Master's Thesis – Master Sustainable Development

Quantifying the environmental benefits of animal-source food replacement

Integrated assessment of the environmental impact of dietary change to alternative protein sources

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ABSTRACT

The environmental impact of diets high in animal-source foods has led to growing interest in potentially more sustainable alternative protein sources, such as plant-based meat analogues, cultivated meat, insect protein, and plant-based dairy. In this study, the IMAGE Integrated Assessment Model is used to evaluate global land use, water consumption, greenhouse gas emissions and global warming for scenarios in which animal-source foods are replaced by different alternatives. The scenarios are compared to each other and to a baseline trend. The results indicate that replacing all meat by alternatives can reduce global agricultural land use by 32-39%, water consumption by 8-12%, CH_4 emissions by 60%, N_2O emissions by 44%, land-use CO_2 emissions by 100%, and reduce global warming by up to 0.45 degrees Celsius. Replacement of milk by plant-based options can reduce agricultural land use by 6-7%, CH_4 emissions by 14%, N_2O emissions by 14%, land-use CO_2 emissions by 44-47%, and reduce global warming by up to 0.1 degrees Celsius. Furthermore, it was shown that dietary change only in the Global North can achieve up to one third of the potential land-use and global warming reduction and up to half of the potential water use reduction of worldwide dietary change. Overall, the differences between different animal-source food alternatives are small, and a sensitivity analysis shows that small variations in the composition and resource demands of the options could change the order in which they are comparatively ranked. The main takeaway is therefore that ultimately, no single alternative is universally preferable, highlighting the need for context-specific choices to promote sustainable dietary transitions.

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1 INTRODUCTION

1.1 CONTEXT

The current global food system is not sustainable. The food supply chain accounts for roughly 30% of global greenhouse gas (GHG) emissions, making it a major driver of climate change (Poore & Nemecek, 2018). Agriculture occupies half of the world's habitable surface, contributes to environmental pollution and represents the largest share in freshwater demand (Hallström et al., 2015; Poore & Nemecek, 2018; Springmann et al., 2018). Animal husbandry is by far the most environmentally impactful form of agriculture. Though it only constitutes 18% of the global calorie supply, animal-source food accounts for nearly 60% of all agricultural GHG emissions and more than 75% of agricultural land use, including pastureland and land used to grow feed crops. Agriculture is also a major driver of ocean and fresh water eutrophication (Carlsson Kanyama et al., 2021; Machovina et al., 2015; Poore & Nemecek, 2018; UNEP, 2023). Furthermore, animal agriculture is associated with increased risk of zoonotic disease and antimicrobial resistance, next to being responsible for the killing of billions of animals yearly, leading to animal welfare concerns (He et al., 2020; UNEP, 2023).

The need to shift the global food system away from animal-source foods towards more plant-based diets is widely recognized in the literature (Godfray et al., 2018; Hallström et al., 2015; He et al., 2020; Machovina et al., 2015; Poore & Nemecek, 2018; Springmann et al., 2018; Stehfest et al., 2009; Stoll-Kleemann & Schmidt, 2017; UNEP, 2023; Van Vuuren et al., 2018; Westhoek et al., 2014; Willett et al., 2019). Current trend scenarios, however, project that growth of the global population combined with rising incomes will lead to a large increase in global demand for animal-source food in the coming decades, particularly in developing regions, with global meat consumption projected to increase by 50% or more by 2050 (Bodirsky et al., 2015; Henchion et al., 2021; UNEP, 2023).

In some Global North countries, there is an increase in the number of people who are adapting their diets because of the aforementioned concerns or for health reasons (Ajena et al., 2021; He et al., 2020; Leahy et al., 2010; UNEP, 2023). Ranging from flexitarians, who reduce their animal-source food consumption, to vegetarians who cut out all meat, to vegans who don't consume any animal-source food, these people turn to plant-based alternatives to replace the nutritional content of animal-source food, particularly its protein content. Currently available animal source food alternatives include protein-rich plant foods like beans and legumes, plant-based meat analogues, plant-based milks and yoghurts and vegan cheese. Other options that are currently still in development or otherwise not widely consumed include cultivated meat and insects for human consumption. Excluding beans and legumes and insects, these options are called novel animal-source food alternatives (UNEP, 2023). Section 2.1 further elaborates on different types of animal-source food alternatives.

1.2 KNOWLEDGE GAP & PROBLEM DEFINITION

One of the main reasons for consumers to switch to animal-source food alternatives is the reduced environmental impact. This raises the question of how different options quantitatively compare to each other and to their animal source equivalents. Life Cycle Assessment (LCA) studies have been carried out for various types of animal-source food alternatives, including plant-based meat analogues, plant-based dairy, insects, and cultivated meat, to determine the impact per functional unit, usually kg of final product, in several categories including climate impact (expressed in GHG emissions), land use, water consumption and energy consumption (Carlsson Kanyama et al., 2021; Kim et al., 2022; Ruggieri et al., 2023; Shanmugam et al., 2023; Sinke et al., 2023; Smetana et al., 2015).

As stated above, global dietary change away from animal-source food consumption could contribute to reducing environmental harm. In order to understand and quantify the impacts of global socio-economic developments, such as dietary shifts, on the environment, scenario modeling studies can be carried out. In such studies, different scenarios of diverging trends, including of dietary patterns and food system developments, are quantitatively modeled and the resulting environmental and/or economic impacts of the different scenarios are compared. The added value of such studies, compared to studies using simple per-unit LCA results, is that they are able to quantitatively model the effect that demographic and economic trends have on the global food system and the resulting global environmental impacts. Such studies can therefore effectively serve to inform policy choices.

The objectives and methodologies of these studies vary. In some, such as Van Vuuren et al. (2018) and Doelman et al. (2022), the objective is to explore different ways to achieve specific climate or sustainability targets, and dietary change emerges as a part of a set of possible measures to help achieve these targets. Others, such as Stehfest et al. (2009), Kozicka et al. (2023) and Frezal et al. (2022), take a certain dietary change scenario as a basis and use a modeling approach to quantify what the environmental impacts associated with that scenario are.

Because of the novelty of animal-source food alternatives like plant-based meat analogues and cultivated meat, scenario modeling studies that examine the environmental impact of dietary shifts towards these options are scarce. More often, shifts to more plant-based diets are implemented by reducing animal-source food consumption and increasing the consumption of whole plant foods like beans and legumes (e.g., Stehfest et al. (2009)). It is important that studies examining scenarios of dietary change to novel animal-source food alternatives are carried out, since novel animal-source food alternatives may be more acceptable to people who are used to animal-source food consumption (He et al., 2020; Lee et al., 2020; UNEP, 2023). Hence, scenario modeling studies that consider novel animal-source food alternatives are more likely to be an accurate representation of real-world dietary change than studies that consider only whole plant foods.

Four studies were identified that have carried out modeling analyses of dietary shifts to novel animal-source food alternatives, each of them with some limitations in scope or approach. Mason-D’Croz et al. (2022) focuses specifically on plant-based beef substitutes and is limited in scope to the United States. Frezal et al. (2022) considers the impact on land-use and land-use related GHG emissions for plant-based meat analogues, cultivated meat and insect-based protein. Humpenöder et al. (2022) carries out an analysis of a range of environmental impacts specifically for microbial protein. Kozicka et al. (2023) uses the GLOBIOM agriculture and forestry model to assess a wide range of impacts, including undernourishment, GHG emissions, land use and water use, that result from dietary change scenarios to a number of different plant-based meat analogues and plant-based milks.

Table 1: Overview of existing novel animal-source food alternative scenario modeling studies

Study	Scope	animal-source food alternative considered	Environmental impacts	Type of model
Mason-D'Croz et al. (2022)	USA Time scope unclear	Plant-based beef analogue	Land-use GHG emissions, agricultural water use, land use, pesticide use	USAGE, General Equilibrium economic model
Frezal et al. (2022)	Global 2020-2030	Generic plant-based meat analogue, cultivated meat, insects	Land use, land-use GHG emissions	AGLink-Cosimo, partial equilibrium agricultural model
Humpenöder et al. (2022)	Global 2020-2050	Microbial protein	Deforestation, land-use GHG emissions, agricultural water use, nitrogen fixation	MAgPIE, partial equilibrium land use model
Kozicka et al. (2023)	Global 2000-2050	Plant-based beef, chicken and pork analogues; Soy milk; rapeseed milk	Land use, land-use GHG emissions, agricultural water use, fertilizer use, biodiversity	GLOBIOM, partial equilibrium agriculture, bioenergy and forestry model

Table 1 provides an overview of the four studies and their characteristics. It can be seen that a comprehensive modeling analysis that compares a varied range of animal-source food alternative, including plant-based meat analogues, cultivated meat, plant-based milks as well as beans and legumes, to each other and to animal-source food in a variety of environmental impacts, has not yet been carried out.

Additionally, and crucially, none of these analyses include water consumption and emissions from energy use during the manufacturing process of novel animal-source food alternatives, while the literature suggests this to be a significant factor, particularly for cultivated meat (Kim et al., 2022; Shanmugam et al., 2023; Sinke et al., 2023). Furthermore, these studies do not quantify the impact that emissions reduction as a result of dietary change has on global warming.

An analysis incorporating all these aspects, using a comprehensive modeling framework, such as an Integrated Assessment Model (IAM – see Section 2.4) would thus be a valuable addition to the literature in this field. In doing so, it can help inform citizens and policymakers who wish to steer food systems towards sustainability, as the food system and its environmental impacts are associated with a number of Sustainable Development Goals (SDGs), including Zero Hunger, Good Health and Well-being, Clean Water and Sanitation, Climate Action, Life Below Water and Life on Land (Herrero et al., 2021)

1.3 OBJECTIVES AND RESEARCH QUESTIONS

The primary objective of this study is to fill the research gap identified in the previous section: to carry out a comprehensive comparative modeling analysis of scenarios of global dietary change towards different animal source food alternatives. This is done by carrying out a scenario analysis of global dietary change scenarios using the IMAGE Integrated Assessment Model. IMAGE is a modeling framework developed by the Netherlands Environmental Assessment Agency (*Planbureau voor de Leefomgeving* - PBL).

The following research questions are answered in this report:

Research question 1: What are the environmental impacts of scenarios in which different animal-source food alternatives fully replace their animal-source equivalent?

Research question 2: What are the environmental impacts of global dietary change scenarios, in which different animal-source food alternatives are adopted according to distinct storylines?

In this research, environmental impact is assessed using four impact categories: land use, water use, greenhouse gas emissions and global warming.

As evident from the two questions, two different types of scenario were assessed in this research, in order to broaden the scope and usefulness of the results. The first type are maximum potential scenarios, in which 100% replacement of animal-source food by the alternatives is achieved rapidly. These scenarios aim to illustrate the full potential of each animal-source food alternative. This enables the most effective comparison of the different options.

Secondly, four storyline scenarios were modelled. These scenarios are based on sets of coherent assumptions to create possible storylines of future global dietary change. In these scenarios, different animal-source food alternatives are implemented together and replace the conventional animal-source food according to the storyline assumptions, making them more heterogenous than the maximum potential scenarios. The aim of the storyline scenarios is to explore possible future global food systems and assess the impacts on the environment, and through their comparison provide insights to policymakers and other stakeholders on which types of futures they may aim to work towards. Section 3.1 provides further elaboration on the different scenarios and their properties.

In the following chapter, important concepts from the research questions are explained, and the IMAGE modeling framework is introduced.

2 THEORY AND CONCEPTS

In this chapter, key concepts from the research questions are explained and relevant theories and research approaches that will be used are elaborated on. First, an overview of the animal-source food alternatives considered in this study is given. Next, the environmental impact categories that are modelled are introduced. The practice of scenario analysis is then elaborated on, and an overview of the IMAGE Integrated Assessment Model is provided.

2.1 ANIMAL-SOURCE FOOD ALTERNATIVES

Alternatives to animal-source food can take many forms. Here, the different options that are part of the modeling analysis are briefly introduced. They were selected to be a varied representation of different options, ranging from currently available meat analogues to not yet commercialized cultivated meat.

2.1.1 Beans, legumes & pulses

Protein-rich whole vegetables like beans, legumes and pulses are a common option, particularly in regions where animal-source food is not affordable to large parts of the population (UNEP, 2023). A dietary shift away from meat to beans, legumes and pulses is technically very feasible, as these crops are already widely cultivated and no new technological development is needed. To many consumers, however, meat offers culinary and cultural significance that is not easily replaced by beans, legumes or pulses.

2.1.2 Plant-based meat analogues

In regions and cultures where frequent consumption of meat and dairy has become the norm, plant-based substitutes are marketed towards consumers who want to reduce their animal-source food consumption, but not give up on the taste, texture and culinary applications of meat and dairy products. Such plant-based meat analogues are derived from plant-based proteins and processed with other ingredients to mimic the qualities of meat (He et al., 2020; Wild et al., 2014). Plant-based meat analogues have seen a steady market growth over the past decades and can now be purchased in many supermarkets, in variants resembling different types of meat like beef, chicken and pork.

Review of the literature on plant-based meat analogues and inspection of the ingredients listed on dozens of different options available in Europe shows that they are most commonly made with one of two primary plant protein sources, namely soybeans and faba beans. Both options were considered in this research, to allow for a comparison between the two.

The production process is the same for both options. The beans are first ground into meal. This meal is then processed into Texturized Vegetable Protein (TVP). This process involves extrusion, a process which through application of high temperature, pressure, and mechanical shaping, produces TVP, a product with a meat-like texture and neutral flavor profile (Saerens et al., 2021; Saldanha Do Carmo et al., 2021). The meat analogues are then produced using TVP as the main ingredient, with vegetable oils, spices, flavorings and other additives introduced to make the product similar in flavor and texture to the animal product it aims to mimic, as well as provide additional nutrients.

2.1.3 Cultivated meat

Another option to potentially reduce the environmental impact of meat consumption is cultivated meat. Also known as ‘lab-grown meat’, cultivated meat is produced by using modern biotechnology to cultivate animal cells. Cultivated meat is thus not plant-based, but a genuine animal product with the nutritional and culinary profile of conventional meat. Though not implemented yet on a commercial scale, cultivated meat could have a significantly lower environmental impact than conventional meat, depending on the water use, feedstock consumption and energy consumption during the cultivation stage and the carbon footprint of the consumed energy (Kim et al., 2022; Sinke et al., 2023; UNEP, 2023).

2.1.4 Insects for human consumption

In some cultures, insects are consumed as food. Insects for human consumption have attracted attention for being more resource efficient than conventional livestock, while still providing complete animal protein (Liceaga et al., 2022; Ruggieri et al., 2023; UNEP, 2023). LCA studies suggest that insects may have significant environmental benefits compared to conventional livestock (Ruggieri et al., 2023). Insects are not technically an animal-source food alternative, being animals, but their novelty in Global North diets and the potential sustainability benefits make their consideration relevant.

Insect-derived protein can also be processed into more conventional products, like a burger, to increase cultural acceptance. Insect-based products like burgers are usually made from insect powders, mixed with water and some other ingredients to create a meat-like final product. One of the most viable insects for use in this way is the cricket (*Acheta domesticus*). In this research, a product based on cricket protein is modelled.

2.1.5 Plant-based dairy

Plant-based alternatives to dairy include plant-based milks like almond milk, soy milk and oat milk, plant-based yoghurts and vegan cheese analogues. Oat milk and soy milk are modeled in this research, as they are among the most popular options, and both can be used as a basis for dairy-like products such as yoghurt.

