat

Cultured meat has not yet reached the market, but high prices are anticipated given the current high production costs (Section 2.2.3). It is available in a single restaurant, located in Singapore, which offers their lab-grown chicken dishes – served as a mixture with vegetable proteins – at about USD 23.[18] According to the CEO of Eat Just, the supplying company, this price does not allow them to make a profit (Scipioni, 2020[56]). However, the price of cultured meat should go down in coming years following an expected decline in production costs. Witte et al. (2021[53]) and McKinsey & Co. (2021[57]) estimate that cultured meat (most likely minced cultured meat products) could reach price parity with meat by the early 2030s. Some analysts, however, consider this optimistic (Heinrich Böll Foundation, 2021[58])

Although meat alternatives have not yet reached price parity with meats, consumers could be willing to pay a price premium for these products in view of their perceived higher health, sustainability, and animal welfare standards.[19] Indeed, there is evidence in today's market that consumers are willing to pay extra for products they believe to be healthier or more sustainable (e.g. organic, grass-fed) (McKinsey & Company, 2021[57]).

It is important to note that if the externalities associated with the production of meats and meat alternatives were internalised – e.g. via a carbon price – it would change production costs and therefore the price of the different products, likely altering the price ranking between meats and selected alternatives (World Economic Forum, 2019[1]) (Section 2.2.2).

Human health and nutrition

Meat is a complete source of protein and contains important nutrients such as minerals and B-complex vitamins (Section 1.2). However, processed and red meats also contain ingredients the overconsumption of which has been linked to increased risks of non-communicable diseases, such as cardiovascular disease and some cancers (Pan, 2012[10]).

[17] The prices for the Beyond and Impossible burgers in this report are the retail prices at Walmart in 2021.

[18] The price per kg of these dishes is not available.

[19] A recent consumer acceptance study from the Netherlands reported that 58% of participants were willing to pay a 37% premium for cultured beef compared to conventional beef (Rubio, Xiang and Kaplan, 2020[14]).

In order to substitute for meats, meat alternatives aim to provide similar to superior nutrition. The following section compares the nutritional composition of meats and selected alternatives in terms of protein content, quality, and digestibility; micronutrient availability; and health-sensitive nutrients (e.g. saturated fat, sodium, and sugar).

a) Plant-based alternatives

The nutritional composition of plant-based meat products available on the market is heterogeneous. In this section, we look at the nutritional composition of the Beyond and Impossible burgers. These products are among the most popular meat alternatives in today's market and complete nutritional data are available online. The recipes of these plant-based burgers have been changed several times to match as closely as possible the nutritional profile of beef. Table 1 presents the nutritional composition of the Beyond and Impossible, beef and insect burgers.

Table 1. Nutritional composition of the Beyond and Impossible burgers (100g), of an insect burger (100g), and a beef burger (100g, 80% lean meat 20% fat)

	US Beef Burger	Beyond Burger	Impossible Burger	Insect Burger (Bugfundation)
Calories (kcal)	254	252	212	282
Protein (g)	17.2	17	17	21
Total fat (g)	20	19	12.4	19
Saturated fat (g)	7.58	5.6	7	2.1
Total carbohydrate (g)	0	3.5	8	4.5
Fibre (g)	0	1.3	2.7	1
Iron (mg)	1.94	4	3.7	n.a.
Cholesterol (mg)	71	0	0	n.a.
Sodium (mg)	66	345	327	1600
Sugar (g)	0	0	0	1.4

Note: n.a.: Data is not publicly available.
Sources: Beef burger: (USDA, 2019[59]); Beyond burger: (Beyond Meat, 2022[60]); Impossible burger: (Impossible Foods, 2022[61]); Insect burger (Smetana et al., 2021[62]).

The energy and protein content, as well as the protein quality and digestibility of plant-based burgers are in line with the ones of a beef burger (Table 1). Peas and soybean are the main sources of protein in the Beyond and Impossible burgers, respectively (Gelsomin, 2019[63]).[20] As plant proteins are usually limited to one or more essential amino acids, legumes are combined with cereals to match the amino acid profile in animal protein.[21] The protein digestibility-corrected amino acid score (PDCAAS) of the Impossible Burger is in line with that of the beef burger, indicating that they have similar protein value in human nutrition (Khan et al., 2019[64]).[22] PDCAAS data are not available for the Beyond burger.

Like ground beef, plant-based burgers are generally good sources of minerals and vitamins. The Beyond and Impossible burgers provide 25% of the daily value (DV) of iron, which is twice as much as a beef

[20] Protein content of soybean and pulses as set in Aglink-Cosimo: soybean= 24.7% of dry weight and pulses=22% of dry weight.

[21] Legumes lack methionine while cereals lack lysine.

[22] The PDCAAS is an indicator to assess protein quality by its ability to meet the human body's amino acid requirements (Berrazaga et al., 2019[72]).

burger (Table 1). However, the iron in meat is heme-bound and might be better absorbed than the iron in plant-based burgers. The Beyond and Impossible burgers also display higher calcium content than a regular beef burger and similar to higher potassium content. Moreover, the Impossible Burger matches the beef burger on zinc – both provide about half the daily requirement.[23] With respect to vitamins, the Impossible Burger provides as much, if not more, of nearly every vitamin found in the beef burger. These include vitamins B1, B2, B3, B6, B9 and B12. Vitamin B12 has to be supplemented in the Impossible burger as it is only found in food of animal origin (ruminant mainly). The Beyond Burger, however, provides none of the vitamins usually found in beef (ConsumerLab.com, 2019[65]).

As a result of seeking to replicate a beef burger, these products contain a comparable amount of saturated fats (Gelsomin, 2019[63]).[24] Saturated fats in plant-based burgers originate mainly from vegetable oils.

As opposed to a beef burger, however, plant-based burgers contain dietary fibre. In both the Beyond and Impossible burgers, fibre accounts for about 10% of the recommended daily amount. Increased consumption of fibre, typically from cereals, is positively associated with reductions in coronary heart disease, cancer and stroke (World Economic Forum, 2019[1]).

Finally, the plant-based burgers studied in this report lack cholesterol, but contain five times the amount of sodium found in a beef burger – accounting for about 10% of the recommended daily amount (Afshin et al., 2019[8]).[25]

Concerns have been raised about the health effect of consuming plant-based alternatives as these products are highly formulated and processed, and contain food additives (Rubio, Xiang and Kaplan, 2020[14]) (O'Connor, 2020[66]) (Section 2.1.1). Excessive consumption of processed foods has been linked to increased risk of diet-related diseases (dos Santos et al., 2020[67]). Food processing may also lead to the loss of certain nutrients and phytochemicals found in plant-based foods (FAO, 2022[68]). However, not all processed foods are unhealthy and it remains unclear which aspects of food processing and formulation are primarily associated with diet-related diseases (Tso and Forde, 2021[69]) (OECD, 2021[5]).

Overall, more research is needed on the nutritional and health impacts of substituting animal foods with plant-based alternatives, particularly in terms of micronutrient and health-sensitive nutrient intake. Much more is known about the health benefits of substituting meats with traditional plant-based foods such as legumes, with evidence demonstrating lowered risks of cardiovascular disease, diabetes, cancer and obesity (Tso and Forde, 2021[69]) (World Economic Forum, 2019[1]).

A few studies have recently looked at the impact on diet of substituting animal foods with plant-based alternatives. These studies found that substitution led to higher intake of fibre, vitamins E and B9 and of some beneficial fatty acids, but a lower intake of vitamin B12, zinc, iron, and other micronutrients (Tso and Forde, 2021[69]) (Salomé et al., 2021[70]). Substitution also increased the energy share of ultra-processed foods (Salomé et al., 2021[70]).

b) Insect-based alternatives

Insects are considered to be a good source of human nutrition. Their nutritional value, however, varies considerably according to the species, feeding, and stage in the life cycle (i.e. egg, larva, pupa or adult) (FAO, 2021[40]). This section looks at the nutritional composition of insect species that are the most promising for consumption in high-income countries, and for which there is complete nutritional data,

[23] The Beyond Burger, however, does not contain zinc.

[24] Diets high in saturated fats have been associated with increased rates of heart disease and premature death (Gelsomin, 2019[63]).

[25] High sodium content is considered to be nutritionally undesirable and to contribute to high blood pressure and increased risk of heart disease and stroke (WHO, 2020[128]).

i.e. the cricket and the yellow mealworm. The nutritional composition of an insect burger is then compared with the beef and plant-based burgers (Table 1).

The protein content of insects varies widely between species (with a range of 13% to 81% of dry weight). The protein content of locusts and grasshoppers (13-28g/100g of fresh weight), yellow mealworm (14-24g/100g of fresh weight), and cricket (8-25g/100g of fresh weight) is in line with the protein content of meats but shows a greater range (FAO, 2013[43]) (Payne et al., 2016[71]).

Like meats, insects are considered a complete source of protein as they contain all nine essential amino acids. In mealworms, some amino acids are present in higher quantities than in beef (i.e. isoleucine, leucine, valine, tyrosine and alanine), while others are present in lower quantities (i.e. glutamic acid, lysine and methionine) (FAO, 2013[43]). The digestibility of insect protein is also species dependant, but is generally lower than that of meat protein. Crickets, for example, have a PDCAAS of 73% (McKinsey & Company, 2019[31]) compared to between 90% and 99% for meats (Berrazaga et al., 2019[72]).

Insects tend to have high content levels of vitamins (e.g. vitamins A, B and C) and minerals (e.g. iron, zinc, magnesium, manganese, phosphorus, and selenium). Most edible insects have similar to higher iron and zinc content than beef (FAO, 2013[43]). The median value for iron content in crickets, for instance, is almost three times higher than for beef (Payne et al., 2016[71]). Mealworms generally have higher vitamin content than beef, except for vitamin B12. Crickets contain a high level of vitamin B12 (FAO, 2013[43]).

Edible insects are a considerable source of fat, including beneficial fatty acids such as omega-3 and omega-6. Moreover, the medium value for saturated fat content in both cricket and mealworm is lower than in beef and pigmeat, but higher than in poultry (Payne et al., 2016[71]).

However, insects tend to contain high levels of sodium. The median value for sodium content in crickets is more than twice that of meats (Payne et al., 2016[71]).

The nutritional composition of some insect-based burgers is publicly available. Bugfoundation's burger patty, made of buffalo worm flour, soy and other plants, exceeds both beef and plant-based burgers in terms of protein content. It matches beef and plant-based burgers in terms of fat content, but has lower amount of saturated fat. However, it contain less dietary fibre than the plant-based burgers, more sodium than the beef and plant-based burgers, and contains sugar (Table 1) (Smetana et al., 2021[62]). Bugfoundation's insect burger contains about half the recommended amount of sodium one should consume per day (Afshin et al., 2019[8]). No data is available on its mineral and vitamin content.

c) Cultured meat

Comprehensive, baseline nutritional data for cultured meat is not publicly available. The nutritional data of prototypes is privately held as companies continue to iterate on their future products (Good Food Institute, 2021[48]). Data should become available with the launch of initial products, scale-up, and additional interest from the scientific community (Rubio, Xiang and Kaplan, 2020[14]).

As cultured meat is intended to be molecularly extremely close to meat, it could become an almost perfect substitute in terms of nutritional value. Differentiated muscle cells are likely to be the primary source of protein, and mature adipocytes could contribute to the fatty acid profile. However, certain compounds that are provided by meats are not present in cultured cells. Vitamin B12, for example, is only synthesized by bacteria and will need to be supplemented (Rubio, Xiang and Kaplan, 2020[14]).

Moreover, several techniques such as co-cultured, growth medium supplementation, and genetic modification could be used to fortify cultured meat. The growth medium could be tailored for desired outcomes such as increased omega-3 fatty acids or higher vitamin and mineral content. Genetic engineering, if allowed, could be used to insert genes that could fortify products with vitamin A precursors not found in meats, or create personalised nutrition for specific populations (Good Food Institute, 2021[48]).