Oat milk is produced from oats, which are milled and then subjected to an enzymatic process that degrades the starch content to make for a milk-like beverage (Riofrio & Baykara, 2022). Additives may be added to the final product to enhance the flavor or nutritional profile.

In its most basic form, soy milk is produced by grinding soybeans in water, filtering the resulting mixture and then boiling it (Jiang et al., 2013). As with other products, the flavor and nutritional profile of the final product may be enhanced with additives.

In this research, almond milk is excluded because of poor compatibility with the IMAGE modeling framework, almonds being a highly nice crop subsumed under the fruits and vegetables category. Vegan cheese analogues were excluded because of their very low nutritional value. These analogues consist mainly of plant-based fats, binding agents and additives, making them a nutritionally unviable option to actually replace cheese as a dietary staple.

2.2 ENVIRONMENTAL IMPACT

Environmental impact can be defined as *“Potential impact on the natural environment, human health or the depletion of natural resources, caused by the interventions between the technosphere and the ecosphere”* (Hauschild et al., 2018, p. 170).

In this research, four key environmental impact categories are addressed. They are land use, water use, greenhouse gas emissions, and global warming. The scope of this research is limited to these impacts because they were judged to be the most relevant, as well as because of data availability, compatibility with IMAGE and in order to keep the project time manageable. There are more environmental impacts associated with food systems, including nitrogen and phosphorus pollution, acidification, eutrophication and particulate air pollution. These were not considered here.

Land use is the human occupation, alteration and usage of habitable land for a specific purpose (Ellis, 2021). In the case of agriculture, land may be used to grow crops (either for direct human consumption or for livestock feed) and as pastureland for livestock. Expansion of human activities that require land use, such as agriculture, may lead to the conversion of natural land to agricultural land. This is called land-use change. Land use, land-use change and forestry (LULUCF) is an important source of GHG emissions, and also a key driver of biodiversity loss (Ellis, 2021; IPCC, 2023; Machovina et al., 2015). Land use is expressed in terms of area.

Water use is the consumption of freshwater resources. In the case of agriculture, this is mainly for crop irrigation and partially as drinking water for livestock. Animal agriculture is very water-intensive because of the irrigation requirements of livestock feed. Agriculture has a bidirectional relationship with water use: agricultural sectors with high water use demands may be more vulnerable to climate impacts such as droughts, but may also play a large role in causing droughts or water shortages (IPCC, 2023). It is expressed in terms of water volume.

Greenhouse gas (GHG) emissions are emissions of gases that cause global warming. Major GHGs include carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). GHG emissions from human activities such as fossil fuel combustion and agriculture are the main drivers of climate change (IPCC, 2023). Total GHG emissions are expressed in CO_2 equivalents (CO_2eq), where the global warming potential of non-CO_2 GHGs is weighted in terms of their relative strength compared to CO_2. Animal agriculture causes GHG emissions through land-use change, enteric methane from livestock, and manure fermentation, among other factors (IPCC, 2023; Johnson & Johnson, 1995).

Global warming is the increase of the earth's surface temperature. In the period 2011-2020, the global surface temperature was 1.1°C higher than in the period 1850-1900. This warming is caused by the emissions of GHGs from human activity (IPCC, 2023). Human-caused climate change causes widespread adverse impacts on nature, society, food and water security, and human health, among many others (IPCC, 2023). In the Paris Agreement on climate change, it was agreed that global warming in 2100 should be limited to well below 2°C, and preferably to 1.5°C. Global warming is expressed in degrees Celsius increase compared to pre-industrial levels.

2.3 SCENARIO ANALYSIS

Integrated assessment models (IAMs) like IMAGE model key processes in the interaction between human activity and the natural environment (Stehfest et al., 2014, p. 14). They are used to provide insight in how driving factors, including global diets, cause a range of impacts, including environmental impacts like climate change and biodiversity loss. Often, IAMs are used to model scenarios - coherent pathways of possible developments of key driving factors - and assess the resulting impacts. Such scenario analyses can provide insight on what the future may look like if no big changes in current trends occur – a business-as-usual scenario – or how specific measures, policies or other changes may change the development of impacts (PBL, 2021). Scenario analyses are explicitly *not* predictions of the future *will look like*, but rather serve to explore what the future *may look like*, depending on the policy choices and socio-economic developments that are described in the scenario.

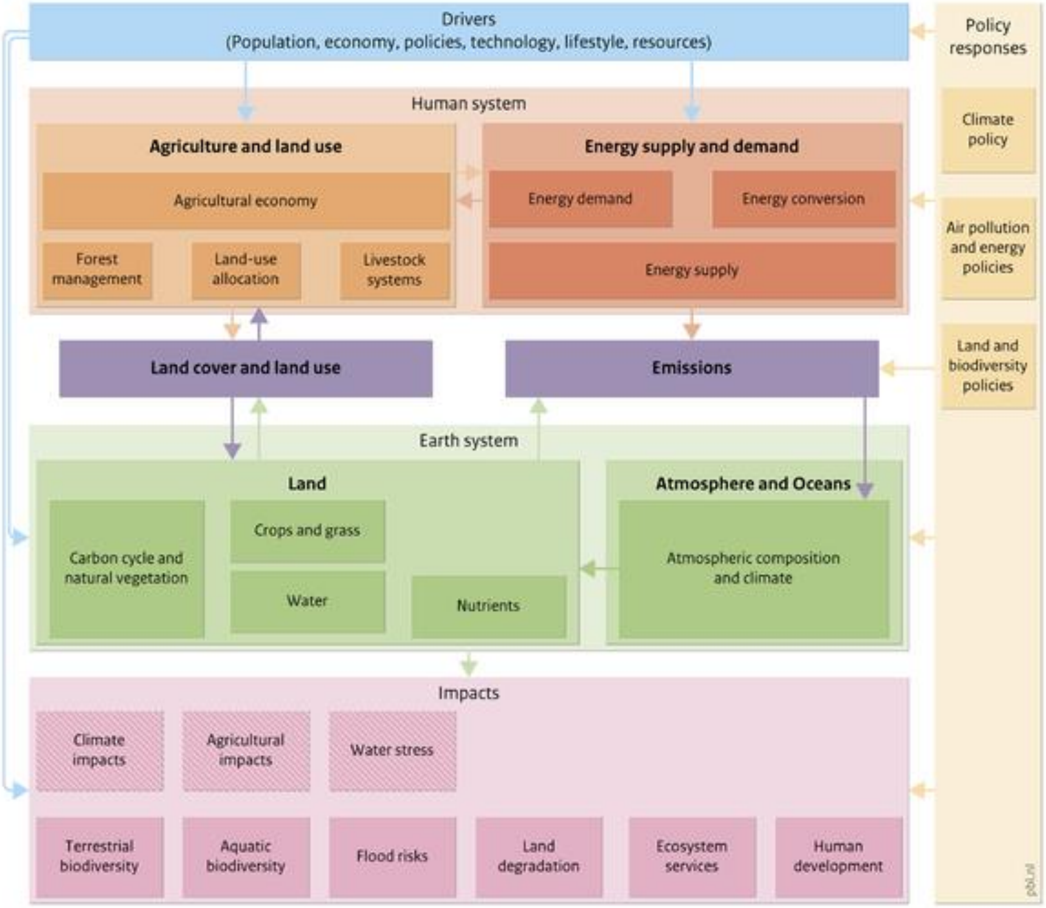
In this research, each of the dietary change scenarios is created by modifying food system data of an existing baseline scenario. The baseline scenario is based on the Shared Socioeconomic Pathways (SSPs). The SSPs are five distinct trajectories for human development and global environmental change in the 21st century, with the aim of providing insight in global-scale developments as a result of policy choices and socio-economic developments (Van Vuuren et al., 2017). Each SSP is distinct in how challenging it will be to mitigate and adapt to climate change.

SSP2-2.6 is taken as the baseline for this research. This is a the 'Middle of the Road' pathway in which the Paris Agreement target of limiting global warming by 2100 to well below 2 degrees Celsius is met (Riahi et al., 2017). Using SSP2 as a baseline is common practice in scenario modeling studies, including Humpenöder et al. (2022), Kozicka et al. (2023) and Van Vuuren et al. (2018), so using it here will assure comparability of results. Another reason for choosing this baseline in which Paris climate targets are met, is that it was judged more realistic for large-scale, sustainability-minded dietary transitions to occur in a setting in which effective climate policy also occurs in sectors not related to the food system, such as in the energy and industrial sectors. Furthermore, taking a scenario in which the 2 degrees target is achieved as a baseline for the dietary change scenarios allows the results to show the extent to which global dietary change may help to 'move the needle' towards hitting the more ambitious 1.5 degrees target. This approach adds to the policy relevance of the research.

2.4 THE IMAGE MODEL

The IMAGE (*Integrated Model to Assess the Global Environment*) IAM framework will be used in this research. IMAGE is a framework of interacting human and natural systems. These systems are represented by submodels, which are linked to determine a wide range of outputs, including the environmental impacts described above. Figure 1 provides a schematic overview of the different components of IMAGE and their interlinkage.

***Figure 1 - Overview of IMAGE framework and components. Taken from* Stehfest et al. (2014)**



Compared to other IAMs, IMAGE includes biophysical processes and environmental indicators in a relatively detailed way (Stehfest et al., 2014). IMAGE models on a global scale, divided into 26 geographical regions. It contains a dedicated land-use submodel, called IMAGE-land. Among many other things, IMAGE-land can calculate global land use and water use trends, and the associated land-use GHG emissions, based on inputs describing production of agricultural goods and other input parameters. Agricultural production is specified in terms of five animal categories and sixteen crop categories. Table 2 provides an overview of the agricultural production categories in IMAGE. Many of these categories subsume several different crops. For example, faba beans and chickpeas are both part of the 'pulses' category, and are thus equivalent in the eyes of the model.

Table 2 - Agricultural production categories in IMAGE

Animal categories	Crop categories	
Beef	Wheat	Tropical oil crops
Dairy	Rice	Temperate roots & tubers
Pork	Maize	Tropical roots & tubers
Mutton & goat meat	Tropical cereals	Sugar Crops
Poultry & eggs	Other temperate cereals	Oil, palm fruit
	Pulses	Vegetables & fruits
	Soybeans	Other non-food, luxury, spices
	Temperate oil crops	Plant-based fibers

The IMAGE livestock module distinguishes between two livestock production systems; extensive pastoral-based livestock systems and intensive mixed/industrial livestock systems. In the pastoral systems, animals are predominantly fed through grazing of grassland, while in the mixed/industrial systems, livestock production are fed by a mix of food crops, crop by-products, fodder crops and grass (Bouwman et al., 2006). As a result, a decrease in consumption of animal-source food products will lead to a decrease in pastoral grassland area and food and feed crop demand.

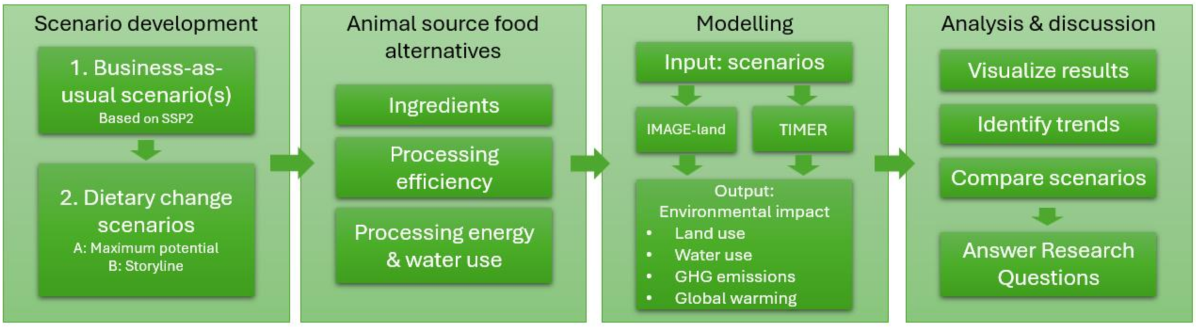
The IMAGE energy submodel, called TIMER, is a detailed model of the energy system. It is able to model the food processing industry and its associated energy use and GHG emissions, based on inputs describing the quantities in which different food types are produced, just as with IMAGE-land.

Using IMAGE-land and TIMER, the land use, water use, and total GHG emissions including land-use and energy-use emissions are calculated for each of the dietary change scenarios. Afterwards, IMAGE can determine global warming in the scenarios based on the previously calculated emissions trends. These characteristics of the IMAGE model made it especially well-suited to assess the impacts of global dietary change and answer the research questions.

3 METHODS

In this chapter, the proposed method to answer the research questions will be laid out step by step. Figure 2 shows an analytical framework that visualizes the connection between the concepts introduced in the previous chapter and the research question. This framework forms the basis for the methods as described in this chapter. Each part of the framework corresponds to a step in the methodology. First, the scenarios which were run to answer the research questions using the IMAGE model are described. Second, the crop and resource requirements of the different animal-source food alternatives are established. Lastly, the way in which these scenarios were implemented in IMAGE to obtain quantitative results is detailed.

Figure 2 - Analytical framework



3.1 DEFINITION OF SCENARIOS

As stated in the introduction, two types of scenario are modelled in this research. Firstly, a maximum potential scenario for each of the seven selected animal-source food alternatives is created and ran. Next, storyline scenarios are created, serving to illustrate more realistic, coherent storylines and their potential implications. The following sections will describe them in more detail.

3.1.1 Maximum potential scenarios

These scenarios serve to illustrate the full potential of switching to a specific animal-source food alternative, and to enable comparison between the different options. Table 3 gives an overview and description of these scenarios, which are all assigned an acronym to facilitate ease of reference throughout the rest of this report.

Table 3 - Description of maximum potential scenarios

Scenario name (Acronym)	Description
Maximum potential Beans & Legumes (MPBL)	Meat of all types is replaced by beans and legumes. Replacement rate linearly increases from 0% in 2020 to 100% in 2050, and stays at 100% until 2100. No novel alternatives need to be produced as these beans and legumes are eaten in a conventional way. Eggs and dairy are not replaced, their consumption follows the baseline trend.
Maximum potential Soy-based meat analogue (MPSO)	Meat of all types is replaced by a soy-based meat alternative. Replacement rate linearly increases from 0% in 2020 to 100% in 2050, and stays at 100% until 2100. The production and processing of the soy-based analogues consumes additional resources compared the MPBL scenario. Eggs and dairy are not replaced, their consumption follows the baseline trend.
Maximum potential Faba-based meat analogue (MPFA)	Same as MPSO, but with a faba-based meat alternative.
Maximum potential Cultivated Meat (MPCM)	Same as MPSO, but with cultivated meat.
Maximum potential Cricket-based product (MPCR)	Same as MPSO, but with a cricket-based product.
Maximum potential Soy Milk (MPSM)	Dairy of all types is replaced by soy milk. For simplification, it is assumed that the soy milk can be used to produce equivalents to milk-derived products like yoghurt. Replacement rate linearly increases from 0% in 2020 to 100% in 2050, and stays at 100% until 2100. The production and processing resource consumption of the soy milk is taken into account. Eggs and meat of all types are not replaced, their consumption follows the baseline trend.
Maximum Potential Oat Milk (MPOM)	Same as MPSM, but with oat milk.
Maximum potential Soy-based meat analogue + Soy Milk (MPSS)	Meat of all types is replaced by a soy-based meat alternative, and dairy of all types is replaced by soy milk. Additionally, eggs are also replaced by the soy-based meat alternative, to create a scenario in which all animal-source foods are replaced by a plant-based option. It is assumed that the soy milk can be used to produce equivalents to milk-derived products. Replacement rate linearly increases from 0% in 2020 to 100% in 2050, and stays at 100% until 2100. The production and processing resource consumption of the soy milk and meat alternative is taken into account.

3.1.2 Storyline scenarios

Four storyline scenarios are assessed: two scenarios in which dietary change occurs evenly at a global scale, meaning that the alternatives are adopted at the same rate in all regions, and two scenarios in which dietary change happens only in Global North regions, while Global South regions continue on the current path of growing demand for animal source food. The Global North is defined as comprising the following IMAGE regions, following the classification by the United Nations: Canada, USA, OECD Europe, Eastern Europe, Ukraine, Russia, Japan, Korea, Oceania (UNCTAD, 2024). The Global South is formed by the remaining regions: Mexico, Rest of Central America, Brazil, Rest of South America, Northern Africa, Western Africa, Eastern Africa, South Africa, Rest of Southern Africa, Turkey, Central Asia, Middle East, India, China, South East Asia, Indonesia, Rest of South Asia. Table 4 provides a description of each of these scenarios and the underlying storyline.

Table 4 - Overview of storyline scenarios

Scenario name (Acronym)	Description
Global shift towards plant-based diets (GLOPB)	Global awareness about the environmental impact of animal agriculture leads to a shift away from animal-source foods. Plant-based alternatives are embraced due to their low cost, which 'technological' options like cultivated meat cannot compete with. By 2050, two-thirds of meat consumption is replaced by a plant-based option: 75% of this is a soy-based meat analogue, 25% is replaced by beans and legumes. Furthermore, two-thirds of dairy is replaced by soy milk.
Shift towards plant-based diets in the Global North (GNPB)	Same as GLOPB, except the dietary change occurs only in the Global North. These regions have historically emitted disproportionately large amounts of GHGs due to animal-source food consumption. Higher levels of education and welfare lead to increased awareness about the environmental impact of animal agriculture in the Global North regions. In the Global South, baseline dietary trends continue.
Global emphasis on technological solutions (GLOTEC)	Global awareness about the environmental impact of animal agriculture leads to the will to shift away from animal source foods, but consumers are not willing to give up the culinary and cultural significance of meat. As a result, cultivated meat is developed and quickly reaches large-scale uptake and implementation, becoming affordable to populations worldwide. Plant-based meat analogues are also a popular choice. By 2050, two-thirds of meat consumption is replaced: 75% of this is cultivated meat, 25% is replaced by a soy-based meat analogue. Furthermore, two-thirds of dairy is replaced by soy milk.
Emphasis on technological solutions in the Global North (GNTEC)	The same as GLOTEC, except here the dietary change occurs only in the Global North. Cultivated meat is developed and reaches large-scale uptake in these richer, developed regions, but remains unaffordable for those living in the Global South, where baseline dietary trends continue.

These scenarios present more coherent storylines, in which developments are based more on an internal logic. This way, they can help inform policy decisions and paint a more realistic picture of possible futures. GNPB and GNTEC are particularly policy relevant as they serve to illustrate the impact that dietary change in the most economically advanced regions, which have a much larger historical share of animal source food consumption and associated emissions, can have, while allowing Global South nations, which have contributed much less to historical emissions, to continue on the existing trend of development without the additional burden of having to orchestrate a large-scale dietary transition.

3.1.3 Sensitivity runs

The IMAGE model outputs are quite sensitive to changes in the input values. The values for crop and resource requirements per animal-source food alternative used in this research, which are presented in Section 3.2, are quite specific numbers taken from the academic literature. It is very likely that the crop and resource requirements in the real world will vary from the literature. This is a particularly important factor for the scenarios with cultivated meat, as the data used for this research is taken from an 'ex-ante', predictive assessment. Sensitivity runs are conducted with values representing the boundaries of higher and lower ranges of the relevant variables, to investigate how large the impact of variation in the variables can be. Table 5 describes these sensitivity run scenarios.

Table 5 - Overview of sensitivity runs

Scenario name (Acronym)	Description
Sensitivity run Soy-based meat analogue, high range (SRSH)	15% higher demand for ingredients and resources compared to MPSO
Sensitivity run Soy-based meat analogue, low range (SRSL)	15% lower demand for ingredients and resources compared to MPSO
Sensitivity run Global emphasis on technological solutions, high range (SRGTH)	15% higher demand for plant-based meat analogue and soy milk ingredients and resources compared to GLOTEC. Cultivated Meat feedstocks and water use according to high range in Sinke et al. (2023): 1.89 kg maize, 0.36 kg soybean, 108.1 L water per kg CM Energy consumption 15% higher than in GLOTEC
Sensitivity run Global emphasis on technological solutions, low range (SRGTL)	15% lower demand for plant-based meat analogues and soy milk ingredients and resources compared to GLOTEC. Cultivated Meat feedstocks and water use according to low range in Sinke et al. (2023): 1.06 kg maize, 0.18 kg soybean, 26.1 L water per kg CM Energy consumption 15% lower than in GLOTEC

Each of the scenarios spans a time period from 1970 until 2100. Between 1970 and 2020, the scenarios follow historical trends and are thus equal to each other. From 2020 onward, the scenarios start to diverge.

3.2 CROP REQUIREMENTS, ENERGY USE AND WATER USE OF SELECTED ANIMAL-SOURCE FOOD ALTERNATIVES

In order to model these dietary change scenarios, the quantities of different crops that are required for each option to be produced were established. These are the values by which specific crop type production needs to be increased in the model inputs, for each kilogram of animal-source food that is replaced.

For the plant-based meat analogues, soy milk and oat milk, these are the crops that are used as ingredients for the final product. For cultivated meat, these crops are the feedstocks that are used in the cultivation process. For the cricket-based product, this includes the crops fed to crickets during rearing, as well as further vegetables that are added to the final product.

Through a thorough literature review, the ingredients and/or feedstock requirements of the different options were determined, as well as water and energy use during the production phase. Table 6 displays all values as applied in the modeling analysis. The calculations that were performed to arrive at these values can be found in the appendix.

The primary ingredients or feedstocks are given in terms of crop categories in the IMAGE model. For example, all beans, pulses and legumes except soybeans, are subsumed in a larger ‘pulses’ category, and all vegetables are subsumed in the ‘vegetables & fruits’ category. The following subsections detail how these values were established for each different option.

Table 6: Overview of ingredients and/or feedstocks, water use and electricity and heat consumption of the modelled animal-source food alternatives

animal-source food alternative	Composition	Primary ingredients or feedstocks (kg / kg final product)	Production / processing phase water use (L/kg)[1]	Production phase electricity consumption (MJ/kg)[2]	Production phase heat consumption (MJ/kg)[1]	Protein content (% mass)	Sources
Beans & legumes	60% soybeans 40% other beans, legumes and pulses	Soybean 0.6 Pulses 0.4	0	0	0		
Soy-based meat analogue	70% hydrated soy TVP 20% vegetable oil 10% cereal flour	Soybean 0.41 Tropical oil crop 0.43 **or** Temperate oil crop 0.57 Cereal (wheat **or** Tropical cereals **or** Other temperate cereals) 0.14	12.6	0.56	0.15	16.1%	(Baasandorj et al., 2015; Dalgaard et al., 2008; Hong et al., 2022; Pourmehdi & Kheiralipour, 2020; Saerens et al., 2021; Wang, 2014; Waseem et al., 2017)
Faba-based meat-analogue	70% hydrated faba TVP 20% vegetable oil 10% cereal flour	Pulses 0.41 Tropical oil crop 0.43 **or** Temperate oil crop 0.57 Cereal (wheat **or** Tropical cereals **or** Other temperate cereals) 0.14	12.6	0.56	0.15	21.9%	(Baasandorj et al., 2015; Dalgaard et al., 2008; Hong et al., 2022; Pourmehdi & Kheiralipour, 2020; Saerens et al., 2021; Wang, 2014; Waseem et al., 2017)
Cultivated Meat	100% cultivated meat	Soybean 0.26 Maize 1.42	52.1	81.3	9.2	18-25%	(Marinussen & Kool, 2010; Sinke et al., 2023)
Cricket-based product	36% cricket powder 54% water 10% vegetable	Soybean 0.37 Maize 0.56 Rice 0.10 Vegetables & fruits 0.10	1.1	0.12	0.43	22.1%	(Halloran et al., 2017; Ververis et al., 2024)
Soy milk		Soybean 0.07 Sugar crop 0.03	0.9	0.47	0.19	3.5%	(Ercin et al., 2012)
Oat milk		Oat grain 0.19	1.0	0.47	0.19	0.5%	(Riofrio & Baykara, 2022)

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[1] Includes ingredient water, e.g. water added to ground soybeans to create soy milk

[2] Includes energy use in processing and production of feedstocks and ingredients, such as flour, vegetable oil, corn glucose, etc.

3.2.1 Beans & legumes

There is a wide variety of beans and legumes that are commonly eaten as a protein source. In IMAGE, these are split between two crop categories: Pulses and Soybeans. The pulses category includes foods like faba beans, chickpeas, kidney beans and black beans. When replacing 1 kg of meat with beans & legumes in the scenarios, it is assumed that 60% of this will be replaced by soybeans, and 40% by pulses. This assumption is taken from Stehfest et al. (2009), who make it based on the total share of soybeans in total food pulse production.

3.2.2 Plant-based meat analogues

As stated in Section 2.1.2, plant-based meat analogues are most commonly produced using soy or faba TVP as the main component. The amount of beans needed to produce 1 kg of hydrated TVP was determined to be 0.59 kg. This includes losses during milling of beans into meal and during the TVP production process, taken from Saerens et al. (2021) and Dalgaard et al. (2008). Energy and water use during these production steps were taken from the same sources. Such data was not available for the milling of faba beans, so the values for soybeans processing were assumed to represent the process for faba bean TVP as well.

Market heterogeneity in composition of plant-based meat analogues required the formulation of generic, representative recipe to be implemented in IMAGE. The approach taken by Kozicka et al. (2023) served as the basis for the approach taken here. The representative recipes consist of 70% hydrated TVP, 20% vegetable oil, and 10% cereal flour. These recipes result in meat analogues with protein contents in the same range, roughly 15 to 22%, as commercially available options and close to most conventional meat types.

Separate modeling analyses are carried out for soy-based and faba-based meat analogues. The meat analogue recipe is agnostic to the specific oil crop and cereal type used as ingredients, to allow for regional differentiation. In a scenario of global dietary change, it is assumed that regions produce plant-based meat analogues using the most widely available type of oil crop (excluding palm oil) and cereal type. Since tropical and temperate oil crops differ in oil content, the amount of primary oil crop needed to produce the required 200g of oil in 1 kg of meat analogue differs between the two crop groups (Waseem et al., 2017). Both are shown in Table 6.

To arrive at the demand for primary cereals from the 10% cereal flour content, the milling efficiency of cereals is taken to be 70% (Baasandorj et al., 2015). 140 grams of cereal is thus required per kilogram of plant-based meat analogue, see Table 6.

3.2.3 Cultivated meat

Cultivated meat is still in the early stages of its development, and so it is not clear what the resource requirements of cultivated meat production on a commercial scale will look like. The most recent and comprehensive study on the resource requirements of cultivated meat, Sinke et al. (2023), provides an ex-ante assessment of commercialized cultivated meat production in 2030. It includes three scenarios of varying optimism about resource efficiency of future cultivated meat production at a commercial scale. The middle-of-the-road scenario from this study is taken as a reference for the feedstock, energy and water requirements for cultivated meat.

The main feedstocks for cultivated meat production are soy hydrolysate, corn glucose, conventionally produced amino acids and salt. Amino acids may be produced using corn as a feedstock (Marinussen & Kool, 2010). Thus the feedstock demand for cultivated meat production can be simplified to only soybeans, corn and salt, using loss factors from the production of soy hydrolysate from soy and corn glucose from corn. Table 6 displays the calculated feedstock quantities and resources required to produce a kilogram of cultivated meat in the baseline scenario from Sinke et al. Salt production is not a part of IMAGE and could thus not be included in the modeling analysis.

3.2.4 Cricket-based product

The recipe for the cricket-based product considered here consists of 36% cricket powder, 54% water and 10% other vegetable ingredients. This recipe is based on Ververis et al. (2024). This product has a protein content of 22.1%, a similar value to conventional meat types. Halloran et al. (2017) details the feed and water consumption of cricket cultivation. From this source, the crop requirements to cultivate 1 kg of cricket powder were calculated. All feedstocks and resources necessary to produce 1 kg of cricket-based product are shown in Table 6.

3.2.5 Plant-based milks

The composition and water use of soy milk is based on Ercin et al. (2012). Very little data on the details of the production process of soy milk could be found, particularly on the energy use of the production process. No reliable values could be established. As a result, an approximate guess had to be made regarding this energy use. It was decided to use the same energy consumption values as were established for oat milk, as the production processes are not completely dissimilar.

The data values for oat milk production are taken from Riofrio & Baykara (2022). Table 6 displays the ingredients and resource requirements of both plant-based dairy options.

3.3 MODELING

In this section, the steps taken to calculate the land use, water use, GHG emissions and global warming in the different dietary change scenarios using IMAGE are laid out.

3.3.1 SSP2 baseline run

As discussed, the SSP2-2.6 scenario serves as the baseline. An IMAGE run using SSP2 input data was carried out to establish the performance of the baseline scenario in the key environmental impact categories. This scenario was previously published in Doelman et al. (2018) and Van Vuuren et al. (2021). The baseline scenario data is then used to produce new inputs for the alternate scenarios. This process is described in the following section.

3.3.2 Model input preparation

Dietary trends are represented in IMAGE-land through input files that contain data on agricultural production. Two input files are modified compared to the SSP2 baseline scenario:

- *AgrProdA.scn* specifies the production of animal products, per model timestep, region and animal category.
- *AgrProdC.scn* specifies the total production of all modeled agricultural crop types, including crops for human consumption and feed crops.

IMAGE input files, including *AgrProdA* and *AgrProdC,* contain data in multiple dimensions. The first dimension is time, with annual timesteps from 1970 to 2100. The second dimension is regions, of which there are 26. The remaining dimensions depend on the specific purpose of the file. *AgrProdA,* for example, has a further dimension containing the different categories of farm animals. So, for each timestep, *AgrProdA* has a data point for the produced quantity of a specific animal product in each region, and *AgrProdC* has a data point for the produced quantities of specific crop types per region. In the formulae in this section, the data are represented as $AgrProdA_{y,a,r}$ and $AgrProdC_{y,c,r}$. Here, the index *y* represents the yearly timestep, *a* the specific animal type, *c* the crop type, and *r* the region.

The SSP2-2.6 *AgrProdA* and *AgrProdC* data serve as the basis for the new scenarios. The data files include historical data between 1970 and 2020 and modeled output between 2021 and 2100.