Human-animal nexus

Meat production involves close interactions between human and farm animals, with the associated risks of diseases and infections, and ethical concerns regarding the rearing and slaughtering of animals (Section 1.2). By removing farm animal from the production process, meat alternatives could address some of the negative externalities and ethical concerns associated with meats. This could be a key driver of consumer demand, particularly in high-income countries where there is growing awareness of health and animal welfare issues.

a) Plant-based alternatives

Plant-based meat products are generally free of animal by-products and thus do not have direct negative impacts on animal welfare. However, a small number of products contains dairy-based or egg-based additives, which could raise concerns about the welfare of laying hens and dairy cows (Rubio, Xiang and Kaplan, 2020[14]) (Santo et al., 2020[16]). Several companies selling these products have recently been adding (e.g. Quorn Foods) and/or transitioning to 100% plant-based products (e.g. Morningstar Farms) (Santo et al., 2020[16])

Moreover, as opposed to foods of animal origin, plant-based foods are generally not associated with food-borne illnesses, infectious diseases, and antimicrobial resistance issues. Antibiotics are used for crop production, but at relatively low levels. In the United States, for example, the use of antibiotics for plant production is equivalent to less than 1% of that used in animal production (Rubio, Xiang and Kaplan, 2020[14]).

b) Insect-based alternatives

Insect-based alternatives are not animal-free. However, little is known on the extent to which invertebrates experience stress, pain, and discomfort and it is often suggested that it might be lower than for mammals in part due to their lack of developed nervous system. Until more research is available, experts recommend precautionary principle be used, i.e. treat insects as “sentient’’, meaning that when farming them, steps to minimize pain should be adopted (FAO, 2013[43]).

More research is also needed on the risks of foodborne illnesses, zoonotic infection and antimicrobial resistance associated with insects. However, some of these risks might be lower than for conventional livestock. As insects are taxonomically more distant from humans than are farm animals, for example, the risk of zoonotic infections is expected to be low. However, this risk could rise with the careless use of waste products, the unhygienic handling of insects, and direct contact between farmed insects and insects outside the farm (FAO, 2013[43]). Moreover, as insects naturally live in large groups in small spaces, they can be raised intensively without the need for antibiotics or other medicines to prevent the spread of diseases (Dossey, Tatum and McGill, 2016[73]).

c) Cultured meat

Cultured meat is often presented as a form of animal-free agriculture, since meat can be produced without the slaughtering of farm animals. However, cultured meat might never be fully free from animals as these are needed as living donors of stem cells (Treich, 2021[2]). Nevertheless, the stock of farm animals that would need to be maintained would be drastically reduced (Chriki and Hocquette, 2020[26]) (Heinrich Böll Foundation, 2021[58]).

Ethical problems arise with regard to the use of animal serum in the upstream formulation of the growth medium. To date, the most efficient medium is known to contain foetal bovine serum – a serum extracted from the blood of a dead calf[26] – which partly defeats the purpose of replacing meats and contributes to high production costs (Chriki and Hocquette, 2020[26]). An efficient process to manufacture animal-free medium appears to be a major challenge for the industry and a barrier to cultured meat adoption. However, the development of growth medium made of plants only and/or other non-animal products (e.g. cyanobacteria, algae, yeast and fungi) seems possible, and some start-ups have already claimed to be using entirely animal-free medium. Once this issue is solved at an industrial scale, cultured meat will be in a better position to compete with meats in terms of animal ethics, but also on costs.

Advocates of cultured meat also claim that meat produced in a fully controlled and sterile laboratory environment is safer than meats produced from farm animals in contact with the external world (Chriki and Hocquette, 2020[26]). First, the sterile conditions required for cell proliferation eliminate exposure with enteric pathogens and thus reduces the risk of contamination with disease-causing pathogens. Sterile conditions could also eliminate the need for antibiotics (Heinrich Böll Foundation, 2021[58]). Moreover, as cultured meat is not produced from animals raised in confined spaces it could drastically reduce the risk of infectious diseases and outbreaks, including zoonotic. However, some researchers estimate that the risk of contamination might increase when moving from laboratory to factory scale as the mass multiplication of cells could significantly increase the risk of infection (Minisini and Mraffko, 2021[74]).

Consumer acceptance

Meat protein alternatives have the potential to alleviate some of the negative externalities and ethical concerns associated with the production and consumption of meat (Sections 2.2.1 and 2.2.2), which could be a key driver of consumer demand. At the same time, these new foods and associated technologies are raising concerns, some of which are lowering consumer acceptance.

Onwezen et al. (2021[4]) produced a systematic review, identifying 91 articles focused on the drivers of consumer acceptance of five alternative proteins. They found that overall acceptance of alternative proteins is relatively low compared to acceptance of meats. Acceptance of insects is the lowest, followed by acceptance of cultured meat. Pulses and plant-based alternatives have the highest acceptance level among alternative proteins.

For insects, consumer concerns include food neophobia (i.e. the aversion to trying novel food), unfamiliarity, fear, disgust, as well as price and taste. Consumer acceptance in high-income countries, where insects are not part of the diet, is viewed as a key challenge by the edible insect sector (FAO, 2021[40]).

The main factors limiting acceptance of cultured meat relate to unnaturalness, disgust, food neophobia, safety, healthiness and also taste and anticipated price (Treich, 2021[2]). Although the level of acceptance of plant-based alternatives is relatively higher, there are concerns about unfamiliarity, taste and healthiness, in particular for newer plant-based alternatives which are often perceived as highly processed (Rubio, Xiang and Kaplan, 2020[14]).

Several studies suggest that meat hybrids could bridge the acceptability gap between meats and meat alternatives. Neville et al. (2017[75]) found no significant differences in consumer acceptability between meat hybrids (defined in this study as blends of meat and plant-based ingredients) and meat products, whereas plant-based alternatives were found to have lower acceptance levels. Meat hybrids could thus be a compromise for consumers who want to reduce their meat intake without sacrificing the taste, convenience, and familiarity of meat (Neville et al., 2017[75]) (Profeta et al., 2021[76]).

[26] The first approved cultivated meat product in Singapore was produced using foetal bovine serum, which is removed from the final product before consumption (Good Food Institute, 2021[48]).

Consumer acceptance studies generally found the acceptance level of meat alternatives to vary significantly between age groups, gender, education level, countries/regions, and between meat eaters/vegetarians/vegan. Acceptance of meat alternatives tends to be higher among young and educated individuals who have low levels of meat consumption. Several studies also highlight the importance of education on the benefits of meat alternatives to increase consumer acceptance (Post et al., 2020[49]).

Clear regulation and labelling of meat alternatives will be key to ensuring these new foods and ingredients are safe and thus increase consumer confidence. At present, the global regulatory environment around meat alternatives is vague and fragmented, although developing rapidly. Box 1 offers an overview of the regulatory framework on selected meat alternatives in OECD countries. The potential food safety risks (e.g. microbiological and chemical hazards) associated with plant-based alternatives, insects and cultured meat are not discussed here but are reviewed in detail by the Food and Agriculture Organization of the United Nations (FAO) (FAO, 2022[68]).

Box 1. Regulation of meat alternatives in OECD countries

Some OECD countries have started to provide clarity about which agencies will be responsible for the regulation of different alternative protein products and on the regulatory pathway these products will be subject to. An overview of the existing regulatory framework for the meat alternatives studied in this report is provided below.

Plant-based alternatives

Plant-based alternatives made from commonly used ingredients generally do not require regulatory approval in the form of market authorisation and are regulated in a similar manner as other non-animal foods (Witte et al., 2021[53]) (Rubio, Xiang and Kaplan, 2020[14]). Pulses and other protein-rich plants (e.g. soybean, chickpeas, lentils, peas) that might be categorised as alternative proteins are usually not considered as novel foods (Lahteenmaki-Uutela et al., 2021[32]). Alternatives using novel ingredients (e.g. leghaemoglobin[1], mung bean), however, may be classified as “novel foods’’, or in some countries as “genetically modified” if genetic engineering has been used, requiring approval and being subject to additional evaluation processes. Pathways for approval for many novel foods and ingredients exist, including in the European Union, Australia, Canada, and New Zealand (Rubio, Xiang and Kaplan, 2020[14]).

The use of innovative production and processing methods that might alter the nutritional value of products can also make the final product a novel food. In the European Union, 3D printed foods, which include some plant-based meat products, are deemed novel foods because of their production process, regardless of whether the ingredients are novel or not (Lahteenmaki-Uutela et al., 2021[32]).

Government oversight is also required for the labelling of meat alternatives. In the United States and the European Union, new laws have been enacted to limit the use of words such as '“meat”, “steak” or “sausages” for plant-based meats.[2] The purpose advanced for these laws is to prevent consumers from being misled. It is unclear, however, what will be the impact on demand for these products (Treich, 2021[2]).

Insect-based alternatives

In the European Union, since January 2018 all insect-based products fall under the EU Novel Food Regulation 2015/2283. This implies that it is necessary to submit an application to the European Commission, with a follow-up scientific evaluation by the EU food safety agency, before putting an insect-based product on the market (FAO, 2021[40]). In 2021-2022, EU-wide approvals of insects for human consumption were granted to the yellow mealworm, the migratory locust, and the house cricket (European Comission, 2022[77]).

In the United-States, Canada, New Zealand and Australia, edible insects have not so far been characterised as novel foods. Therefore, they should comply with the same safety and hygiene standard and regulations as other foods available in these countries. In Canada, certain insect species may be considered novel foods as per Division 28 of the Food and Drug Regulations if they do not have a history of safe use and thus require a mandatory premarket safety assessment. Others such as the silkworm, house cricket and mealworm can be found under the List of Non-novel Determinants for Food and Food Ingredients as determined by Health Canada (FAO, 2021[40]). In Australia and New Zealand, the super worm, the yellow mealworm, and the house cricket are considered non-traditional food, but not novel food. This indicates they need to comply with the regular Food Standards Code, providing a degree of freedom from pre-market approval requirements (FAO, 2021[40]).

Cultured meat

In December 2020, the Singapore Food Agency authorised the commercialisation of the cultured chicken produced by the US company Eat Just. This was an important milestone as it was the first – and so far only – authorization of a cultured meat product by a food safety institution (Treich, 2021[2]). Some OECD countries, however, have begun to work on a regulatory framework for cultured meat.

In the European Union, cultured meat will be applicable to the Novel Food Regulation pathway due to the novel production process. The EU authorisation application procedure includes a risk assessment, and requires that cultured animal products and production are proven to be safe by the applicants (Treich, 2021[2]). However, if the cell lines used in the bioreactor are genetically modified, then cultured meat production will most likely be covered by the EU GMO legislation (Lahteenmaki-Uutela et al., 2021[32]). The use of genetically modified cells could create regulatory hurdles as several European countries (e.g. France, Germany, Greece) have banned the production and sale of GM foods (Rubio, Xiang and Kaplan, 2020[14]). The use of sex hormones in cultured meat growth factor could also be a source of regulatory complications. No limit currently exists for the concentration of these hormones in cultured meat, but the European Union has prohibited their use in meat production since 1981 due to the risks they impose on human health (Heinrich Böll Foundation, 2021[58]).

In the United-States, the FDA and the US Department of Agriculture Food Safety and Inspection Service (USDA–FSIS) have agreed to jointly regulate cell-based meat and poultry and have set some details on the regulatory framework (Treich, 2021[2]). The FDA will oversee pre-harvest processes (i.e. cell collection, development, proliferation and differentiation processes), while the USDA will oversee the production and labelling stages. As of January 2020, twelve US states have passed laws that restrict the use of certain terms such as “meat’’ on cultured meat products even though cultured meat is not yet on the market. However, a clear labelling scheme disseminated by the FDA/USDA will pre-empt state laws on labelling of cultured meat products (Post et al., 2020[49]).

In Canada, products of cellular agriculture origin meet the definition of a novel food in Division 28 of the Food and Drug Regulations and require a mandatory premarket safety assessment before being made available for sale.

Food Standards Australia New Zealand (FSANZ) announced that cultured meat is likely to be regulated either as a novel food or, if genetically modified cell lines have been used, as genetically-modified food, with both requiring premarket approval (Guan et al., 2021[78]).

Notes: 1. In the United-States, Impossible Foods received FDA approval in 2019 to use soy leghaemoglobin, which is made using genetically modified yeast in the production process. However, the company is facing market access issues in many countries (including the European Union) due to regulatory requirements on GMO products.
2. The US Cattlemen’s Association (USCA) submitted a petition to USDA in 2018 asking them to establish meat labelling requirements that exclude products not derived directly from animals that have been raised and slaughtered (Rubio, Xiang and Kaplan, 2020[14]).

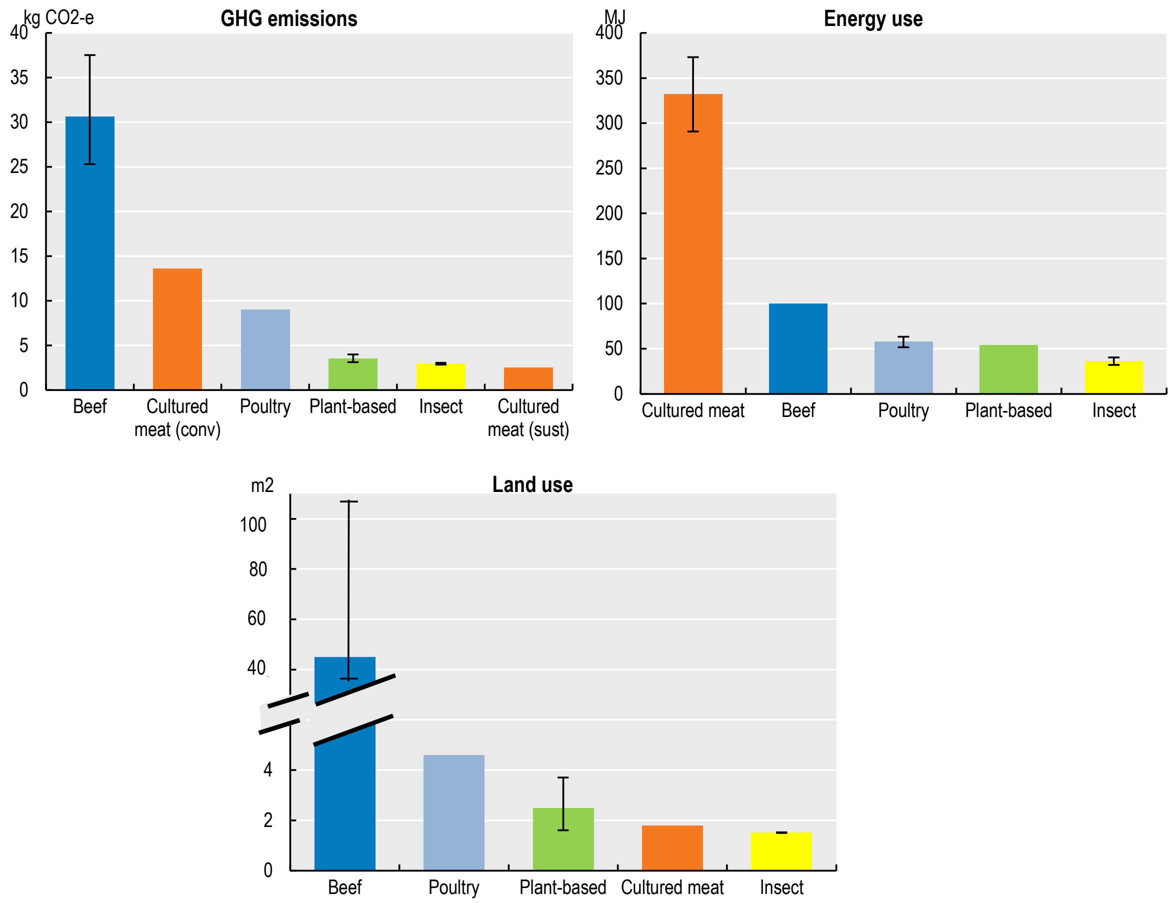
2.2.2. Environmental sustainability

Meat production is associated with negative externalities on the environment (Section 1.2). A key benefit of meat alternatives is their potential to reduce some of these externalities. This section compares the environmental performance of meats and selected meat alternatives using life cycle analysis (LCA) published in the academic literature and by the industry. It focuses on the environmental indicators that are the most documented, namely GHG emissions, and land and water use.

It is important to note that the different estimates from the LCA literature are not always fully comparable as the functional unit (e.g. weight, protein or calorie basis) and the system boundaries of the LCA assessments (e.g. cradle-to-gate; cradle-to-plate) can differ between studies. There are also important variations depending on the regions and production systems considered, in particular for ruminant meats (Herrero et al., 2013[79]). Nevertheless, a review of these estimates gives an indication of the relative environmental performance of meats and meat alternatives on the above selected indicators.

Figure 5 shows GHG emissions, and energy and land use associated with 1 kg of ground beef, poultry, cultured meat, and plant and insect-based burgers. Water use is not presented in Figure 6 due to the lack of comparable data.

Figure 6. The environmental impact of 1 kg of meats and meat alternatives



Notes: Error bars show 95% confidence intervals.
All studies use a cradle-to-gate system boundary except (Smetana et al., 2015[80]), which use a cradle-to-plate approach.
Cultured meat (conv) refers to cultured meat under current technology and energy mix. Cultured meat (sust) refer to cultured meat under a clean energy scenario, as in (CE DELFT, 2021[37]).
Sources: 1) GHG emissions: US beef burger and plant-based burger (Impossible burger) (Khan et al., 2019[64]); cultured meat and poultry (CE DELFT, 2021[37]); Insect-based meat alternative (Smetana et al., 2015[80]); 2) Energy use: cultured meat, poultry and insect-based meat alternative (Smetana et al., 2015[80]), US beef burger and plant-based burger (Beyond burger) (Heller and Keoleian, 2018[81]) 3) Land use: US beef burger and plant-based burger (Impossible burger) (Khan et al., 2019[64]), cultured meat and poultry (CE DELFT, 2021[37]), and insect-based meat alternative (Smetana et al., 2015[80]).

GHG emissions

Based on life-cycle analysis, the livestock sector is responsible for 14.5% of global GHG emissions. About 44% of the sector's emissions are in the form of methane emissions (CH_4) from enteric fermentation and manure management. The remainder is almost equally shared between nitrous oxide emissions (N_2O) (29%) from fertiliser use and manure management and CO_2 (27%) from land use change (mainly) and fossil fuels use. While half of livestock sector emissions are associated with livestock production itself, feed production, processing and transport are responsible for another 45% of the sector GHG emissions (Gerber et al., 2013[21]).

Available estimates from the LCA literature suggest that all meat protein alternatives studied here have a lower carbon footprint per kg of product than does beef, and that plant and insect-based alternatives also have a lower carbon footprint than pigmeat and poultry (Figure 5). A switch from meats to meat alternatives could therefore have important benefits in terms of GHG mitigation.

a) Plant-based alternatives

Overall, plant-based foods have lower emission intensities than animal-based foods (Poore and Nemecek, 2019[82]) (World Economic Forum, 2019[1]). Key plants used in plant-based meat recipes, e.g. pea and wheat, have emission intensities below 1 kg CO_2-e/kg product, which is considerably lower than beef (>30 kg CO_2-e/kg product), pigmeat and poultry (Figure 5). The carbon footprint of soybean is more variable, depending on the producing regions and production systems, but is estimated to be below 2 kg CO_2-e/kg product (Escobar et al., 2020[83]) (Gil, 2020[84]), which is also lower than for all meat types.

Published LCAs suggest that plant-based alternatives to meat also have lower emission intensities than their meat equivalents (Smetana et al., 2021[62]) (blue horizon, 2020[85]). Beyond Meat and Impossible Foods have released LCA of their products indicating that the carbon footprint of their plant-based burgers, as measured in kg CO_2-e/kg product, is 89% lower than the that of a US beef burger (Heller and Keoleian, 2018[81]) (Khan et al., 2019[64]) (Figure 5).[27] Almost 60% of the emissions associated with these plant-based burgers come from the production of ingredients (i.e. soy, pea, cereals, vegetable oils), while the rest is associated with product processing, packaging, and distribution (Heller and Keoleian, 2018[81]).

b) Insect-based alternatives

The literature on GHG emissions associated with insect production is limited. Direct GHG emissions are estimated for only five species and LCAs have been published for only four species (van Huis and Oonincx, 2017[86]). The potential main sources of emissions from insect production are feed production, and energy use to maintain climate-controlled facilities and for processing.

Overall, LCAs published in academic journals suggest that farmed insects have a lower carbon footprint than all meats, both on a weight and on an edible protein basis. Direct emissions are estimated to be lower as well as emissions associated with feed production due to higher feed conversion ratios. (Oonincx and de Boer, 2012[87]), for instance, found that mealworms emit 1.32-2.67 times less GHG per kg of protein than poultry, 1.51-3.87 times less than pigmeat, and 5.52-12.51 times less than beef. Vauterin et al. (2021[88]), however, suggest that depending on the location of production and the insect species, the carbon footprint of insect protein may be larger than that of poultry protein. A reduction in the carbon footprint of insect protein can be achieved by using side streams as insect fodders or via a switch to clean energy sources.

[27] Beyond burger and Impossible burger = 3.5kg CO_2-e/kg product vs beef burger (US) = 30.6-32.7 kg CO_2-e/kg product.

There are a couple of LCAs of insect-based alternatives published in the academic literature and by the industry. These studies suggest that the carbon footprint per kg of product of insect-based alternatives, such as insect burgers, is significantly lower than the one of a beef burger, lower than poultry meat, and lower or similar to the one of plant-based alternatives (Figure 5) (Smetana et al., 2021[62]) (Smetana et al., 2015[80]) (Bug Foundation, n.d.[89]).

c) Cultured meat

Cultured meat production is an energy intensive process as industrial processes replace biological functions. Most GHG emissions are CO_2 emissions from energy use due to electricity use during the production process, but also electricity and heat use in the upstream production of the growth medium (CE DELFT, 2021[37]).[28] Producing 1 kg of cultured meat requires significantly more energy compared to 1 kg of meats, plant and insect-based alternatives (Figure 5).

There are a few anticipatory/prospective LCAs that model commercial-scale culture meat facility published in the academic literature (Tuomisto and Teixeira de Mattos, 2011[90]) (Tuomisto, Ellis and Haastrup, 2014[22]) (Mattick et al., 2015[91]) and by research institutes (CE DELFT, 2021[37]). These studies found that cultured meat – under the current production technology and energy mix – has a lower carbon footprint per kg of product than beef, but higher than poultry and pigmeat (Figure 5).

A switch to clean energy sources, however, could enable a significant reduction in GHG emissions that are associated with cultured meat production. CE DELFT (2021[37]) estimates that under a clean energy scenario, the carbon footprint of cultured meat could decrease to 2.5 kg CO_2-e/kg product, which is lower than all meat types (Figure 5). There is generally more scope to reduce CO_2 emissions from energy use than agricultural GHG emissions, which are mainly CH_4 emissions from enteric fermentation and manure management, and N_2O emissions from soil (Tuomisto and Teixeira de Mattos, 2011[90]).