In order to implement the new scenarios, a new variable is introduced, the replacement factor $RepFactor_{y,a,r}$. For example, in MPSO, where 100% of beef consumption in Canada is replaced by alternatives in 2050, the reduction factor is:

$$RepFactor_{2050,beef,Canada} = 1$$

3.3.2.1 AgrProdA

The following formula is used to calculate the new *AgrProdA.scn* data for the new scenarios:

$$(1)\ AgrProdA_{y,a,r}^{new} = AgrProdA_{y,a,r}^{SSP2} * \left(1 - RepFactor_{y,a,r} * (1 - PoultryEggMeatRate_{y,a,r})\right)$$

Here, $PoultryEggMeatRate_{y,a,r}$ is a variable that accounts for the fact that broiler chickens for meat and egg laying chickens are combined in a single category in IMAGE. In the meat replacement scenarios, only meat is replaced, while egg consumption remains the same. $PoultryEggMeatRate_{y,a,r}$ is the mass share of eggs in the total poultry production. For the non-poultry categories, this factor is equal to zero, since cows and sheep don't usually lay eggs. In MPSS, where eggs are also replaced, the factor is also set to zero for poultry.

3.3.2.2 AgrProdC

The crop production input *AgrProdC.scn* in the new scenarios is calculated as follows:

$$(2)\ AgrProdC_{y,c,r}^{new} = AgrProdC_{y,c,r}^{SSP2} - FeedCropReduction_{y,c,r} + ReplacementCrops_{y,c,r}$$

In Formula 2, $FeedCropReduction_{y,c,r}$ is the quantity of feed crops that no longer needs to be produced because there is less livestock. $ReplacementCrops_{y,c,r}$ is the additional quantity of crops that needs to be produced in order to supply the new demand for animal-source food alternatives.

The feed reduction is calculated as follows:

$$(3)\ FeedCropReduction_{y,c,r} = \sum_{a} (Feed_{y,a,c,r}^{SSP2} * RepFactor_{y,a,r})$$

In Formula 3, $Feed^{SSP2}_{y,a,c,r}$ indicates the baseline feed consumption per year, animal category, crop category and region. This is then multiplied with the replacement factor of that specific animal type in that specific year. The assumption is made that a 30% reduction in meat consumption leads directly to a 30% decrease in feed consumption. The reduction in crop consumption per animal and crop type is then summed over the different animal types to arrive at $FeedCropReduction_{y,c,r}$.

In Formula 4, $AltProd_{y,r}$ denotes the total amount of alternative that needs to be produced per region, and is calculated by multiplying the total AgrProdA per animal type and region by the replacement factor, and summing:

$$(4)\ AltProd_{y,r} = \sum_{a} \left(AgrProdA^{SSP2}_{y,a,r} * RepFactor_{y,a,r} \right)$$

The quantity of new crop production needed to produce the new animal-source food alternatives is then calculated as follows:

$$(5)\ ReplacementCrops_{y,c,r} = AltProd_{y,r} * RepIngr_{c,r} * WasteFactor_{c,r}$$

In Formula 5, $AltProd_{y,r}$ is multiplied by the quantities of ingredient or feedstock crops required to produce an equal mass of ASF alternative: $RepIngr_{c,r}$. Note that $RepIngr_{c,r}$ may vary per region, since not each region produces the ASF alternatives using exactly the same ingredients or feedstocks (see Section 3.2). $WasteFactor_{c,r}$ is a factor that is appended to convert crop consumption to production. It indicates the percentage of produced crops that are lost before it can be consumed, for example on fields, during harvest or in transport.

The application of these formulae to the baseline numbers produced the new AgrProdA.scn and AgrProdC.scn datafiles to serve as model input for IMAGE-land and TIMER.

3.3.3 Run new scenarios in IMAGE-land

Having created the new input data, the scenarios were ran in the IMAGE-land submodel to calculate developments in the agricultural sector, including agricultural land use, water use and land-use emissions. Apart from the newly created *AgrProdA* and *AgrProdC*, the rest of the input data was kept the same as in the baseline runs, so that any observable trends in the model results are a direct result of the scenario input.

IMAGE-land calculates the cropland area required by looking at regional crop demands, crop yields and existing crop production. If an expansion of the production of a specific crop is required, the model looks for the most appropriate location to produce these crops. If an area that is already classified as cropland is available, production of the new crop will be moved there. If no cropland is available, the total cropland area is expanded into regions that were not cropland before. Thus, land-use change occurs, which causes GHG emissions. The same applies for the pastureland required to produce animal-source products. If more farmland is available than necessary to meet demand, farmland gets abandoned and turns back into natural area, which has the added effect of creating negative emissions as the growth of plants and trees sequesters carbon. IMAGE-land produces output data detailing agricultural land use (in km^2) per IMAGE region.

Agricultural GHG emissions are calculated based on the amount of livestock and the rate of land-use change, among other factors. IMAGE-land produces separate output data for land-use CO_2, NH_4, and N_2O emissions.

Crop water demand is based on cropland area, crop types grown and precipitation. For cropland planted with a specific crop, moisture demand is determined. Insofar as precipitation over the cropland is insufficient to fulfill the moisture demand, additional demand for irrigation water is calculated. Based on the irrigation water demand, actual irrigation water consumption is calculated, taking factors like freshwater availability and process losses into account. Output data detailing irrigation water consumption in km^3 per region and crop type is produced.

3.3.4 Compile water use results

For land-use and the associated land-use emissions, the previous steps yield the final results. For water use, some additional calculations are needed. IMAGE-land calculates irrigation water consumption for crops, as explained in the previous section. For the sake of completeness of this analysis, two further water consumption categories are calculated: livestock servicing water consumption and consumption of water during the manufacturing of animal-source food alternatives.

To calculate the total water footprint of agriculture and the production of animal-source food alternatives, these factors are added up after the IMAGE-land run is completed:

$$(6)\ TotalWater_{y,r} = IrrWater_{y,r} + ServiceWater_{y,r} + AltProdWater_{y,r}$$

Where $IrrWater_{y,r}$ represents irrigated water consumption as calculated by IMAGE-land, $ServiceWater_{y,r}$ represents livestock servicing water consumption, and $AltProdWater_{y,r}$ represents water consumption in the production process of animal-source food alternatives.

Livestock servicing water includes water consumed by livestock as drinking water and other on-site water use for the purpose of cleaning animals, flushing manure, et cetera. This accounts for a relatively small fraction of total water use of animal source foods (Chapagain & Hoekstra, 2003). It is currently omitted from IMAGE for reasons of simplification. However, since the scenarios assessed in this research deal with a drastic decrease in total livestock, it was relevant to include this water use here.

Table 7: Yearly per-animal service water consumption, for different farming systems. Based on Chapagain & Hoekstra (2003)

Yearly service water consumption (m^3)		
Farming system	Intensive	Extensive
Beef cattle	15.3	8.51
Dairy cattle	28.3	13.9
Pigs	20.2	10.6
Sheep	4.23	3.62
Goats	2.90	2.80
Meat poultry	0.09	0.09
Laying poultry	0.16	0.16

Chapagain & Hoekstra (2003) provide data on per-animal service water consumption for different types of livestock in intensive and extensive farming systems. Table 7 shows these values, obtained after some conversion calculations, which are shown in the appendix. Intensive farming denotes industrial farming as common in the Global North, while extensive farming means more traditional pastoral farming, more common in the Global South.

The IMAGE-land run executed in the previous step produced the total number of animals in each livestock category and per farming system as an output. By multiplying these quantities with the values from Table 7, total servicing water consumption was calculated per year, animal type and region:

$$(7)\ ServiceWater_{y,a,r} = IntStock_{y,a,r} * IntWaterUse_{y,a,r} + ExtStock_{y,a,r} * ExtWaterUse_{y,a,r}$$

Where $IntStock_{y,a,r}$ and $ExtStock_{y,a,r}$ are the number of animals in intensive and extensive farming systems, respectively, and $IntWaterUse_{y,a,r}$ and $ExtWaterUse_{y,a,r}$ the service water consumption in intensive and extensive systems, respectively.

In Table 6, the water consumption during the manufacturing and processing phase of the selected animal-source food alternatives was given. When considering the consequences of dietary change away from animal-source food and towards these alternatives, it is important to consider not only reductions in water demand arising from a decrease in animal-source food production, but also a potential rise in water consumption because of the manufacturing processes of the alternatives. The production water demand from Table 6 was multiplied by the total quantity of alternatives manufactured in each year to arrive at total water consumption for animal-source food alternatives manufacturing:

$$(8)\ AltProdWater_{y,r} = AltProd_{y,r} * \ ProdWaterDem_{y,r}$$

Using the formulae above, total water consumption for the modeled period is calculated and plotted for each scenario.

3.3.5 Run scenarios in TIMER to calculate food processing emissions

The TIMER energy model calculates the energy use of the food processing sector. For this research, the TIMER code was modified to add new food categories for each of the alternatives in Table 6, along with the electricity and heat requirements associated with their production. As a result, TIMER can read the quantities of the produced alternatives, $AltProd_{y,r}$ in the above, and calculate the associated total energy demand for their production in the scenarios. It then matches energy demand with energy sources and calculates the associated CO_2 emissions. After the TIMER runs are completed, output data describing food processing emissions is available for all the scenarios to plot and compare.

3.3.6 Determine global warming using IMAGE post-processing

Having calculated the trends in global GHG emissions, the IMAGE post-processing module is then used to determine global warming in the scenarios. In post-processing, the outputs of the IMAGE-land and TIMER runs are combined to determine the aggregate outcome of the model runs, which produces output files in which global warming, expressed in degrees Celsius, is given over the modeled time period. This trend is then plotted to compare the scenarios to each other.

4 RESULTS

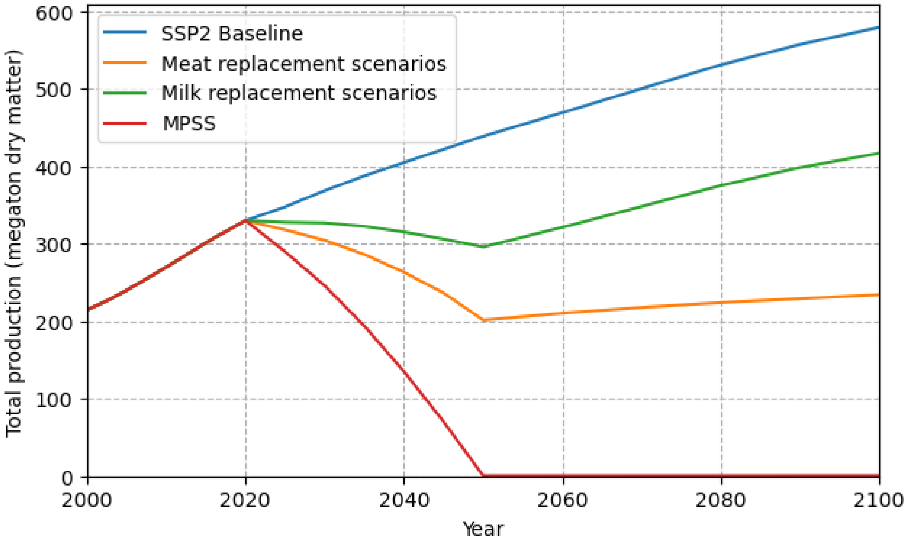
In this chapter, the modeling results are presented. First, the results for land use, water consumption, greenhouse gas emissions and global warming are presented and discussed for the maximum potential scenarios. Subsequently, the results for the storyline scenarios are presented and discussed.

4.1 MAXIMUM POTENTIAL SCENARIOS

4.1.1 Agricultural production

The results of the steps described in Section 3.3.2 are the *AgrProdA* and *AgrProdC* model input data, which describe the production of animal-source products and crops. Figures 3 and 4 show the trends for these categories, respectively.

Figure 3: Total global production of animal-source foods for the maximum potential scenarios, in megaton dry matter



In Figure 3, all the scenarios in which only meat is replaced (MPBL, MPSO, MPFA, MPCM and MPCR) are grouped together, because the production of animal-source foods declines in exactly the same manner, the only difference is the way in which they are replaced. The same goes for the milk-replacing scenarios, MPOM and MPSM.

In this graph, the opposite effects of dietary change and population growth are easily visible. Between 2020 and 2050, the share of total animal-source foods that is replaced by alternatives in the scenarios increases year by year, and therefore the total production of animal-source foods declines in this period. After 2050, the share of replacement remains equal – 100% of the respective animal-source food types is replaced by the alternative, and thus its production stays at zero, but the production animal-source food types that are not replaced continues to grow according to the SSP2 baseline trends, and therefore, in the meat and milk replacement scenarios, an increase in the total production of animal-source foods can be observed between 2050 and 2100.

In the SSP2 baseline scenario, production of animal-source grows from 330 megatons in 2020 to 579 megatons in 2100, an increase of 75.5%. In the scenarios where milk is replaced by alternatives but meat production follows the baseline trend, production reaches 417 megatons in 2100, and increase of 26.4% compared to 2020, and 28.1% less than the 2100 production in the SSP2 baseline. In the scenarios where meat is replaced, global animal-source food production in 2100 reaches 234 megatons, a decrease of 29.1% compared to 2020, and 59.6% less than the 2100 production in the SSP2 baseline. In the MPSS scenario, in which all animal-source foods are replaced by soy-based products, global animal-source food production goes to zero by 2050 and remains so until 2100, a decrease of 100%.

Figure 4: Total global production of crops in the maximum potential scenarios, in gigaton dry matter

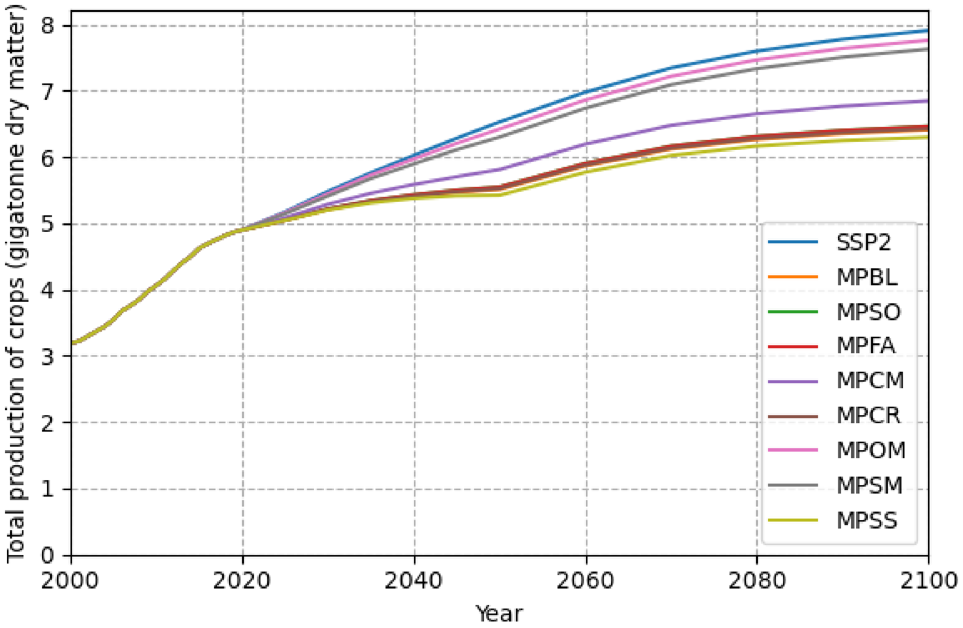


Figure 4 shows the total crop production for all the scenarios. Note that, even though there is an added demand for crops to produce the new animal-source food alternatives in these scenarios, total crop production is reduced substantially, particularly in the scenarios where meat is replaced. This is because the demand for livestock feed decreases linearly with the decreased livestock production. Figure 4 shows that the increased crop demand to produce new alternatives does not outweigh the decreased crop demand for livestock feed in these scenarios, as total crop production is less than in the SSP2 baseline in each of the scenarios.