Nevertheless, there is a high level of uncertainty around these estimates of energy use and GHG emissions given that cultured meat technology is in its infancy. Current estimates are highly dependent on the assumptions made regarding the production technology, and in particular those related to the composition and amount of growth medium and the design of the bioreactor, both having major impact on the environmental performance of cultured meat. Future emissions will largely depend on how cultured meat production is completed and scaled up.

Given the estimated lower carbon footprint of meat alternatives, switching from meats – beef in particular – to meat alternatives could have significant benefits in terms of GHG emissions mitigation. The World Economic Forum estimates that replacing beef in each regions' diet with different meat alternatives could lead to a 7% to 26% reduction in total food-related GHG emissions, with the highest reduction coming from a switch to plant proteins and insects, and the lowest from a switch to cultured meat under the current production technology. While assuming a complete replacement of beef is unrealistic, these estimates give an idea of the mitigation potential of the different meat alternatives (World Economic Forum, 2019[1]).

Land use

Livestock production is a large user of land. The FAO estimates that 26% of the world's ice-free land is used for livestock grazing, and 33% of croplands are used for livestock feed production (FAO, 2013[92]).

A clear environmental benefit of meat protein alternatives is lower land use requirements compared to meats (Figure 5). Meat alternatives do not require pastureland and have a lower need for cropland as they have higher feed conversion ratios than do meats (Section 2.1).

[28] The major energy input in the cultivation of cultured meat consists of heating energy required to heat the nutrition media and maintain the bioreactor temperature at 37°C (Tuomisto, Ellis and Haastrup, 2014[22]).

Land that is freed up from livestock and feed production could be released for other uses (e.g. forest, native vegetation) and provide further GHG mitigation options, including through afforestation and bioenergy production (Alexander et al., 2017[45]).

a) Plant-based alternatives

Published LCAs suggest that both traditional (e.g. tofu) and newer plant-based alternatives (e.g. plant-based meats) have lower land use requirements per kg of product than do meats (Smetana et al., 2021[62]) (CE DELFT, 2021[37]) (blue horizon, 2020[85]) (Heller and Keoleian, 2018[81]) (Khan et al., 2019[64]). The LCAs of the Beyond and Impossible burgers, for instance, suggest that 92% to 96% less land is needed to produced 1 kg of plant-based burgers compared to 1 kg of US beef burger (Heller and Keoleian, 2018[81]) (Khan et al., 2019[64]). The land use impact of plant-based burgers is mainly associated with the production of ingredients (80%) (Heller and Keoleian, 2018[81]).

b) Insect-based alternatives

Almost all land use requirements associated with insect production come from feed production as insect production facilities require almost no land. Overall, insects have a higher land use efficiency than conventional livestock (FAO, 2021[40]). Oonincx and de Boer (2012[87]) estimated that 2.3-2.85 times less land is needed to produce 1 kg of mealworm protein compared to 1 kg of poultry protein, 2.57-3.49 times less compared to 1 kg of pigmeat protein, and 7.89-14.12 times less compared to 1 kg of beef protein.

Published LCAs suggest that insect-based alternatives such as insect burgers also have lower land use requirement per kg of product than both beef burgers and poultry meat (Smetana et al., 2021[62]) (Smetana et al., 2015[80]). Land use requirements are also found to be lower than for cultured meat and for several types of plant-based alternatives (Smetana et al., 2015[80]) (Figure 5).

c) Cultured meat

Reduction in land use is potentially the main environmental benefit from cultured meat production. Moreover, there is less uncertainty than around energy use and GHG emissions estimates.

Published LCAs suggest that cultured meat has lower land use requirements per kg of product than all meat types (Tuomisto and Teixeira de Mattos, 2011[90]) (Mattick et al., 2015[91]) (CE DELFT, 2021[37]). CE DELF, for example, estimates that only 1.8m^2 is needed to produce 1 kg of cultured meat; this is 60% less than what is needed to produce 1 kg of poultry, and 94% less than what is needed to produce 1 kg of beef (CE DELFT, 2021[37]).[29]

As the land use impact of cultured meat production is mostly associated with the production of feedstock for growth medium formulation, estimates provided in the literature depend on the assumptions made regarding the composition of the growth medium, and the share of feedstock that comes from conventional agriculture (e.g. soy, maize, sugar beet). Tuomisto and Teixeira de Mattos (2011[90]) estimated that if a cyanobacteria and microalgae-based growth medium is used, cultured meat production could require only 2% of the land global livestock sector uses today. The authors updated their study using wheat and maize-based growth media, which although resulted in higher land use requirements, was still significantly lower than for meats (Tuomisto, Ellis and Haastrup, 2014[22]).

[29] In this study, the growth medium is assumed to be soy and maize-based.

Water use and pollution

Animal agriculture is a large user of water. While direct use of water by farm animals is proportionally low, indirect water use for cultivating and processing feed crops and growing animal feed (including pasture) is the largest component of water use intensity for livestock products. Heinke et al (2020[93]) estimated that on annual basis, 4,387 km^3 of blue and green water are used for the production of livestock feed, which equal to about 41% of total agricultural water use.[30]

Livestock production also contributes to water pollution. Nitrogen and phosphorus runoffs and discharges from animal manure, and the use of synthetic fertilisers are major sources of pollution for both surface and ground water (Gruère, Ashley and Cadilhon, 2018[25]).

Published LCAs suggest that all meat alternatives have a lower water footprint per kg of product than does beef, and that plant- and insect-based alternatives also have lower water requirements than do pigmeat and poultry meat. Due to the lack of comparable data, however, water use is not presented in Figure 6. Indeed, the scope of the water footprint assessments vary significantly between studies; some only including blue water use, for example, while others also account for green and grey water use.

a) Plant-based alternatives

Published LCAs suggest that both traditional (e.g. tofu) and newer plant-based alternatives have lower water requirements per kg of product than meats (CE DELFT, 2021[37]) (blue horizon, 2020[85]) (Heller and Keoleian, 2018[81]) (Khan et al., 2019[64]). The LCAs of the Impossible and Beyond burgers, for instance, suggest that producing 1 kg of plant-based burger requires 87% and 99% less water, respectively, than producing 1 kg of a US beef burger (Heller and Keoleian, 2018[81]) (Khan et al., 2019[64]). For these plant-based burgers, almost 80% of water use is associated with product processing and packaging, with the remaining 20% is linked to the production of ingredients (Heller and Keoleian, 2018[81]).

Furthermore, the LCA of the Impossible burger suggests the eutrophication potential per kg of product of this plant-based burger is 92% lower than for a US beef burger (Khan et al., 2019[64]).

b) Insect-based alternatives

Farm insects require less water than conventional livestock. They can satisfy their water needs from their feed or substrates. Most of the water needs for insect farming is thus related to feed production and processing steps, such as cleaning (FAO, 2021[40]).

Miglietta et al. (2015[94]) is the only publicly available study that provides an estimate of the water footprint of insects. They estimated that it takes 1.5 times less water to produce 1 kg of mealworm protein compared to 1 kg of protein from poultry, 2.5 times less compared to 1 kg of pigmeat protein, and five times less compared to 1 kg of beef protein.

The LCA of the insect-burger commercialised by the company Bugfoundation also suggests a significantly lower water footprint per kg of product than for a beef burger (Bug Foundation, n.d.[89]).

c) Cultured meat

Only a few studies provide estimates of the water footprint of cultured meat. These studies suggest that the water footprint of cultured meat per kg of product is lower than the one of beef, but similar or higher

[30] Blue water refers to irrigation water, green water refers to rainwater and grey water to water required to dilute pollutants.

than the ones of poultry meat and pigmeat (CE DELFT, 2021[37]) (Tuomisto and Teixeira de Mattos, 2011[90]) (Tuomisto, Ellis and Haastrup, 2014[22]).

The water footprint of cultured meat includes both direct (i.e. water input used in the production process) and indirect (i.e. water used for the production of feedstock and of energy) water use. It is therefore influenced by the composition of the growth medium. Tuomisto, Ellis and Haastrup (2014[22]), for example, found a higher water footprint when using a maize-based growth medium compared to a wheat-based one.

Cultured meat was also found to have lower eutrophication potential than beef and pigmeat, and similar to poultry on a per kg of product basis (Mattick et al., 2015[91]).

Finally, some LCA studies provide composite indicators – or environmental single scores – which allows to compare the total environmental impact of meats and meat alternatives, as well as to identify the main drivers of the environmental impact of each product. These environmental single scores usually aggregate a large set of environmental indicators, such as GHG emissions, land and water use, but also fine particulate matter formation, human toxicity, fossil fuel depletion. Overall, cultured meat – under the current production technology and energy mix – is the meat alternatives with the highest environmental impact, while insect- and plant-based alternatives appear to be the least environmentally-impactful protein sources (CE DELFT, 2021[37]) (Smetana et al., 2015[80]).

2.2.3. Livelihood

This section discusses the livelihood of the producers of meat and meat alternatives along the food value chain. For producers of meat alternatives, this section focuses on production costs and the economic viability of selected alternatives. For meat producers, the potential employment impact of an increase in the market share of meat alternatives is explored. This section also touches on opportunities for coexistence and collaboration between actors involved in the meats and meat alternative industries.

1) Production costs and economics of meat alternatives

a. Production costs

In high-income countries, decades of intensification of livestock production and advances in farming technology have increased the cost efficiency of meat production, making it challenging for meat alternatives to compete. At present, selected meat alternatives have higher production costs than meats. However, there is significant potential for costs reduction in the coming years by scaling up production and optimising production processes.

In addition to economic viability, the regulatory framework around meat alternatives will affect producers' ability to access market, sell their products, and earn revenues. Box 1 gives an overview of the current regulatory environment on meat alternatives in OECD countries.

i. Plant-based alternatives

Plant inputs used in the formulation of plant-based alternatives to meat are relatively inexpensive. The agricultural prices (per kg) of soybean, pulses and wheat, for example, are lower than those for cattle, pigs and chickens.[31] However, plant-based alternatives tend to cost more than meats. One reason for this discrepancy is high processing costs; those associated with post-harvest processes are estimated to account for more than 90% of retail costs of crop products, against 50% of the retail costs of beef, for instance. Moreover, plant-based alternatives include other ingredients, such as plant-based fats, flavour enhancers, and colour additives, which add to the final cost of the product (Rubio, Xiang and Kaplan,

[31] International prices in USD/t, average 2018-20: pulses (203), wheat (233), soybean (413), poultry (1520), pigmeat (1398) and beef (4058) (OECD/FAO, 2021[6]).

2020[14]). Finally, plant-based meat companies do not benefit from the same economies of scale as do meat manufacturers (Cohen, 2021[51]).

Several reports suggest that plant-based alternatives will become cost-competitive in coming years as R&D costs are recouped, meat processing companies enter the meat alternatives marketplace, manufacturing operations achieve economies of scale, and raw material varieties and prices are optimised (Santo et al., 2020[16]) (Witte et al., 2021[53]).

ii. Insect-based alternatives

Information on the production cost of insects and insect-based alternatives are scarce. However, available estimates all point to higher production costs than meats. McKinsey & Co. (2019[31]), for example, report that production costs of insect protein currently range between USD 9 and USD 11/kg, compared to USD 4/kg, on average, for meat protein.

The main factors behind these high production costs are high labour costs – the low level of mechanisation of most insect farms makes insect farming a labour intensive process – and small production scale (FAO, 2021[40]) (Niyonsaba et al., 2021[54]) (Rabobank, 2021[95]). There is therefore important scope to reduce production costs through industrial-scale production techniques, as well as lower cost feed, and more efficient breeding techniques (Heinrich Böll Foundation, 2021[58]). Some highly modernised insect production facilities are already in activity. Aspire Food Group, for example, has recently built the world's largest automatised cricket farm in Ontario, Canada (Aspire Food Group, 2021[96]).

iii. Cultured meat

High production costs remain a significant challenge for the cultured meat industry and the main barrier to cultured meat commercial viability.

The first cultured meat burger made by Mark Post in 2013 after two years of development costed USD 300 to produce (USD 2 470/kg). This very high cost was partly explained by the use of products and compound traditionally used in medical sciences, such as hormones and nutrients (Chriki and Hocquette, 2020[26]).

Since then, several commentators have indicated that important cost reductions have been achieved (Peters, 2018[97]) (Scipioni, 2020[56]) (Lavars, 2021[98]), which is difficult to verify. Current production costs are hard to gage because production techniques are not stabilised, private costs of start-ups are largely hidden, and the effects of large-scale production are difficult to anticipate (Treich, 2021[2]).

A few studies provide preliminary economic analysis that project the cost of cultured meat for large-scale production scenario (Omholt et al., 2008[99]) (van der Weele and Tramper, 2014[100]) (CE DELFT, 2021[3]) (Risner et al., 2021[101]). However, their estimates vary by several orders of magnitude depending on assumptions made on the production technology, in particular those related to the composition and the price of the growth medium, which is the main driver of cost for cultured meat. The cost of the growth medium is estimated to account for 55% to 95% of the marginal cost of the product (The Good Food Institute, 2020[102]).

CE DELFT (2021[3]) has issued the most recent study and the only one that is based on industry data. They estimate the production cost of cultured meat at industrial scale based on current production technology and cost of inputs. They found that current production costs are an order of magnitude of 100 to 10 000 higher than the benchmark value for comparable meat products, ranging from USD 149/kg to USD 22 422/kg, depending on the requirements for medium components and its prices.

All available studies consider that important cost reduction could be achieved in coming years, mainly through reductions in the cost of the growth medium. There are different ways to reduce medium cost; these include minimising the use of growth factors, optimising the filtration processes and maximally recycling the growth medium. (CE DELFT, 2021[3]), estimates that production costs of cultured meat could go down to between USD 5.66/kg and 116 USD/kg by 2030, through reduction in the use of growth medium and other improvements in the production process.

Nevertheless, opinions remain divided on whether cultured meat will ever be able to compete with meats on costs. Some believe that major challenges remain for cultured meat to become cost competitive and that it might never achieve cost parity with meats (Risner et al., 2021[101]) (Humbird, 2020[103]). Others argue that cultured meat will likely reach cost parity with meats when produced at industrial scale. McKinsey & Co. (2021[57]) highlight that if the cost of cultured meat goes down at the same rate as other biotechnologies – e.g. human genome sequencing – it could achieve cost parity with meats by 2030.[32]

In the meantime, cultured meat companies have developed a number of strategies to lower the bar for reaching cost parity with meats. Some are targeting high-value products (e.g. foie gras, kangaroo meat) (Rubio, Xiang and Kaplan, 2020[14]) (Ministère de l'Agriculture et de l'Alimentation, 2021[34]), while others are developing hybrid products by blending cultured meats with plant proteins (McKinsey & Company, 2021[57]). In December 2021, the Israeli start-up Future Meat Technologies announced it had produced a 4 lb cultured chicken breast mixed with plant proteins at USD 1.70 (i.e. USD 15/kg), down from USD 7.50 (i.e. USD 66/kg) in February 2021 (Lavars, 2021[98]).

Another concern about the cultured meat industry is the risk of market concentration and its implications for the price of cultured meat. With the introduction of a new technology with high entry costs and constant or increasing returns to scale, there is a potential for a natural monopoly (Treich, 2021[2]) (Heinrich Böll Foundation, 2021[58]). If a firm is able to produce and patent the most competitive cultured meat product, it is likely that this firm could duplicate the production essentially everywhere and secure the whole market (Treich, 2021[2]).

However, this risk should not be overestimated. First, it is not clear whether the same cultured meat producer can simultaneously obtain a key advantage on most types of meat. Indeed, as we are observing now, start-ups specialize in the production of a specific type of meat. Moreover, there is wide heterogeneity in consumers' taste, both within and across countries, so it seems unlikely that one firm can capture the entire market. Finally, meat alternatives might actually introduce more, rather than less, competition in the global protein market as meats and meat alternatives will likely coexist for several decades (Treich, 2021[2]).

Although production costs of meat alternatives are currently higher than those of meats, post-farm supply chain costs associated with meat alternatives could be lower than for meats. First, transportation costs could be reduced due to the possibility to locate production sites closer to consumers. Cultured meat, for example, might be produced in small factories such as "urban breweries", potentially collapsing global supply chains (Treich, 2021[2]). Insects can be reared in small, modular spaces, making them suitable for urban farm settings. Moreover, refrigeration costs and possibly waste products might be lower as selected meat alternatives have (or are expected to have) longer shelf-lives and less cooling might be required (Kearney, n.d.[35]) (Treich, 2021[2]). Refrigeration needs for cultured meat could also be reduced as cultured meat has lower mass than meats because the excess bones, fat, and blood are not present (Tuomisto and Teixeira de Mattos, 2011[90]). Note also that cultured meat production does not raise issues of carcass waste management (Treich, 2021[2]).

2) Employment impact along the livestock value chain

Producing animal feed, rearing, distributing and selling animal food is responsible for the livelihoods of hundreds of millions people worldwide, overwhelmingly concentrated in low-income countries. It has been estimated that about 3% of global GDP is from agriculture, of which 40% is from livestock (FAO, 2013[92]).

[32] The cost of human genome sequencing dropped by 45% annually between 2001 and 2021, on average (McKinsey & Company, 2021[57]).

If meat protein alternatives were to become cost competitive and broadly accepted, and reach a significant market share (Section 2.3), this could disrupt employment along the livestock value chain, with large socio-economic consequences, particularly in regions and countries that depend heavily on agriculture (Newton and Blaustein-Rejto, 2021[104]). This section looks at the potential implications of a growing market in meat alternatives for employment along the livestock value chain.

a) Impact on the feed industry

In 2018-20, about 1.7 billion tonnes of cereals, protein meals and processing by-products were used as animal feed (OECD/FAO, 2021[105]). If there were to be a decline in meat demand, demand for feed crops would also be reduced (Dongoski, 2021[106]).

However, some of these losses might be offset by switching to the production of feedstock for alternatives protein products (World Economic Forum, 2019[1]). Arable crops are currently the main inputs into meat alternatives production, as described in Section 2.1. A growing market in meat alternatives could thus create opportunities for farmers to grow ingredients for the production of these products, such as high-value protein crops (e.g. peas, lentils, mug beans, and other legumes) for plant-based alternatives. In recent years, for example, pea demand has increased significantly in the United States, partly in response to demand from Beyond Meat. Moreover, as many leguminous crops can be incorporated into rotations with double-cropping, they could represent an additional rather than an alternative source of income (Newton and Blaustein-Rejto, 2021[104]).

The demand for feedstock crops as an input for cultured meat production is more uncertain, and will ultimately depend on the main source of input used for growth medium production. If traditional agricultural crops (e.g. barley, sugar beet, maize, peas, soybean, wheat) are the main sources of input, this could create additional market opportunities for farmers. If, however, cultured meat growth medium is produced mainly from non-agricultural sources (e.g. algae, fungi, seaweed, yeast), opportunities for feed producers will be limited (Newton and Blaustein-Rejto, 2021[104]).

There exist nevertheless barriers to transitioning to the production of feedstock for meat alternatives. First, many farmers are locked into crop production for the animal farming sector. Most of their physical, human, social and financial capital is tied to maize and soybean production, making the transition to alternative crops difficult and costly (Newton and Blaustein-Rejto, 2021[104]). Moreover, neither soybean nor peas are currently optimised for use in plant-based alternatives. Most soybean grown today is bred for animal feed, and new varieties more suitable for human consumption will need to be developed and grown (Witte et al., 2021[53]). Finally, as meat alternatives have higher feed conversion ratios than meats (Section 2.1), this could lead to a net reduction in the total amount of crop required (World Economic Forum, 2019[1]) (Newton and Blaustein-Rejto, 2021[104]).

b) Impact on livestock farming

A reduction in livestock production will also create unemployment in the livestock farming sector and cause farms to go out of business, with knock-on effects for the rural economy (World Economic Forum, 2019[1]).

Some of these job losses could be offset by increasing employment in the alternative protein sector although it is unclear how many jobs these new industries would create (Treich, 2021[2]) (Heinrich Böll

Foundation, 2021[58]).[33,34] Moreover, these new jobs might require a different set of skills, inducing a costly transition for workers in the animal farming sector. For example, if meats were to be replaced by cultured meats this would involve a transition from a system based mainly on farmers, farm workers and meat processors to one based on chemists, cell biologists, engineers, and factory and warehouse workers (Heinrich Böll Foundation, 2021[58]). The very different skills required to produce cultured meat raises the question of how labour will be reskilled and redeployed (McKinsey & Company, 2021[57])

However, concerns about the potential negative employment effects of a growing market in meat alternatives should not be overestimated. First, global meat consumption is projected to continue increasing over the next decade, with strong growth foreseen in middle-income countries (Figure 2). The market share of meat alternatives, on the other hand, is expected to remain small in the near future (Section 2.3); meats and meat alternatives will likely coexist for several decades.

Furthermore, meat alternatives will presumably complement or transform rather than fully replace meat production (Newton and Blaustein-Rejto, 2021[104]). These alternatives will most likely meet some of the demand for lower quality meat (e.g. minced meats), providing opportunities for the livestock sector to specialise in higher quality products supplied by smaller-scale farms with higher sustainability and animal welfare standards (Rubio, Xiang and Kaplan, 2020[14]).

Meat hybrids (e.g. meat products blended with plant-based proteins, insect protein or cultured meat[35]) could also lessen the impact of the adoption of meat alternatives on the livelihood of meat producers. The on-farm co-production of meat and plant proteins and/or cultured meat could enable livestock farmers to access new markets and/or create products with a lower environmental footprint (Newton and Blaustein-Rejto, 2021[104]).

Other potential opportunities for diversification include growing crops as ingredients for the production of meat alternatives (as mentioned above); or raising animals for genetic material for cultured meat (Treich, 2021[2]) (Newton and Blaustein-Rejto, 2021[104]). Cultured meat production requires a small number of cells that are originally sourced from a living animal. This could be an opportunity for livestock producers to maintain a small herd as a source of cells for the cultured meat industry. However, only a small share of livestock producers would likely benefit from this opportunity as the amount of cultured meat produced from one animal is much higher than the amount of meat produced. Moreover, it is unclear how lucrative this activity would be (Newton and Blaustein-Rejto, 2021[104]).

Finally, as the production meat alternatives should require less land than meat production (Section 2.2.2), substantial land area could be freed up if meat alternatives displaced an important share of animal agriculture. In this context, a potential source of revenue could be payments for ecosystem services such as carbon sequestration (through tree planting or pasture rehabilitation), or biodiversity conservation generated by habitat restoration (Newton and Blaustein-Rejto, 2021[104]).

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[33] In the European Union, the expansion of the insect farming sector is expected to increase the number of jobs from a few hundred to a few thousand by 2025, thereby contributing to the economy. The primary production and processing of edible insects is predicted to be associated with these job increases. Employment opportunities are also linked to jobs created to support the sector, such as specialized retail, administration, logistics and research (FAO, 2021[40]).

[34] At present, a few hundred people work full- time in cultured meat companies. Many more high- skilled jobs in this knowledge economy, however, are expected to be created in the near future (Treich, 2021[2]). For every 500 000 metric tonnes of cultivated protein, McKinsey & Co. (2021[57]) estimate that 5 000 to 5 500 factory jobs will likely be needed, which is about the same number of production jobs needed to produce protein via conventional methods. The majority of jobs are expected to be those of frontline staff (such as plant operators and supervisors), while 10 to 20% of are expected to be reserved for bio-processing engineer. Beyond direct production, jobs will also be needed to support the development of key inputs (e.g. growth medium, cell lines), equipment (e.g. bioreactors), non-plant tasks (e.g. marketing, finance), and R&D.