Global crop production increases between 2020 and 2100 in all of the scenarios. In the SSP2 baseline scenario, there is an increase of 61.2% from 4.9 gigatons in 2020 to 7.91 gigatons in 2100.

In 2100, there is a substantial decrease in total global crop production in each of the scenarios where meat is replaced, compared to the baseline value in the same year. This decrease ranges from 13.4% in MPCM to 20.4% in MPSS. Crop production savings are less significant in the milk replacement scenarios: the decrease is 1.9% in MPOM and 3.5% in MPSM. Note that the relative differences between the different scenarios here are consistent with the required mass for ingredients and feedstocks established in Table 6. The animal-source food alternatives that require a larger ingredient or feedstock mass see a higher global crop production in 2100 in their respective scenarios.

Figure 5: Global total crop production in 2100 in maximum potential scenarios, percentage difference compared to SSP2 baseline

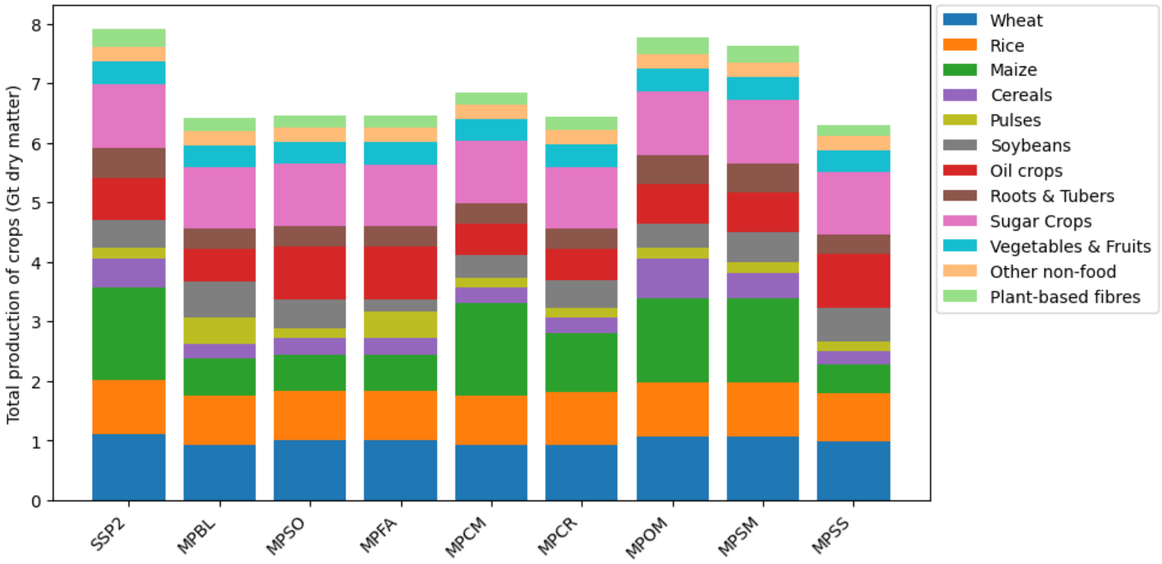


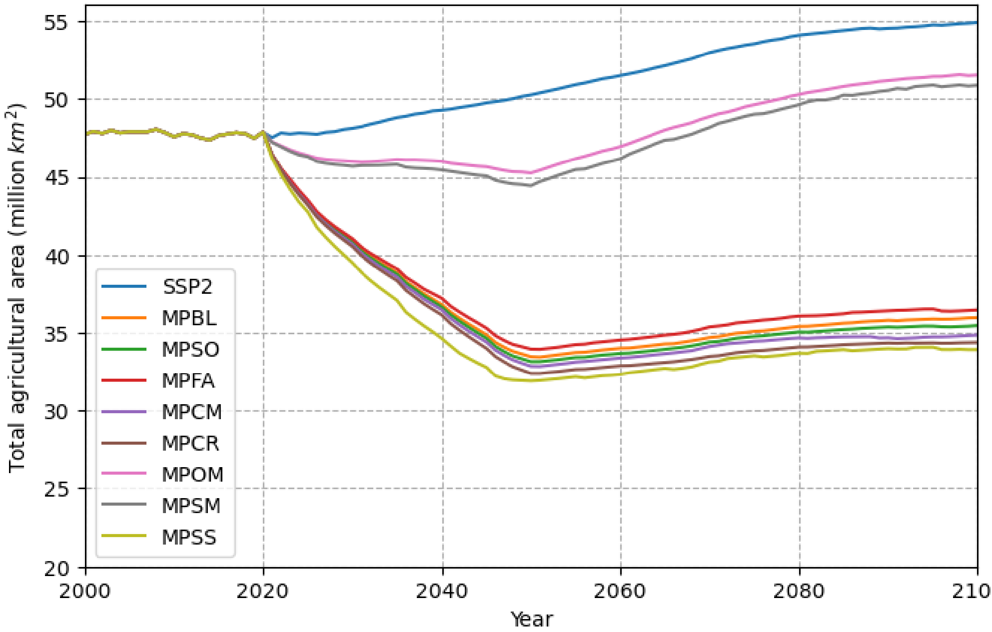
Figure 5 specifies the production of different crop categories in 2100 in the scenarios. It can be seen that, compared to the baseline, MPBL, MPSO, MPFA and MPSS see a large decline in maize production, and increases in the crops that constitute their respective animal-source food alternatives, such as soybeans for MPSO and MPSS and pulses for MPFA. Maize production decreases because maize is an important feed crop for livestock. In MPCM and MPCR, the decrease in maize production is much smaller, since cultivated meat and crickets require maize as a resource.

Having established the production of animal-source foods and crops for each of the scenarios, the following section presents the results of running IMAGE-land with these inputs to determine global agricultural land use.

4.1.2 Land use

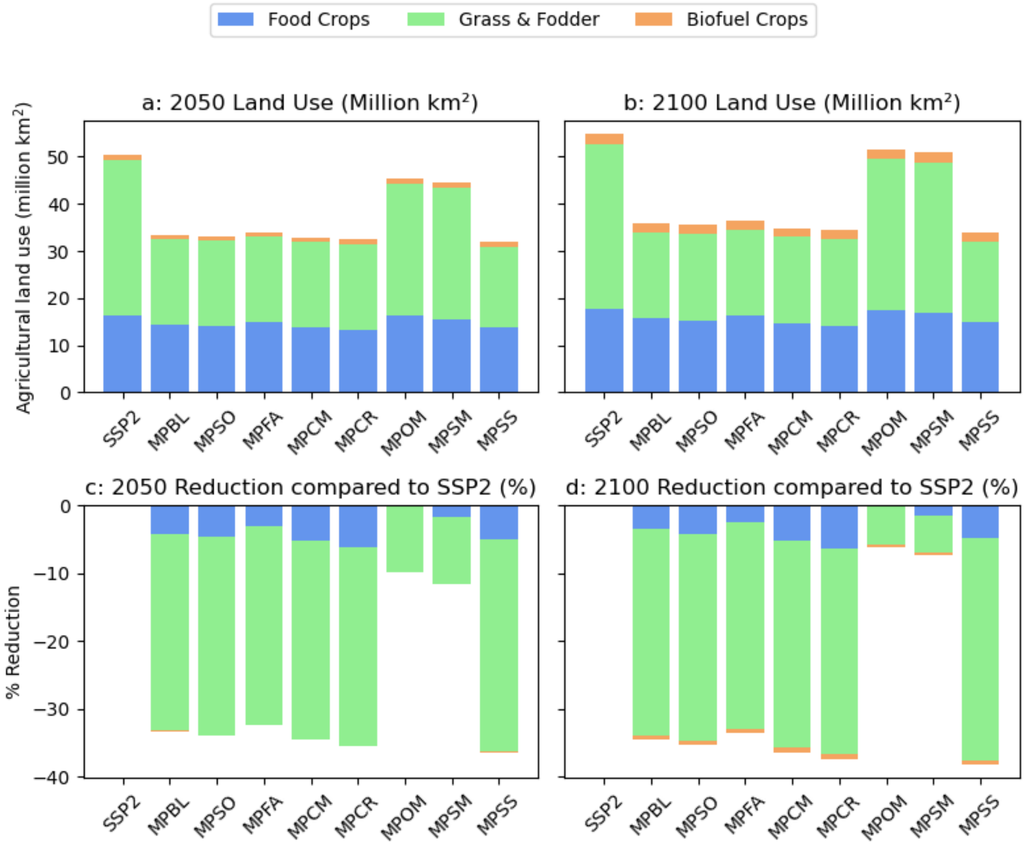
Figure 6 displays the modeling results for agricultural land use for the maximum potential scenarios. It can be seen that the results are fairly similar for each scenario which replaces meat, and for the two scenarios that replace dairy. Compared to the large impact that the replacement of animal-source food with any alternative at all makes on global land use, the differences between the different options are small. Figure 7 shows the agricultural land use in more detail, including the share of different land-use types in the total, and the difference between the new scenarios and the baseline in 2050 and 2100.

Figure 6: Total global agricultural area for maximum potential scenarios



In Figure 7, it can be seen that the reduction in agricultural area is achieved mostly due to a large reduction in land use for grass and fodder, which includes land used to grow fodder as well as pastureland for livestock.

Figure 7: Agricultural land use per type in 2050 and 2100, totals and percentage difference to SSP2, for the maximum potential scenarios



The plant-based meat analogues (MPSO and MPFA) and MPBL achieve the least land use reduction out of the different meat-replacing options, although the reductions are substantial in all scenarios. In 2100, land use is 34.5% lower compared to the baseline in MPBL, 35.5% lower in MPSO and 33.4% lower in MPFA.

This could be considered somewhat surprising, seeing as they don't necessarily have the highest total demand for ingredients mass (recall Table 6). Additionally, the faba-based meat analogue performs slightly worse than the soy-based meat analogue, while these two options require an identical mass of ingredients. The difference in land use can be explained by the difference in crop yield of the different ingredient crops. Pulses have a slightly lower yield in mass per area than soybeans, and thus MPFA and MPBL, which have higher pulse demand, have higher total land-use.

MPCM and MPCR, the cultivated meat and cricket-based product scenarios, perform the best out of the meat-replacing scenarios, when it comes to land use reduction. In MPCM, a land use reduction compared to the baseline of 36.6% is realized. In MPCR, this is 37.4%. Again, this is due to the fact that the crops used to produce these alternatives, chiefly maize, have a higher yield than pulses and soybeans.

In terms of land use, MPCR achieves the largest decrease out of the meat-replacing scenarios. However, the differences between the scenarios are very small. This suggests that small variations in crop demand for the different options may result in a different ranking of the scenarios' land use. This is further investigated in the sensitivity analysis in Section 4.3.

Soy milk (MPSM) achieves more land use reduction than oat milk (MPOM). In MPSM, a land use reduction of 4.3% is realized by 2100. In MPOM, this is 3.2%. This can be attributed to the fact that soy milk requires less ingredient crop mass per kg of product than oat milk, recall Table 6.

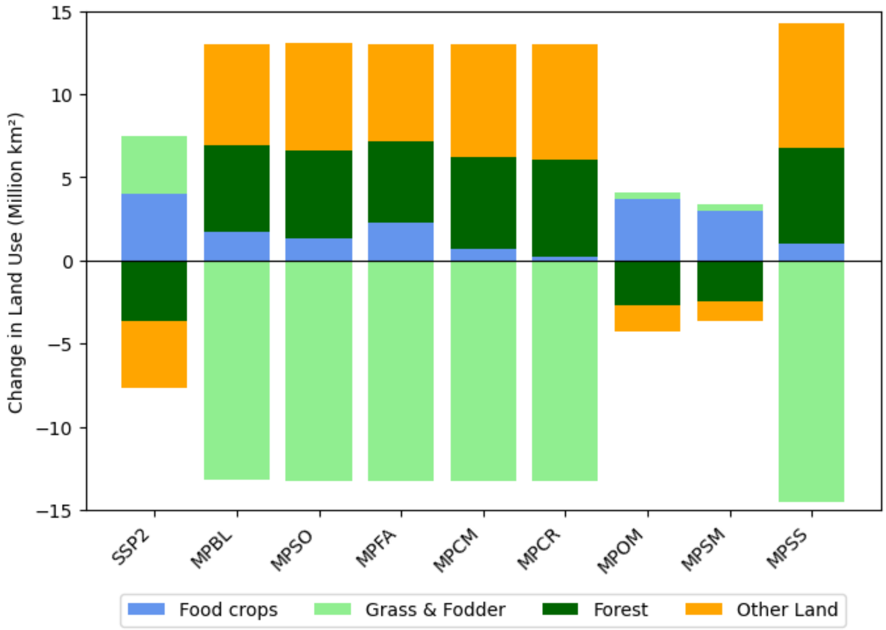
MPSS, the scenario in which all animal products are replaced by a soy-based alternative, results in the largest decrease in land use, which reaches 38.6% in 2100. It is interesting to note that this decrease is less than those of MPSO and MPSM put together, which would be 40%. This indicates that there is some sort of trade-off in total land-use reduction. Possibly, this is related to the fact that, particularly in traditional, extensive pastoral farming, animals are kept for both milk and meat.

Comparison of the land-use reduction in 2050 and 2100 shows another interesting trend. For the meat-replacing scenarios, the relative reduction compared to the baseline is larger in 2100 than in 2050, while for the milk-replacing scenarios, it is the other way around. This can be explained by the underlying development in animal-source food consumption in the baseline. Consumption of meat grows at a higher rate than dairy consumption. As a result, the share of meat in all animal-source food consumption is larger in 2100 than in 2050. Replacing milk with alternatives thus has a smaller relative impact on total land use in 2100 than in 2050.

Furthermore, the use of land for biofuel production increases in each scenario, in order to meet demand for biofuels as fossil fuels are phased out towards the end of the century.

In Figure 8, land-use change between 2020 and 2100 in each scenario is shown, for the two agricultural land types as well as forest area and other land types. Negative values indicate a decrease in land use in that category, positive values indicate an increase. The 'other land' category also includes abandoned agricultural land that did not become forest, for example because it is situated in a different natural environment, like extensive ungrazed grassland. In this bar chart, the effect of the scenarios on land use is well illustrated: in the meat-replacing scenarios, there is a drastic decrease in land use for grass and fodder, and this land is subsequently allocated to food crops, forest and other land. In the SSP2 baseline, a different trend is visible, where the total grass and fodder area is expanded at the cost of forest area.

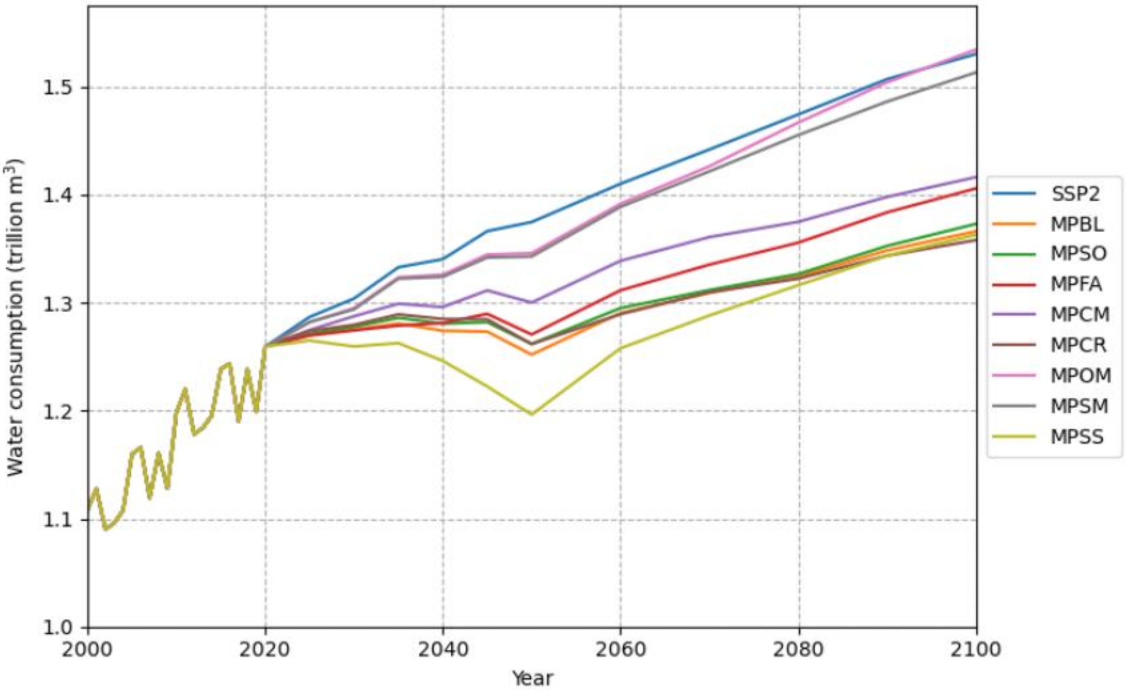
Figure 8: Global land-use change in the period 2020-2100 for the maximum potential scenarios



4.1.3 Water use

Figure 9 shows the model results for water use, including irrigated water consumption by crops, livestock servicing water and water use in manufacturing of animal-source food alternatives.

Figure 9 - Yearly global water consumption, including irrigated water, livestock servicing water and water use in manufacturing of alternatives, for the maximum potential scenarios



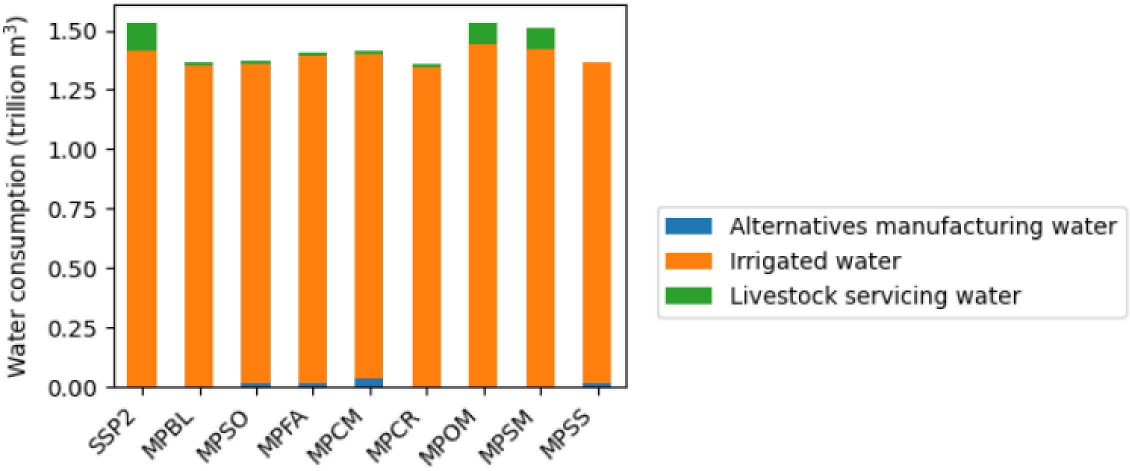
It can be seen from Figure 9 that the water consumption trends for the different scenarios diverge between 2020 and 2050, as the replacement of animal-source foods increases. After 2050, the replacement rate remains at 100%, and thus total water demand grows with the trends for population and diet. In the baseline scenario, water consumption in 2100 reaches 1.53 trillion m^3.

For MPOM and MPSM, the reduction in water consumption compared to the baseline is very small. By 2100, water consumption in MPOM is actually slightly larger than in the baseline scenario, but also rounded off to 1.53 trillion m^3, owing to the relatively high irrigated water demand for oats cultivation. In MPSM, water demand is only slightly lower than in the baseline at 1.51 trillion m^3. Water demand in 2100 for MPFA and MPCM is also very close at 1.41 trillion m^3 and 1.42 trillion m^3, respectively. The remaining scenarios all have water consumption between 1.35 and 1.38 trillion m^3. As with land use before, the difference in water consumption between the different scenarios is small enough that small variations in per-kg crop and water demand could change the order in which the scenarios are ranked. This is discussed further in the sensitivity analysis, Section 4.3.

In Figure 10, the water use in 2100 for the different scenarios is broken down into its constitutive categories. Livestock servicing water and alternatives production water are very small fractions of the overall total, while irrigated water consumption dominates.

The additional water consumption caused by the production of the novel alternatives is thus not a large enough factor to outweigh the water consumption reductions realized by reducing animal agriculture.

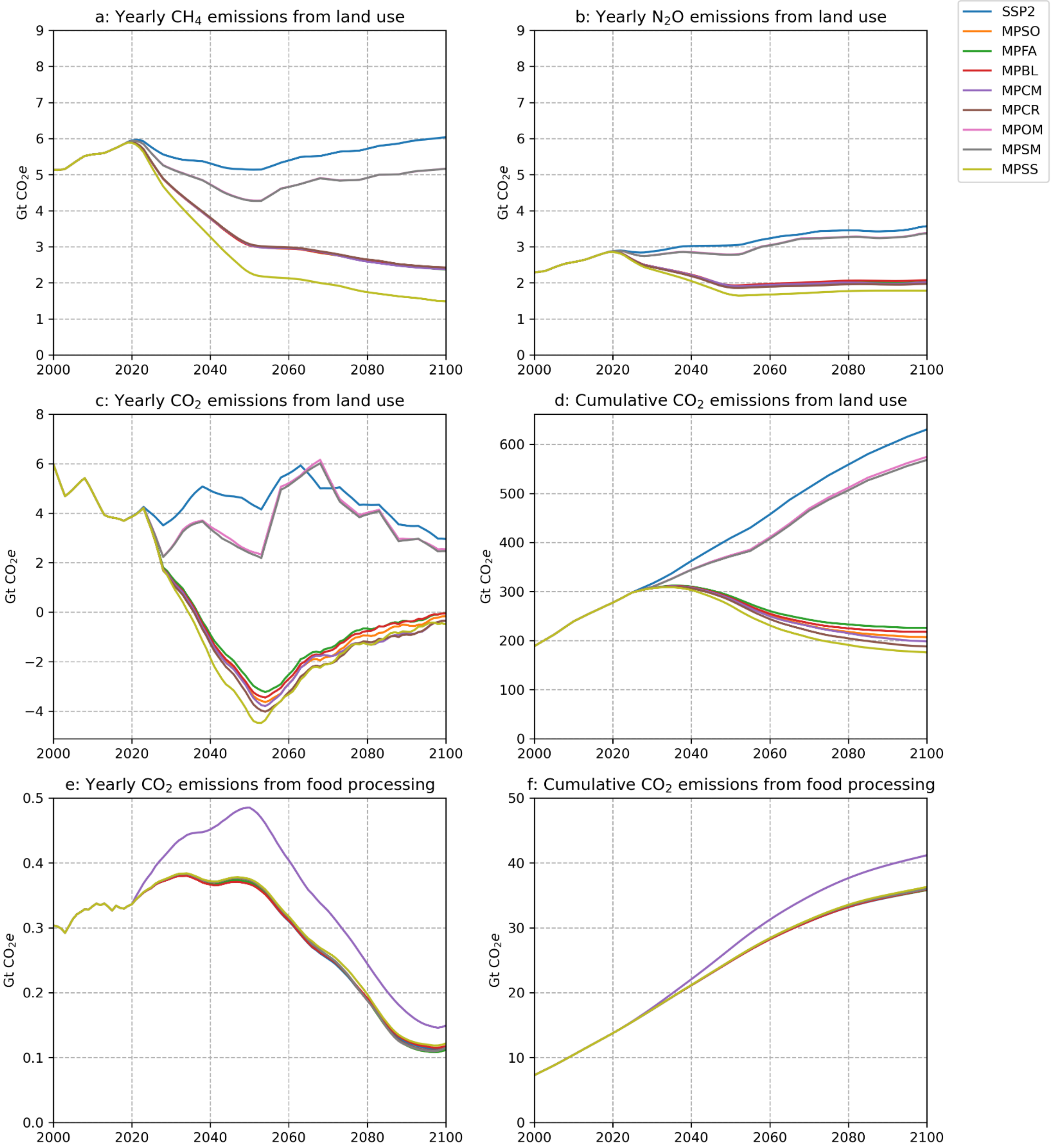
Figure 10 - Water consumption in 2100 by category for the maximum potential scenarios



4.1.4 GHG Emissions

Figure 11 displays emissions of the greenhouse gases CH_4, N_2O, and CO_2 resulting from land-use and food processing for each of the maximum potential scenarios.

Figure 11: Cumulative CH_4, CO_2 and N_2O emissions from land use in the maximum potential scenarios



Figures 11a and 11b show that land-use CH_4 and N_2O emissions are determined strongly by animal agriculture. The trends for each of the meat-replacing scenarios show largely overlap, which indicates that there is little difference in CH_4 and N_2O emissions between the different animal-source food alternatives to meat. The same goes for the two dairy-replacing scenarios. In terms of CH_4 and N_2O, MPSS performs best, with CH_4 emissions of 1.5 Gt CO_2e in 2100, 75% less than the 6.1 Gt CO_2e in the baseline, and N_2O emissions of 1.8 Gt CO_2e, which is 50% less than the 3.6 Gt CO_2e in the baseline.

MPSO, MPFA, MPBL, MPCM and MPCR each have yearly CH_4 emissions of 2.4 Gt CO_2e by 2100, 60% less than the baseline value; and N_2O emissions of 2.0 Gt CO_2e in 2100, 44% less than the baseline. In MPOM and MPSM, yearly CH_4 emissions reach 5.2 Gt CO_2e by 2100, a 14% reduction compared to the baseline, and N_2O emissions reach 5.1 Gt CO_2e, which is 5% less than in the baseline. In terms of land-use CH_4 and N_2O, a clear hierarchy in emissions can thus be established: MPSS performs best, then the meat-replacing scenarios, then the milk-replacing scenarios.

The trend for land-use CO_2 emissions (Figure 11c) is markedly different. For the meat-replacing scenarios the net yearly emissions from land use become negative around 2030. This can be explained by the decreased agricultural land use (recall Figure 6). This decrease allows a large share of agricultural land to return to nature and act as a carbon sink through afforestation. Effectively, in these scenarios, land use becomes a net carbon remover instead of a net carbon contributor. The peak in negative emissions occurs around 2053, where it is -4.6 Gt CO_2 in MPSS and between -3.5 and -4.1 Gt CO_2 for the meat-replacing scenarios. After 2053, it can be seen that the net CO_2 emissions from land use starting moving up towards zero again, as the trees on the renatured land mature and sequester less CO_2. Land-use CO_2 emissions in 2100 range between -0.2 to -0.5 Gt CO_2 for the meat-replacing scenarios, a decrease of more than 100%.

The effect of negative land-use emissions in this period on the cumulative (since 1970) land-use CO_2 emissions can be seen in Figure 11d: instead of more than doubling between 2020 and 2100, as happens in the SSP2 baseline scenario, the cumulative emissions actually decrease in the meat-replacing scenarios, and range from 188 to 225 Gt CO_2 in 2100. In the dairy replacement scenarios, the impact on cumulative carbon emissions is much smaller, as carbon-intensive meat production is left unchanged. In terms of land-use CO_2 emissions, MPSS performs best, followed in order by MPCR, MPCM, MPSO, MPFA, MPBL, MPSM and MPOM.

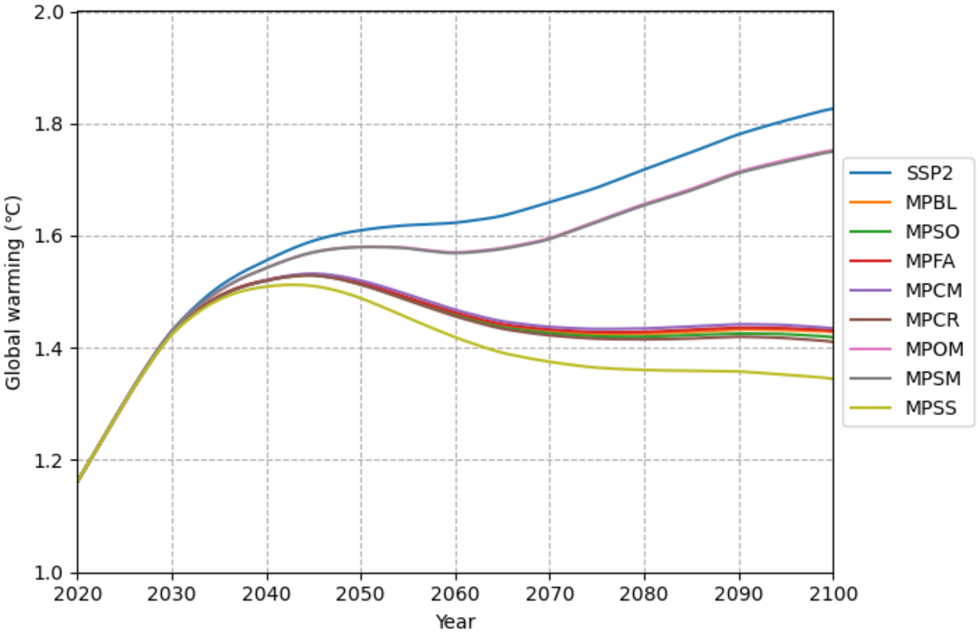
Figures 11e and 11f show the yearly and cumulative CO_2 emissions from food processing as calculated with TIMER for each of the maximum potential scenarios. In Figure 11e, it can be seen that MPCM, the cultivated meat scenario, is a big outlier compared to the other scenarios. Yearly CO_2 emissions from food processing peak at 483 megatons in 2050 in MPCM, while the emissions in all the other scenarios range between 368 and 375 megaton in that year, very close to the baseline emissions of 368 megatons. After 2050, a steady decline in emissions can be observed in all scenarios. This is because, under the SSP2 baseline assumptions, the energy system gets largely decarbonized, and so emissions are greatly reduced, even while total energy demand for food processing sees an increase. Overall it can be said that there is no large difference in food processing emission between the baseline and the maximum potential scenarios, with the exception of MPCM.

Having discussed the trends in land-use and food processing emissions, the next step is to analyze the impact of the developments in emissions have on global warming in the scenarios.

4.1.5 Global warming

Figure 12 shows the development of global warming in the maximum potential scenarios. In the baseline SSP2 scenario, as established earlier, global warming reaches 1.83°C by 2100, as a result of climate mitigation efforts to meet Paris Agreement targets. From Figure 12, it becomes clear that the dietary change prescribed in the maximum potential scenarios has the potential to further mitigate climate change by a significant extent.