[35] In meat hybrids, a fraction of the meat product (e.g. 20% to 50%) is replaced with plant-based proteins or other meat alternatives (e.g. insect protein, cultured meat).

c) Impact on meat processors and distributors

As several steps, such as animal slaughtering, are not required for the production of meat alternatives, job losses can be expected in slaughter houses and abattoirs, the meatpacking industry, and among small processors and distributors – such as butchers.

However, the growth in the alternative protein market is also creating opportunities for diversification, in particular for large meat processors and distributors. Several global meat processors and food companies have already entered the alternative protein market and repositioned themselves as “protein companies’’, complementing existing products with new plant-based products (e.g. Tyson Foods, Nestle, Maple Leaf Foods) or meat hybrids (e.g. Tyson Foods, Perdue Farms) (CB Insights, 2021[107]) (Kateman, 2019[108]). Large food companies are also investing in start-ups producing plant-based alternatives and cultured meat. Tyson Foods, for example, was an early investor in Beyond Meat before starting its own product line (Santo et al., 2020[16]). Finally, meat processors and distributors (e.g. Tyson Foods, Sysco) are partnering with plant-based meat companies for product marketing and distribution. This is an opportunity for the alternative protein sector to make use of existing distribution channels, leverage the expertise and market experience of established companies, and to expand its market share.

Overall, the socio-economic and employment impacts of a growing market in meat alternatives will likely differ between actors along the livestock value chain. Livestock farmers will most likely be the most affected as they have fewer opportunities for diversification.

2.3. Growth potential of meat alternatives over the coming decade

The impact of meat alternatives on food systems will largely depend on whether they capture a significant market share or remain a “niche product’’. If these products become cost-efficient, and broadly accepted, and capture a large share of the meat protein market this could have wide consequences for health, environmental, and ethical outcomes as well as for actors along the livestock value chain. If they remain a niche, market implications for society at large may be small (Treich, 2021[2]).

This section reviews available estimates of the current and projected size of the meat alternative market, using data mainly from consulting companies. Overall, strong growth in sales of meat alternatives is expected in the coming years, but starting from a low base.

a) Current market base

Selected meat protein alternatives have very different levels of market readiness and representation. At present, the alternative meat market mainly consists of plant-based alternatives.

The first processed plant-based alternatives (e.g. veggie burgers) have been on the market for several decades, while plant-based alternatives that more closely mimic meats have been available for about ten years. Leading brands such as Beyond Meat and Impossible Foods are now commercialised in supermarkets, restaurants, and fast food outlets (e.g. Macdonald, Pizza Hut) in several countries. As of December 2020, Beyond Meat products were available at approximately 122 000 retail and foodservice outlets in over 80 countries (Beyond Meat, 2021[109])

However, the global market size of plant-based alternatives to meat remain relatively small. Available assessments of its size vary between USD 5 billion (Grand View Research, 2022[110]) (Polaris Market Research, 2022[111]) and USD 16 billion in 2021 (Business Wire, 2022[112]), while the global meat market is estimated to range between USD 1.4 trillion to USD 1.7 trillion (McKinsey & Company, 2019[31]) (Kearney, n.d.[35]).[36] Thus plant-based alternatives to meat currently account for less than 1% of the meat market.

The COVID-19 pandemic was reported to have a positive impact on the sale of plant-based alternatives, with consumers beginning to favour longer shelf-life foods and plant-based meats avoiding potential viruses transmitted from animals to humans (Rees, 2021[113]).

Insect-based products have been on the market in some high-income countries for more than five years. Several companies have been operating on the insect protein market for food applications, some selling their products in large retail and convenience stores (e.g. Carrefour) (MarketsandMarkets, 2019[114]). Available estimates of the edible insect market vary between USD 154 million (Fortune Business Insights, 2022[115]) and USD 510 million in 2021 (Facts and Factors, 2022[116]). Insect flour accounts for the majority of the edible insect market, followed by protein bars and snacks.

Cultured meat has been commercialised in a single restaurant in Singapore since December 2020. There is also a test restaurant in Israel and some companies are offering public testing of their prototypes. A dozen of companies are currently working to develop and bring their products to the market in the next few years.

b) Projected market growth

Strong growth in the meat alternatives market is projected over the next decade, as suggested by growing private investments from billionaires (e.g. Bill Gates, Richard Branson), the meat sector, and food companies.[37] However, the actual market growth of meat alternatives will be contingent on several factors, including broad consumer acceptance, developments in enabling regulatory frameworks, and significant reductions in production costs.

Consulting firms predict a global annual growth in plant-based alternatives to meat of about 20% in the coming years (Kearney, n.d.[35]), which is higher than the projected growth in the meat market. However, given the low starting base, its market value is projected to reach about USD 25 billion by 2030 (Polaris Market Research, 2022[111]) (Grand View Research, 2022[110]), and up to USD 140 billion according to Barclays; this is still less than 10% of the global meat market (Terazono, 2019[117]) (King and Lawrence, 2019[29]) (BCC Research, 2020[118]). This range in estimates reflects the emerging nature of the sector as well as important uncertainty about future developments.

The global market for edible insects is expected to reach approximately USD 1.5 billion by 2025 (MarketsandMarkets, 2019[114]) and up to USD 8 billion by 2030 (FAO, 2021[40]) (Interreg North-West Europe, 2020[119]). Due to regulatory barriers and the premature level of insect food processing technology, however, the growth potential of insect as feed is probably higher in high-income countries (Rabobank, 2021[95]) (IPIFF, 2021[120]).

There are only a few and hypothetical projections for growth in the cultured meat market. McKinsey & Co. (2021[57]) estimate it could grow from USD 0-2 billion in 2025 to USD 5-25 billion in 2030, depending on

[36] According to the Good Food Institute, US retail sales of plant-based meats increased from USD 804 million in 2018 to USD 1.4 billion in 2021, which is only 1.4% of total meat sales (Good Food Institute, 2022[39]). ING (2020[38]) estimates that the retail sales of plant-based meat alternatives have more than doubled in the European Union and the United Kingdom over the last decade, to reach almost EUR 1.4 billion in 2019. However, this represents only 0.7% of total meat sales. In 2021, sales of plant-based meat totalled USD 2.6 billion in western Europe according to the Good Food Institute (Good Food Institute, 2022[131]).

[37] In 2021, plant-based meat, seafood, egg, and dairy companies secured USD 1.9 billion in investments, which is on par with the USD 2.1 billion raised in 2020 and almost three times the USD 693 million raised in 2019. Cultivated meat and seafood companies secured USD 1.4 billion in investments in 2021, more than three times the USD 400 million raised in 2020 (Good Food Institute, 2022[124]).

several factors such as consumer acceptance, the industry's ability to reproduce different type of meats (only processed meat *versus* wide variety of meat including whole cuts), and the extent of market penetration (only North America and Europe *versus* all large meat consuming regions).

Overall, most reports from consulting firms predict that the alternative meat market will be almost entirely plant-based until 2025-2030 (Kearney, n.d.[35]) (Witte et al., 2021[53]). Thereafter, cultured meat is expected to start playing a small role (e.g. at 6% of the alternative protein market by 2035, according to Witte et al. (2021[53])). However, from 2035 onwards, some predict that cultured meat could overtake the plant-based market and become the largest source of alternative meat protein (Kearney, n.d.[35]).

Geographically, North America and Europe are considered as the most mature markets for meat alternatives, with a number of such products already on grocery shelves for several years. Adoption of meat alternatives in both these markets is expected to grow quickly, thanks in part to growing consumer awareness of health, environmental, and animal welfare issues. Asia-Pacific is also considered a key market for meat alternatives, as population and income growth are fostering an increase in demand for proteins (Section 1) and due to the generally high acceptance of new foods and technologies in this region. Witte et al. (2021[53]) consider that Asia Pacific could become the largest market for alternative proteins.

3. The impact of meat protein alternatives on global agricultural markets: A scenario analysis

Building on the findings from the literature review, two illustrative dietary shift scenarios using the Aglink-Cosimo model were developed[38] to quantify the medium-term impacts on global agricultural markets of a shift in demand from meats to meat alternatives. For the purposes of this report, we focus on the impact of this dietary shift on selected indicators, namely international agricultural prices, land use change, and GHG emissions from the agriculture, forestry, and other land use (AFOLU) sector.

3.1. Description of the dietary shift scenarios

In the two dietary shift scenarios developed on the baseline of the *OECD-FAO Agricultural Outlook 2021-2030* (OECD/FAO, 2021[6]) a share of meat consumption in selected countries is replaced by meat alternatives, to provide an equivalent amount of protein.[39] To calculate a range of plausible impacts, these scenarios make different assumptions about the level and geographical coverage of the meat protein replacement. Specifically:

- *Moderate scenario*: This scenario assumes that 10% of meat consumption in high-income countries is replaced by consumption of meat alternatives by 2030. We assume that 90% of this replacement comes from plant-based proteins (i.e. soybean, pulses, cereals, and roots and tubers)[40] and 10% from insects and cultured meat.

[38] Aglink-Cosimo is a comprehensive partial equilibrium model for global agriculture. It underlies the baseline projections of the *OECD-FAO Agricultural Outlook 2021-2030* (OECD/FAO, 2021[105]). A detailed documentation on the Aglink-Cosimo model is available at:
https://www.agri-outlook.org/documents/2022_Aglink%20Cosimo%20Brochure.pdf .

[39] The reduction in meat consumption is applied as a flat rate across all meat types.

[40] As processed plant-based products are not covered in the Aglink_Cosimo model, we selected plant proteins that are used as key inputs in plant-based meat recipes.

- *Strong scenario*: This scenario assumes that:
  - 25% of meat consumption in high-income countries is replaced by consumption of meat alternatives by 2030. We assume that 80% of the replacement comes from plant-based proteins, and 20% from insects and cultured meat.
  - 10% of meat consumption in upper middle-income countries is replaced by consumption of meat alternatives by 2030. We assume that 90% of the replacement comes from plant-based proteins, and 10% from insects and cultured meat.

These stylised scenarios aim to illustrate the potential impacts a growing adoption of meat alternatives will have on global agricultural markets, not to forecast future developments in consumer demand. Assumptions about the level of meat replacement and the type of alternatives used for protein replacement are mainly based on available market projections by consulting firms.[41]

For substitute commodities that are not covered in the Aglink-Cosimo model, i.e. insects and cultured meat, the protein content[42] and feed conversion ratios[43] are estimated based on data collected in the literature review. The feed for insects and cultured meat is assumed to be produced from the current mix of animal feed. For plant-based alternatives, protein input requirements are calculated using soybean, pulses, cereals, and roots and tuber production.

The dietary shift towards meat alternatives is only implemented in high and upper middle-income countries, as there is more scope to reduce meat consumption in these countries given the high levels of per capita consumption (Figure 1). While only accounting for 16% of the world's population in 2018-20, high-income countries were responsible for 34% of the world's meat consumption. Upper middle-income countries accounted for 35% of the world's population and 50% of global meat consumption. High and upper middle-income countries also accounted for 20% and 37% of global livestock emissions, respectively, in 2018-20.

Moreover, in these countries, and in particular high-income countries, consumers tend to have a high awareness of health, sustainability, and animal welfare issues, and a higher willingness to pay for meat alternatives, which are currently more expensive than meats (Section 2.2.1).

The following sections compare outcomes under the two dietary shift scenarios with the outcomes under the baseline in 2030.

3.2. Results

3.2.1. Impact on meat consumption

To clearly understand the impact of these dietary shifts on agricultural markets, it is important to see how they affect meat consumption across different country income groups (Figure 7).

In high-income countries, meat consumption is projected to grow by 5% between 2018-20 and 2030 in the baseline. Therefore, the 10% decline in meat consumption in 2030 relative to the baseline (as assumed in

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41 Kearney (n.d.[35]) projects that meat replacements will account for 28% of the meat market (i.e. conventional meat + meat alternatives) by 2030 and 45% by 2035. Witte et al. (2021[53]) project that alternative proteins will account for 11-22% of the global protein market (i.e. meat, dairy, seafood and eggs) by 2035.

42 The protein content of insects was set at 18.8%, which is the average of the (range of) protein content of three of the insect species considered the most promising for consumption in the West, i.e. locust and grasshoppers (13-28g/100g of fresh weight), the yellow mealworm (14-24g/100g of fresh weight) and the cricket (8-25g/100g of fresh weight). The protein content of cultured meat was set at 15.4%, which is the average of the protein content of meats (i.e. beef and veal, poultry, pigmeat and sheepmeat) as set in Aglink-Cosimo.

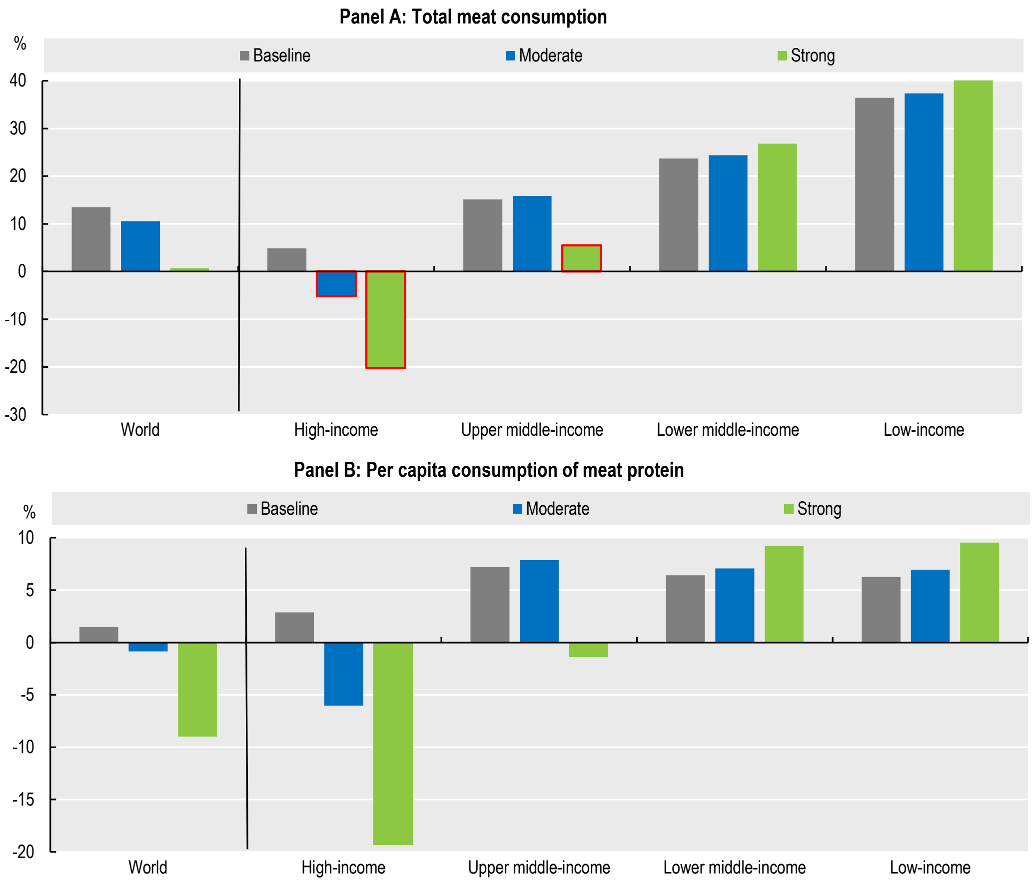
43 The feed conversion ratio for insects was taken from FAO (2021[40]) and set equal to 2.1 kg feed/kg of live weight. The feed conversion ratio for cultured meat was taken from Kearney (n.d.[35]) and set equal to 1.5 kg arable crop/kg of product.

the moderate scenario), translates into a 5% drop compared to today's situation (i.e. 2018-20 average). Similarly, in the strong scenario, the 25% decline in meat consumption assumed for high-income countries translates into a 20% drop between 2018-20 and 2030. In upper middle-income countries, where meat consumption is projected to grow by more than 15% in the baseline, the 10% reduction in meat consumption relative to the baseline translates into a 5% increase over the next ten years (Figure 7, Panel a).

In lower middle and low-income countries, where no dietary shift is implemented, meat consumption increases more strongly in the moderate and strong scenarios than in the baseline over the next decade. This rebound effect is driven by a decline in international meat prices following the change in dietary patterns in high and upper middle-income countries, as explained in Section 3.2.2. In the moderate and strong scenarios, 14% and 4%, of the decline in meat consumption in targeted countries, respectively, is offset by an increase in meat consumption elsewhere.

Overall, the dietary shift assumed in high-income countries in the moderate scenario has a limited impact at the global level. Global meat consumption increases by 10.5% over the next ten years in this scenario, compared to a projected increase of 13.5% in the baseline. In the strong scenario, however, the impact of the dietary shift assumed in high and upper middle-income countries is larger, resulting in zero growth in global meat consumption over the next ten years (Figure 7, Panel a).

Figure 7. Percentage change in meat consumption in the baseline, and in the moderate and strong scenarios, 2018-20 to 2030



Note: Per capita meat protein availability is measured in grams of protein per person per day.
The 38 individual countries and 11 regional aggregates in the baseline are classified into the four income groups according to their respective per-capita income in 2018. The applied thresholds are: low: < USD 1 550, lower-middle: < USD 3 895, upper-middle: < USD 13 000, high: > USD 13 000.
Source: (OECD/FAO, 2021[6]).

The nutritional impact of these dietary shifts is presented in Panel b, which shows changes in per capita consumption of meat protein by country income groups between 2018-20 and 2030, in the baseline and in the two scenarios (Figure 7, Panel b). Despite the 20% decline in per capita consumption of meat protein in high-income countries in the strong scenario, the consumption level of meat remains 4.5 times higher, on average, than in lower middle- and low-income countries in 2030.

3.2.2. Impact on international commodity prices

The drop in meat demand in high and upper-middle income countries leads to a large decline in international meat prices. Meat prices are projected to drop by 8% and 29% below baseline levels in the moderate and strong scenarios, respectively (Figure 8).

The impact of these dietary shifts on the price of plant proteins is less straightforward as there are two counteracting effects: a) higher demand for plant-based foods due to the shift from meats largely towards plant proteins; and b) lower demand for feed crops as selected meat alternatives have higher feed conversion ratios than meats (Section 2.1).

For commodities used primarily as feed, such as soybean and maize, the decline in feed demand outweighs the increase in food demand, causing prices to fall. In the moderate and strong scenarios, soybean prices are projected to decline by 3% and 10% below baseline levels, respectively. For cereals, a 2% and 6% drop in prices are expected, respectively. For pulses – one of the main commodity used for meat protein replacement – the increase in food demand outweighs the decline in feed demand, resulting in a 5% and 18% increase in prices, respectively, in the moderate and strong scenarios.[44] The price of roots and tubers also rises due to growing food demand, by 3% and 6%, respectively, in the moderate and strong scenarios.

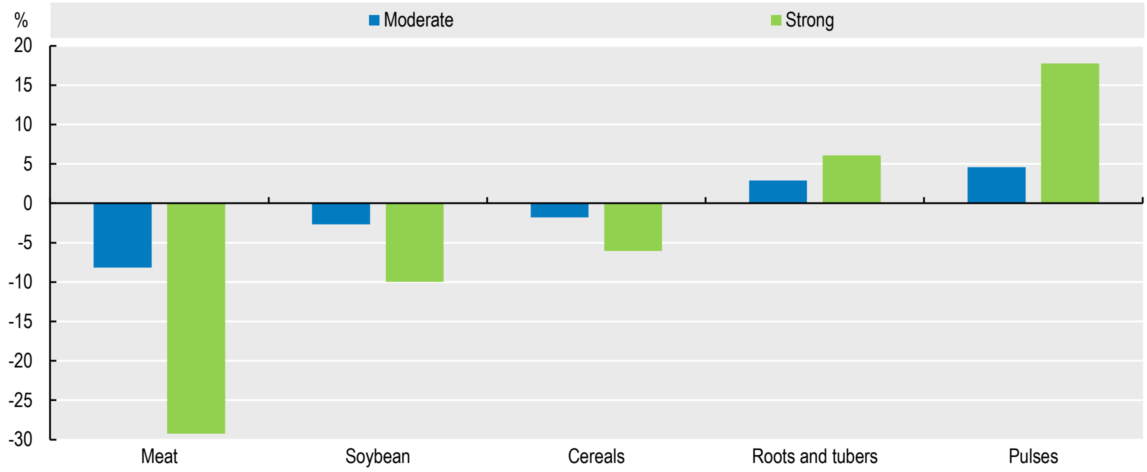
Lower international prices for meat and several crop commodities, including cereals, has spill over effect on protein consumption in lower middle and low-income countries, where no dietary shift is implemented. Per capita consumption of meat protein in these countries is projected to increase by 0.7% and 3% above baseline levels in the moderate and strong scenarios, respectively (Figure 7). Consumers in high and upper middle-income countries that do not switch to meat alternatives also benefit from lower meat prices.

While lower agricultural commodity prices benefit consumers, as it improves affordability and hence access to food, it can also put pressure on the income of farmers who are not lowering their costs sufficiently through improved productivity. Although the price of some commodities benefits from this dietary shift (e.g. pulses, roots and tubers), important price declines are foreseen for meats, soybean, and cereals, which can negatively affect farm revenues.[45] A similar trade-off between the food security and nutrition dimension of the triple challenge, and the livelihood dimension was found by Tallard et al (2022[121]) when considering a reduction in fat and sugar consumption to meet the World Health Organization (WHO) recommendations.

[44] In the moderate scenario, 31.5% of the meat protein replacement in high-income countries is assumed to come from pluses, 31.5% from soybean, 9% from wheat, 9% from maize, 9% from roots and tubers and 10% from insects and cultured meat. In the strong scenario, 28% of the meat protein replacement in high-income countries is assumed to come from pluses, 28% from soybean, 8% from wheat, 8% from maize, 8% from roots and tubers and 20% from insects and cultured meat. In the strong scenario, 31.5% of the meat protein replacement in upper middle-income countries is assumed to come from pluses, 31.5% from soybean, 9% from wheat, 9% from maize, 9% from roots and tubers and 10% from insects and cultured meat.

[45] The impact of these dietary shifts on agricultural revenues is not quantified in this report.

Figure 8. International commodity prices, % change compared to the baseline (2030)



Note: Meat includes beef and veal, poultry, pigmeat and sheepmeat. For Beef and veal, and pigmeat, Atlantic prices are used. Cereals include maize, wheat and rice.
Source: OECD/FAO (2021[6]).