Figure 12: Global warming in the maximum potential scenarios



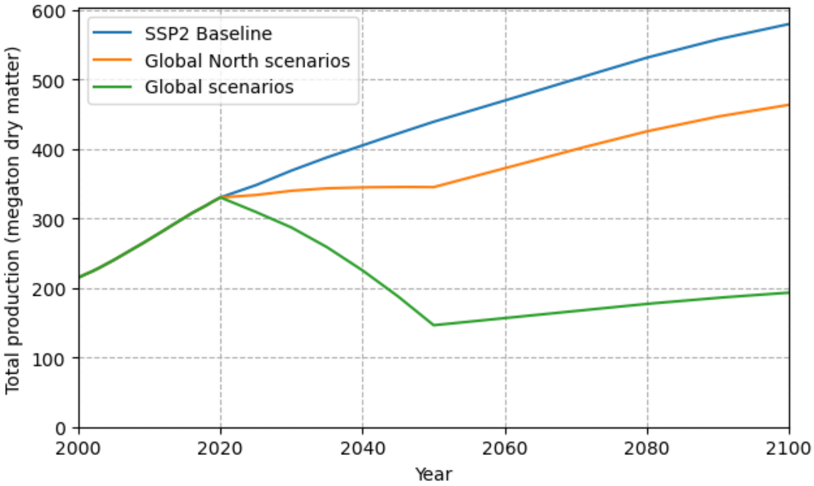
In MPSS, global warming in 2100 is limited to 1.35°C, 0.48°C less than in the baseline. MPCR, MPSO, MPBL, MPFA and MPCM are, in that order, in a range of values between 1.40°C and 1.43°C, a decrease of 0.40-0.43°C compared to the baseline. MPOM and MPSM both lead to global warming of 1.75°C in 2100, 0.10°C less than in the baseline.

4.2 STORYLINE SCENARIOS

4.2.1 Agricultural production

Figures 13 and 14 show the way in which *AgrProdA* and *AgrProdC* develop in the storyline scenarios. These figures are the results of the steps described in Section 3.2.2.

Figure 13: Total global production of animal-source agricultural production for the storyline scenarios, in megaton dry matter



In Figure 13, GNPB and GNTEC are grouped together, as are GLOPB and GLOTEC, since the rate at which animal-source foods are replaced is equivalent. In GLOPB and GLOTEC, the total production of animal-source foods drops dramatically until 2050, after which is grows slightly until 2100 but remains much lower than before the start of the dietary shift in 2020. In GNPB and GNTEC, the consumption of animal-source foods in the Global North declines, but consumption in the Global South increases enough during the same period to result in a slight overall increase in consumption between 2020 and 2050. After 2050, animal-source food consumption remains at zero in the Global North, but population growth and economic development in the Global South result in an overall growth in global animal-source food consumption until 2100.

Figure 14: Total global production of crops in the storyline scenarios, in gigaton dry matter

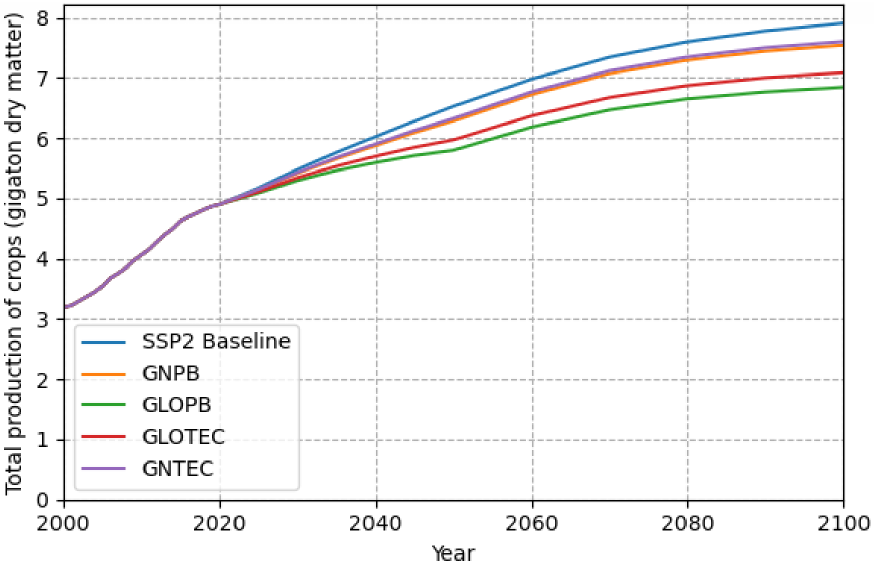


Figure 14 shows that the trend in total crop production for GNPB and GNTEC are very similar, while there is a larger difference between GLOPB and GLOTEC. GLOPB requires the least crops to be produced in 2100 of all the scenarios, which is in accordance with what would be expected considering the composition of the plant-based diet that replaces animal-source foods in this scenario. In GLOPB, 13.% less total dry crop mass is produced in 2100 compared to the baseline. In GLOTEC, this is 10.4%. The Global North lead to a substantially smaller decrease in crop production than the global scenarios: in GNPB, the reduction in 2100 compared to the baseline is 4.6%. In GNTEC, this is 3.9%.

Figure 15: Global total crop production in 2100 in storyline scenarios,specified per crop type

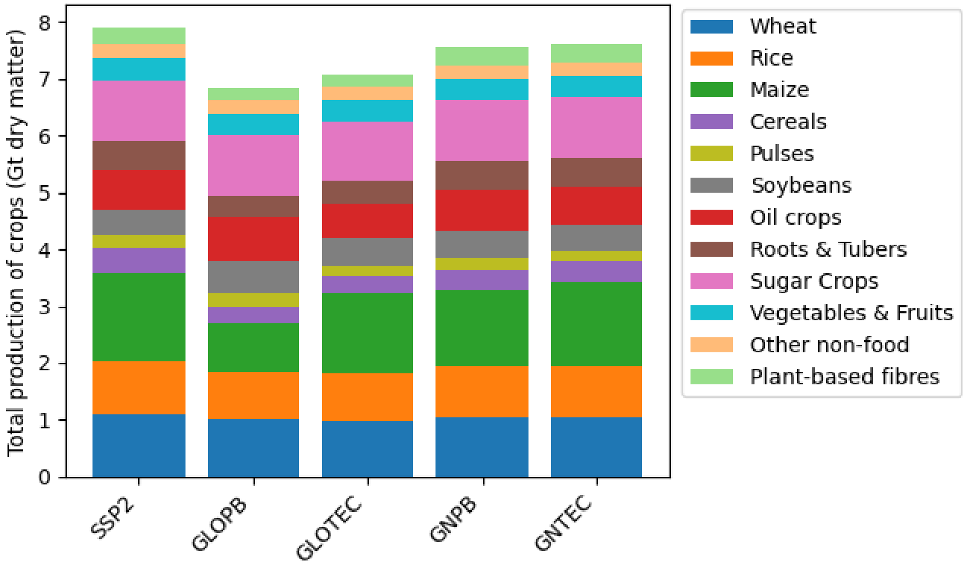


Figure 15 specifies the production of different crop categories in 2100 in the scenarios. It can be seen that, compared to the baseline, GLOPB sees a large decline in maize production and an increase in soybean production, indicative of the decreased need for maize as feed and the demand for soybeans as an ingredient for both soy-based meat analogues and as a whole food. Maize production decreases because maize is an important feed crop for livestock. In GLOTEC, there is no notable decrease in maize production, since maize is the main feedstock crop for cultivated meat. Due to the regional nature of GNPB and GNTEC, the decrease in crop production in these scenarios is very minor.

4.2.2 Land use

In this section, the land-use results from IMAGE-land for the storyline scenarios are presented. Figure 16 displays the trends for total agricultural land use. It can be seen that there is very little difference in land use between GNPB and GNTEC. The trends for GLOPB and GLOTEC are also very similar, but by 2100, GLOPB requires slightly more land than GLOTEC.

Figure 16: Total global agricultural area for storyline scenarios

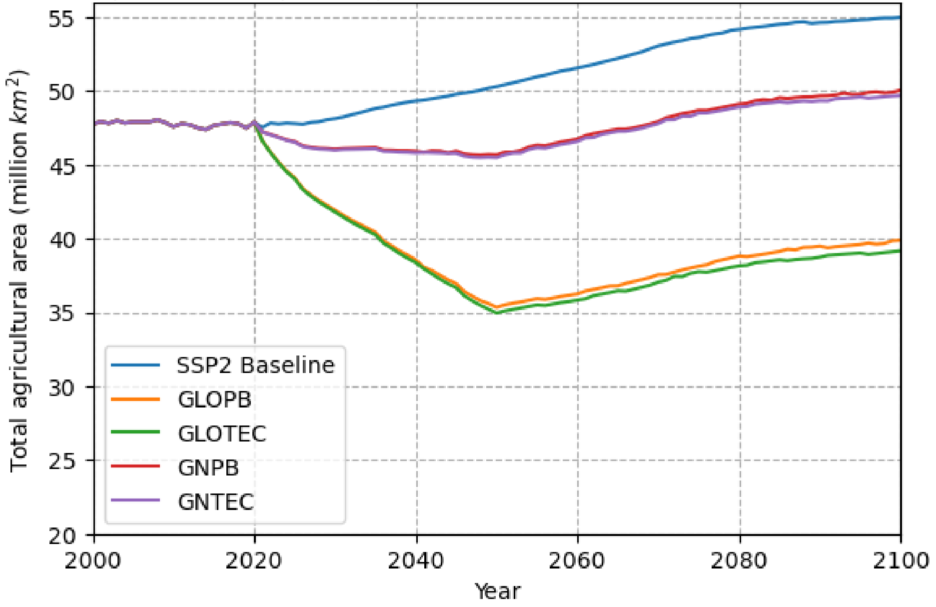
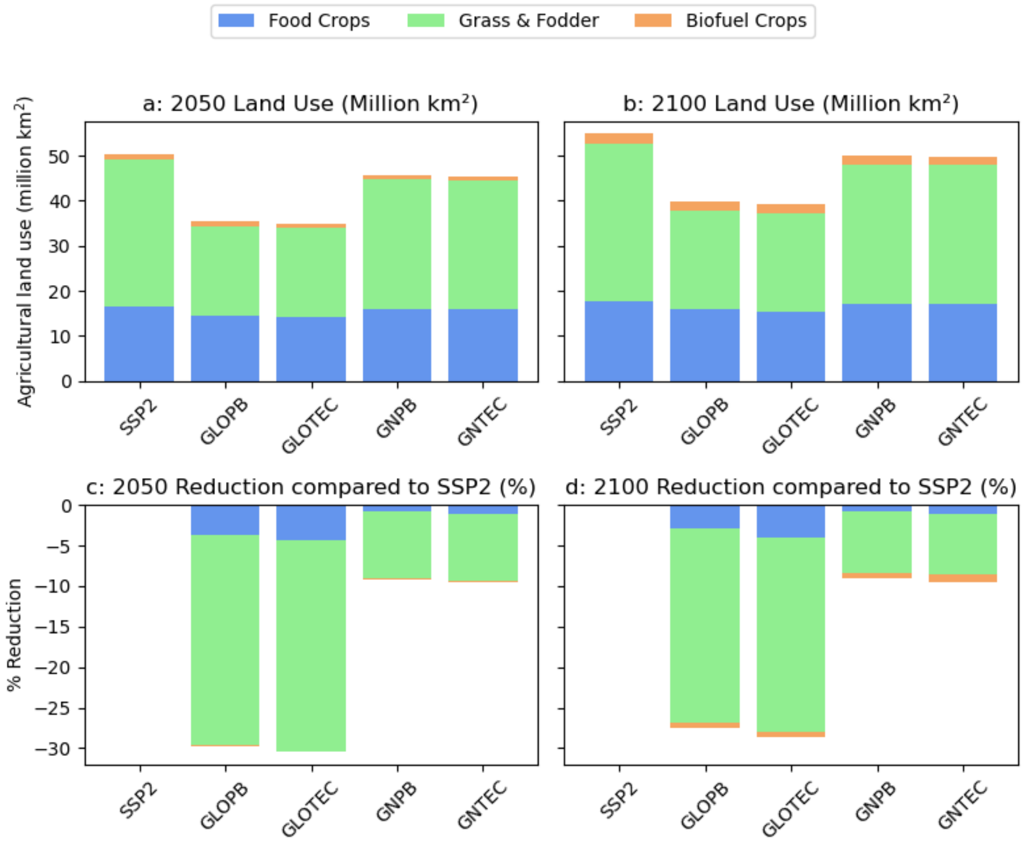


Figure 17 shows the agricultural land use in more detail, including the share of different land-use types in the total, and the difference between the new scenarios and the baseline in 2050 and 2100.

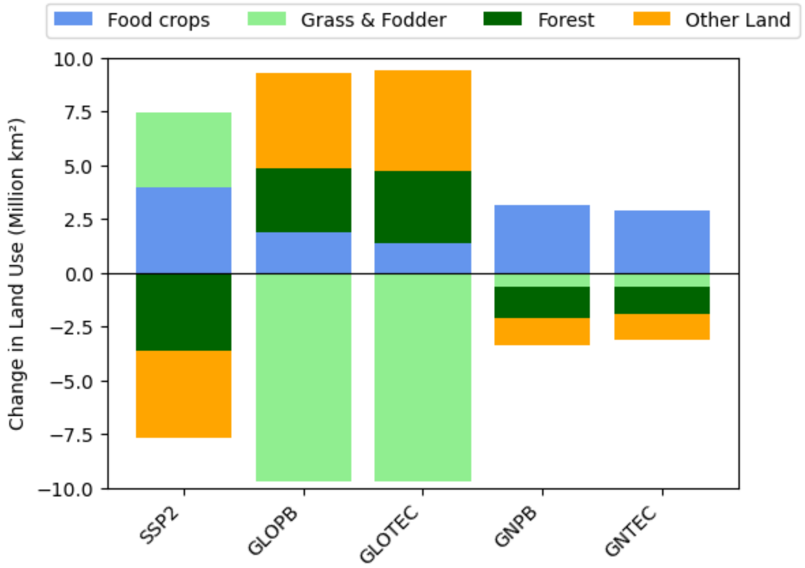
Figure 17: Agricultural land use per type in 2050 and 2100, totals and percentage difference to SSP2, for the storyline scenarios



Overall, Figure 17 shows that there is little difference in land-use between the approaches taken to replacing animal-source foods, either globally or in the Global North. As with the maximum potential scenarios, the reduction in agricultural area is achieved mostly due to a large reduction in land use for grass and fodder. The scenarios with an emphasis on technological solutions, GLOTEC and GNTEC, outperform the scenarios that emphasize plant-based diets, but the differences are very minor. In GLOPB, a reduction compared to the baseline of 27.4% is realized. In GLOTEC, this is 28.8%. The reduction compared to the baseline in GNPB is 9.0%, and in GNTEC this is 9.6%. The reason that the technology-focused scenarios lead to more land use reduction than the scenarios that emphasize plant-based diets, while the latter two scenarios have a larger reduction in crop production (see Figure 15), is the fact that the cultivated meat which is widely implemented in GLOTEC and GNTEC, requires a lot of maize as a feedstock, with a higher yield than the soybeans which are the most important crop in GLOPB and GNPB. Furthermore, it can be seen that, in each scenario, there is an increase in land used for biofuel crops. This is a result of the fact that there is an increase in biofuel demand in each scenario, as fossil fuels are phased out.