3.2.3. Impact on land use change

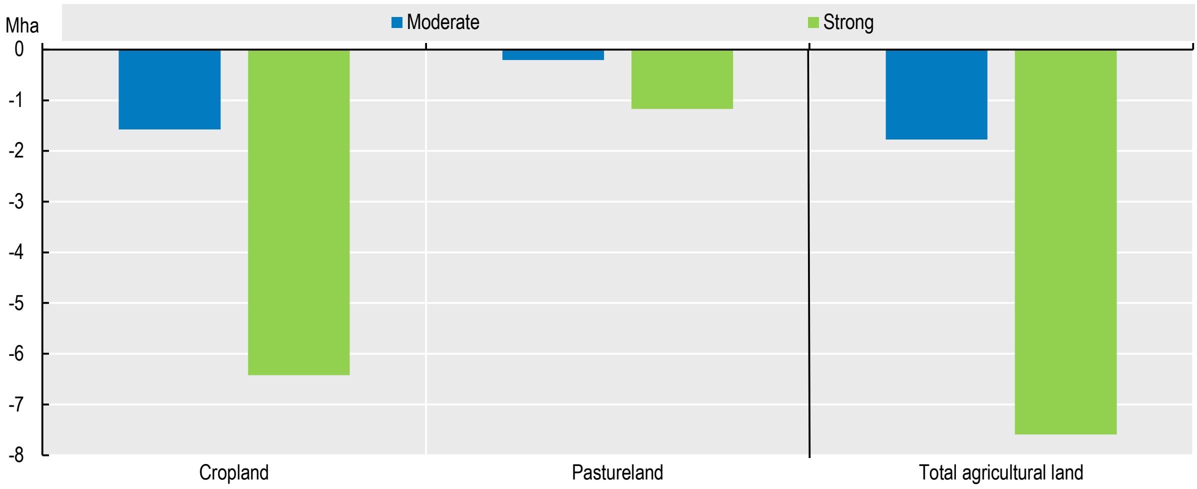
The reduction in meat demand in selected countries and the subsequent drop in global meat production leads to a decline in pastureland.[46] This is not offset by an increase in the production of meat alternatives, as these alternatives do not require pasture. In the moderate and strong scenarios, global pasture area is projected to drop by 204 000 hectares (ha) and 1.2 million ha (Mha), respectively (Figure 9). The global reduction in pastureland is limited as lower meat demand in high and upper middle-income countries is partly offset by growing demand in lower middle- and low-income countries (Figure 6). Moreover, in some countries where the dietary shift is implemented, only a small share of meat production is pasture-based.

The impact of these dietary shifts on cropland is less straightforward as there are two counteracting effects: a) higher demand for and thus production of plant-based foods; and b) lower demand for feed crops as meat alternatives have higher feed conversion ratios than do meats. The net effect is a drop in cropland as the decline in feed production outweighs the increase in food production. In the moderate and strong scenarios, cropland is projected to fall by 1.6 Mha and 6.4 Mha, respectively.

In the moderate and strong scenarios, global agricultural land is thus projected to decline as a result of this change in dietary patterns by 1.8 Mha and 7.6 Mha, respectively. The Aglink-Cosimo model assumes that all the land freed up from agriculture is converted into forests. In reality, how agricultural land released from livestock and feed production is subsequently used will depend on opportunity costs (Treich, 2021[2]).

[46] Global meat production is projected to drop by 2.5% and 11% in the moderate and strong scenarios, respectively.

Figure 9. Agricultural land use, absolute change compared to the baseline (2030)



Source: OECD/FAO (2021[6]).

3.2.4. Impact on GHG emissions from the agriculture, forestry, and other land use (AFOLU) sector

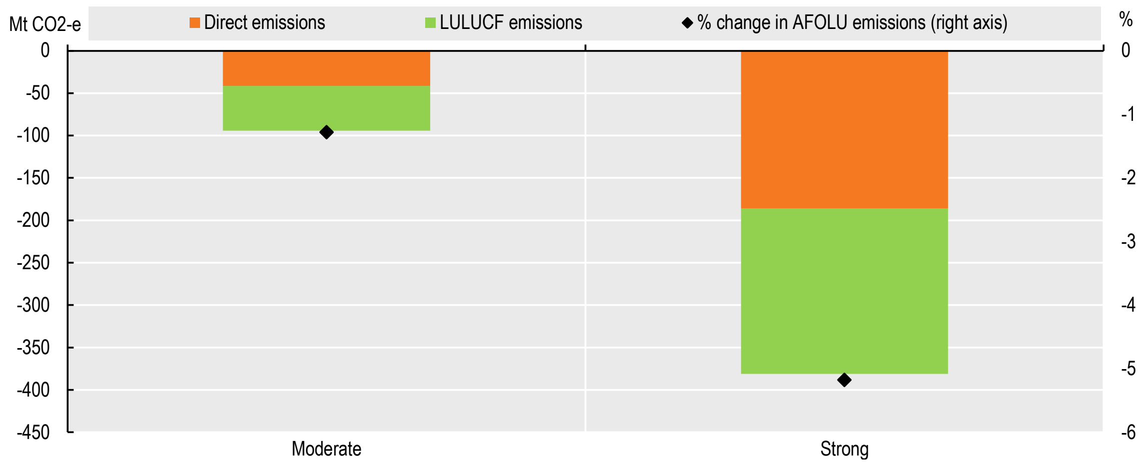
The dietary shifts assumed in high and upper middle-income countries lead to a decline in direct GHG emissions from agriculture, as meat consumption in these countries is mostly replaced by the consumption of plant-based foods, which are less emission intensive (Section 2.2.2). In the moderate and strong scenarios, direct agricultural emissions fall by 42 Mt CO_2-e (-0.8%) and 186 Mt CO_2-e (-3.4%), respectively, compared to the baseline (Figure 10). The emission savings in the strong scenario represent about a fifth of the reduction in direct GHG emissions the agricultural sector could deliver, at carbon prices consistent with economy-wide efforts to achieve the 2°C goal of the Paris Agreement (OECD, n.d.[122]).

These dietary shifts also lead to a decline in GHG emissions from land use, land use change, and forestry (LULUCF) due to the reduction in agricultural land and equivalent increase in forestland (Section 3.2.3). LULUCF emissions are projected to decline by 53 Mt CO_2-e (-3%) and 195 Mt CO_2-e (-10%) below baseline levels in the moderate and strong scenarios, respectively (Figure 10). The projected reductions in LULUCF emissions are due to avoided deforestation and/or afforestation, depending on the country and its trajectory of land use change.

The total mitigation potential of these dietary shifts amounts to 94 Mt CO_2-e and 381 Mt CO_2-e, respectively, in the moderate and strong scenarios. These correspond to a 1.3% and 5% decline in global emissions from the AFOLU sector (Figure 10). However, these global averages mask important differences between country income groups (Figure 11). A substantial reduction in AFOLU emissions occurs in countries where the dietary shifts are implemented. In high-income countries, AFOLU emissions drop by 3.7% below baseline level in the moderate scenario. In high and upper middle-income countries, AFOLU emissions fall by 12% and 8%, respectively, in the strong scenario. Emissions also decline slightly in lower middle- and low-income countries (by about 1% in the strong scenario) due to lower import demand for meats and feed from high and upper middle-income countries.[47]

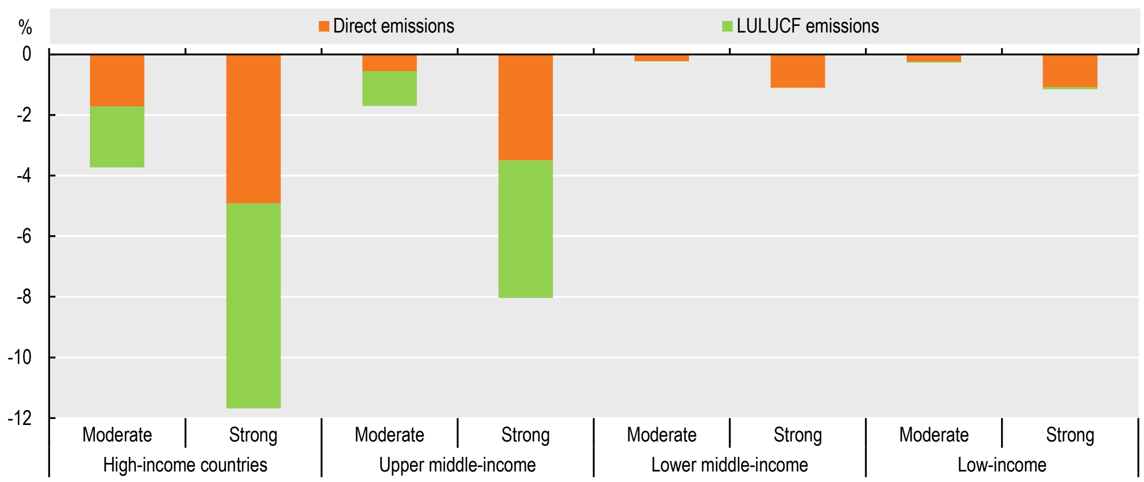
[47] It is important to note that at present lower middle- and low-income countries account for the largest share of global AFOLU emissions, at 37% and 32%, respectively, in 2018-20. High-income countries accounted for only 7% of global AFOLU emissions, and upper-middle income countries for 24% (OECD/FAO, 2021[6]).

Figure 10. Global GHG emissions from the AFOLU sector, absolute change compared to the baseline (2030)



Note: Estimates are based on historical time series from the FAOSTAT Emissions Agriculture databases which are extended with the Outlook database. Direct emissions include GHG emissions from enteric fermentation, manure applied to soils, manure left on pastures, manure management, application of synthetic fertilisers, rice cultivation, crop residues, burning of crop residues, burning of savannahs, and cultivation of organic soils. LULUCF emissions include net forest emissions, emissions from organic soils, and from burning of biomass.
Source: OECD/FAO (2021[6]).

Figure 11. GHG emissions from the AFOLU sector by country income group, % change compared to the baseline (2030)



Note: Estimates are based on historical time series from the FAOSTAT Emissions Agriculture databases which are extended with the *Outlook* database. Direct emissions include GHG emissions from enteric fermentation, manure applied to soils, manure left on pastures, manure management, application of synthetic fertilisers, rice cultivation, crop residues, burning of crop residues, burning of savannahs, and cultivation of organic soils. LULUCF emissions include net forest emissions, emissions from organic soils, and from burning of biomass.
The 38 individual countries and 11 regional aggregates in the baseline are classified into the four income groups according to their respective per-capita income in 2018. The applied thresholds are: low: < USD 1 550, lower-middle: < USD 3 895, upper-middle: < USD 13 000, high: > USD 13 000.
Source: OECD/FAO (2021[6]).

Overall, most of the reductions in AFOLU emissions come from the shift towards plant-based proteins, which accounts for 80-90% of the total protein replacement. The remaining 10-20% of the total protein replacement is associated with the shift towards cultured meat and insects.

For cultured meat and insects, the Aglink-Cosimo model only captures GHG emissions associated with feed production.[48] While for insects this is likely to represent a large share of total GHG emissions, most GHG emissions associated with cultured meat are CO_2 emissions from energy use (Section 2.2.2). Direct emissions from the production of these substitutes might therefore offset some of the reduction in AFOLU emissions. However, even when using the most conservative estimate for the energy intensity of these alternatives, their production offsets less than 1% of the projected reduction in AFOLU emissions they are responsible for.[49] This confirms that a dietary shift away from meats towards meat alternatives is likely to be beneficial in terms of GHG mitigation.

In view of the complexity of these issues, assessing precisely the mitigation potential of a shift away from meats towards meat alternatives calls for an integrated multi-sector model that properly connects agricultural, food, land use, environmental and energy issues (Treich, 2021[2]).

[48] Aglink-Cosimo is a partial equilibrium model. As such, it does not account for general equilibrium effects in energy markets.

[49] 6323 tonnes of insect and cultured meat are produced in 2030 in the strong scenario. We calculate an upper bound of the CO_2 emissions associated with this level of production of insect and cultured meat by using the energy intensity estimate of cultured meat, which is considerably higher than the one for insects. The energy intensity of cultured meat is estimated to be around 300 MJ/kg (Figure 5), or 83 333 kWh/t. About 526 914 559 kwh are used to produce the 6 323 tonnes of cultured meat and insects. This translates into 0.25 Mt of CO_2-e according to EPA GHG equivalencies calculator (US EPA, 2022[125]). This represents less than 1% of the 76.2 Mt CO_2-e of emission savings (20% of 381 Mt CO_2-e) associated with cultured meat and insects in the strong scenario.

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