In Figure 18, land-use change between 2020 and 2100 is plotted for the storyline scenarios. In GLOTEC and GLOPB, there is a large reduction in land use for grass and fodder. This land is used instead for forest, food crops and other land use, which all see an increase. In GNTEC and GNPB, there is a slight decrease in land for grass and fodder, forest area, and other land use, which is used instead for food crops.

Figure 18: Global land-use change in the period 2020-2100 for the maximum potential scenarios



In the sensitivity analysis in Section 4.3, the potential impact of small variations of ingredient and feedstock requirements on the land-use results is discussed. Naturally, the global scenarios have a larger potential to reduce land use, but considering that the Global North only represents 15.2% of the global population, the fact that the Global North scenarios still yield roughly one third of the land use reduction of the global scenarios suggests that dietary change in the Global North has a larger per-capita impact than in the Global South.

4.2.3 Water use

Figure 19: Yearly global water consumption, including irrigated water, livestock servicing water and water use in manufacturing of alternatives, for the storyline scenarios

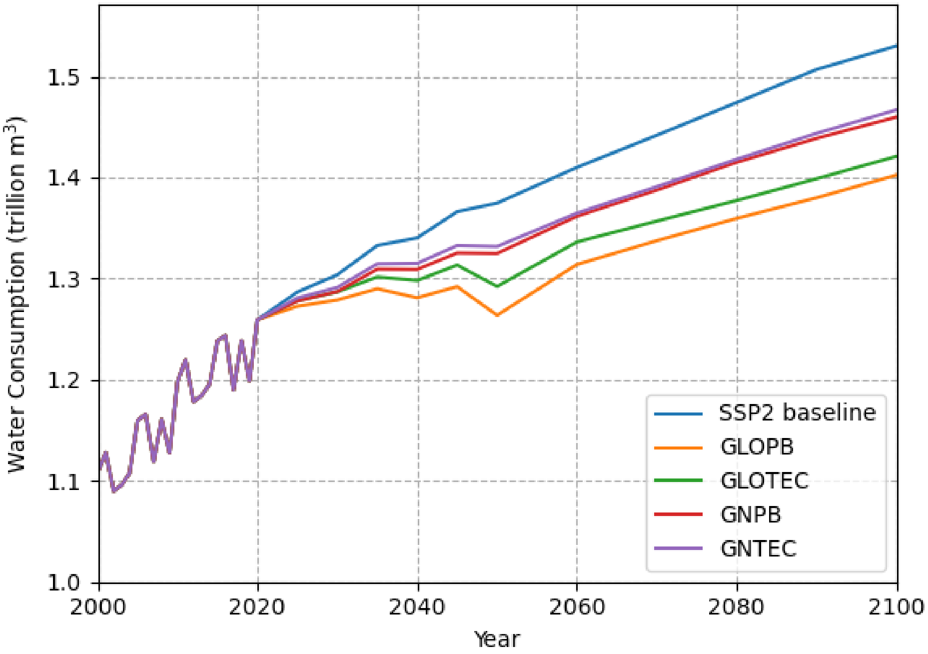


Figure 18 displays the trend for water consumption in the storyline scenarios. GLOPB needs the least water for crop irrigation, livestock servicing and the production of alternatives, with water demand reaching 1.40 trillion m^3 by 2100 in this scenario, a reduction of 8.5% compared to the baseline. For GLOTEC, this is slightly more at 1.42 trillion m^3, a 7.2% reduction. The trends for the Global North scenarios, GNTEC and GNPB, are very close to each other throughout the modeled time period. By 2100, the water demand in GNTEC is 1.47 trillion m^3, compared to 1.46 trillion m^3 for GNPB. These are reductions of 3.9% and 4.5%, respectively. In Figure 19, the separate contributors to this total water demand are displayed. It can be seen that irrigated water consumption is by far the largest factor, followed by livestock servicing water. Water consumption for the production of the novel alternatives is too small to even show up on the plot, except for in GLOTEC, but even there it is still the smallest factor in the overall total.

Figure 20: Water consumption in 2100 by category for the storyline scenarios

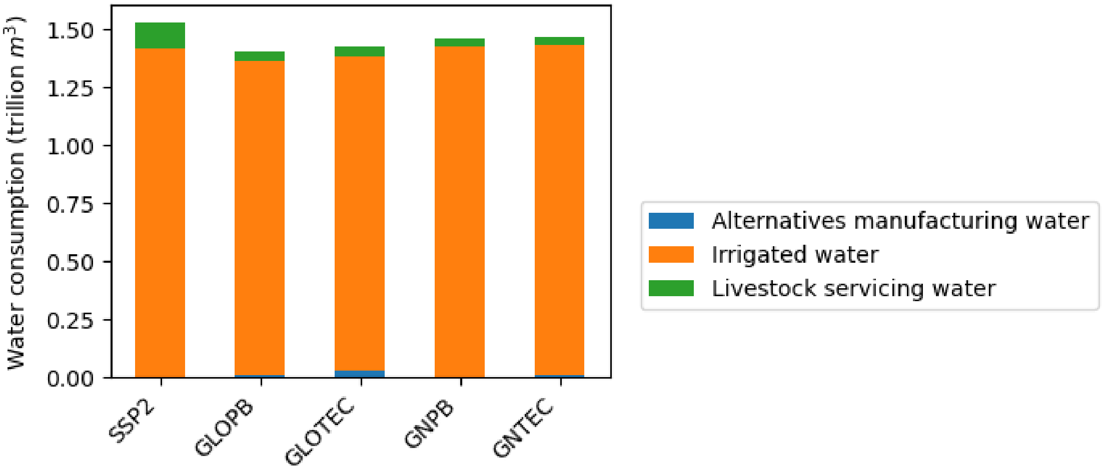
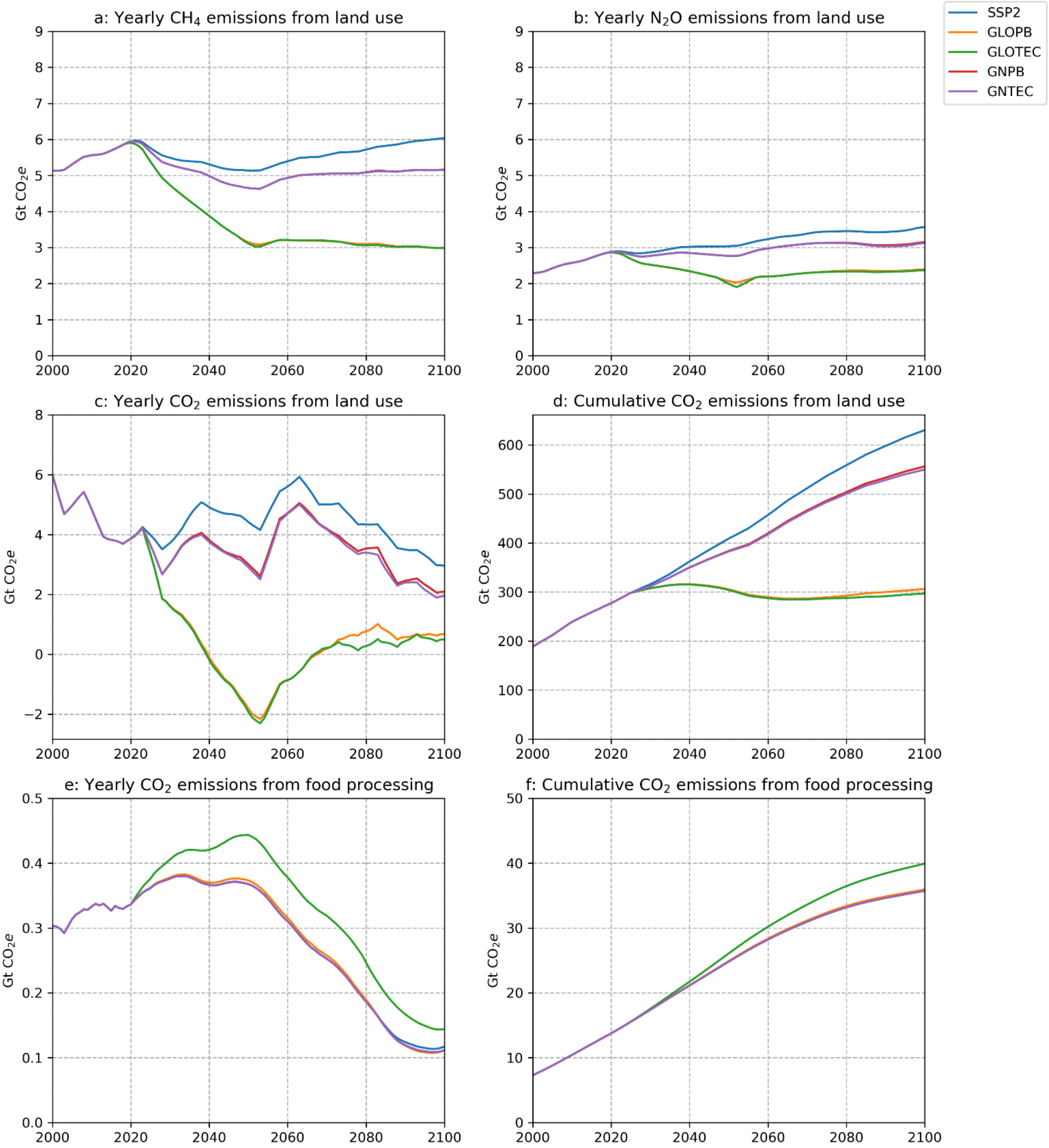


Figure 21: Cumulative CH4, CO2 and N2O emissions from land use in the storyline scenarios



4.2.4 GHG Emissions

Figure 20 displays GHG emissions of the three key greenhouse gases, CH_4, N_2O, and CO_2 for each of the scenarios.

In Figure 20a and 20b, it can be seen that the trends for land-use CH_4 and N_2O emissions are almost identical for the two global scenarios, and for the two Global North scenarios. As discussed in Section 4.1.4, this is because the emissions of these gases is dominated by livestock, and livestock farming follows the same pre-determined trend in each pair of scenarios. In GLOPB and GLOTEC, CH_4 emissions reach 3.0 Gt CO_2e by 2100, less than half of the 6.1 Gt CO_2e seen in the baseline. In GNTEC and GNPB, CH_4 emissions reach 5.2 Gt CO_2e in 2100, a decrease of 15% compared to the baseline.

Land-use N_2O emissions reach 3.6 Gt CO_2e in 2100 in the baseline. For GLOPB and GLOTEC, this is 33% less at 2.4 Gt CO_2e. In GNPB and GNTEC, emissions reach 3.2 Gt CO_2e, a decrease of 12%.

As seen in Figure 20c and 20d, there is also not much to differentiate GLOPB from GLOTEC, or GNPB from GNTEC, in terms of land-use CO_2 emissions. In GLOPB and GLOTEC, we see that these emissions become negative around 2040, with a peak around 2052. For GLOPB, this peak is -2.2 Gt CO_2e, and for GLOTEC it reaches -2.4 Gt CO_2e. After this peak, the emissions rise until they become positive again in 2067 and by 2100 reach 0.6 Gt CO_2e in GLOPB and 0.5 Gt CO_2e in GLOTEC. Overall the land-use CO_2 emissions are slightly higher in GLOPB, owing to the fact that GLOPB requires slightly more agricultural land use, as seen in Figure 16. This is reflected in the cumulative emissions shown in Figure 19d. Cumulative land use CO_2 emissions in 2100 reach 306 Gt CO_2e in GLOPB and 296 Gt CO_2e in GLOTEC, both less than half of the 630 Gt CO_2e value in the baseline.

Land-use CO_2 emissions in 2100 are 2.1 Gt CO_2e in GNPB and 1.9 Gt CO_2e in GNTEC, decreases of 29% and 33% compared to the baseline, respectively. Cumulative land-use CO_2 emissions reach 556 Gt CO_2e by 2100 in GNPB, and 550 Gt CO_2e in GNTEC. These values represent decreases compared to the baseline of 11% and 12%, respectively.

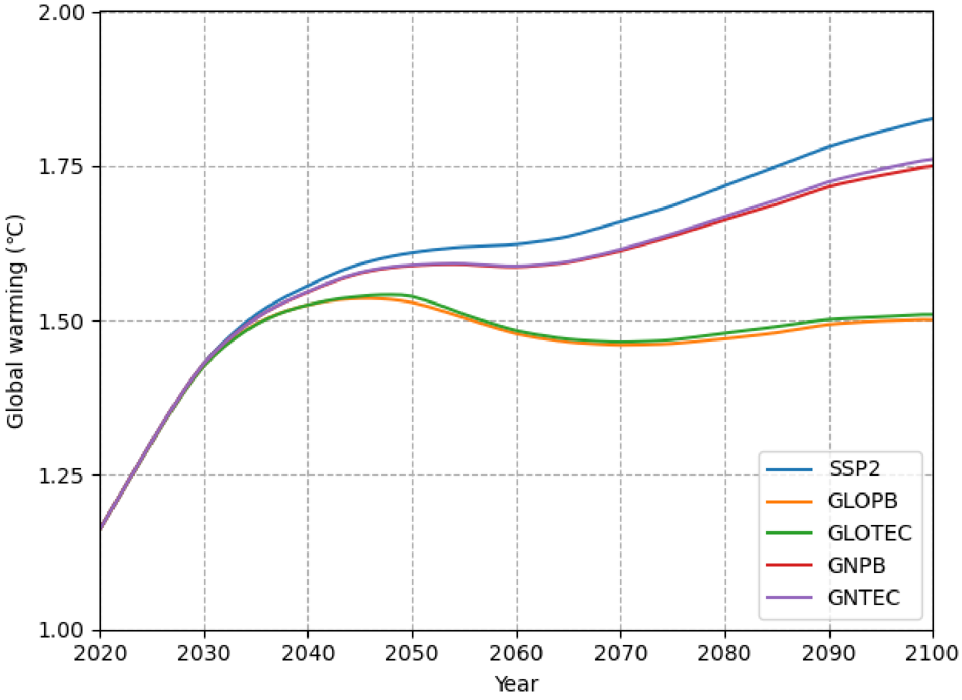
Figure 19e shows that the food processing CO_2 emissions remain nearly equal to the baseline values in each scenario except GLOTEC. It is noteworthy that this is also the case for GNTEC, in which there is large-scale adoption of cultivated meat in the Global North. The fact that this does not lead to notably higher food processing emissions is because, under the SSP2-2.6 baseline assumptions, the energy sector is highly decarbonized in the Global North, leading to low emissions from energy use there. This is less so the case for the Global South, where in GLOTEC there is high energy demand for cultivated meat production, leading to higher emissions.

Having discussed emissions in the storyline scenarios, the following section will present the resulting effects of these emissions on global warming.

4.2.5 Global warming

In Figure 20, the trends in global warming in the storyline scenarios are graphed. The global scenarios lead to a large reduction in global warming by 2100, with GLOPB limiting it to 1.50°C, and GLOTEC limiting it to 1.51°C, compared to 1.85°C in the baseline, reductions of 3.5°C and 3.4°C, respectively . The Global North scenarios have less potential to reduce global warming, with GNTEC leading to 1.76°C of warming by 2100, and GNPB resulting in 1.75°C, reductions of 0.09°C and 0.10°C, respectively.

Figure 22: Global warming in the storyline scenarios



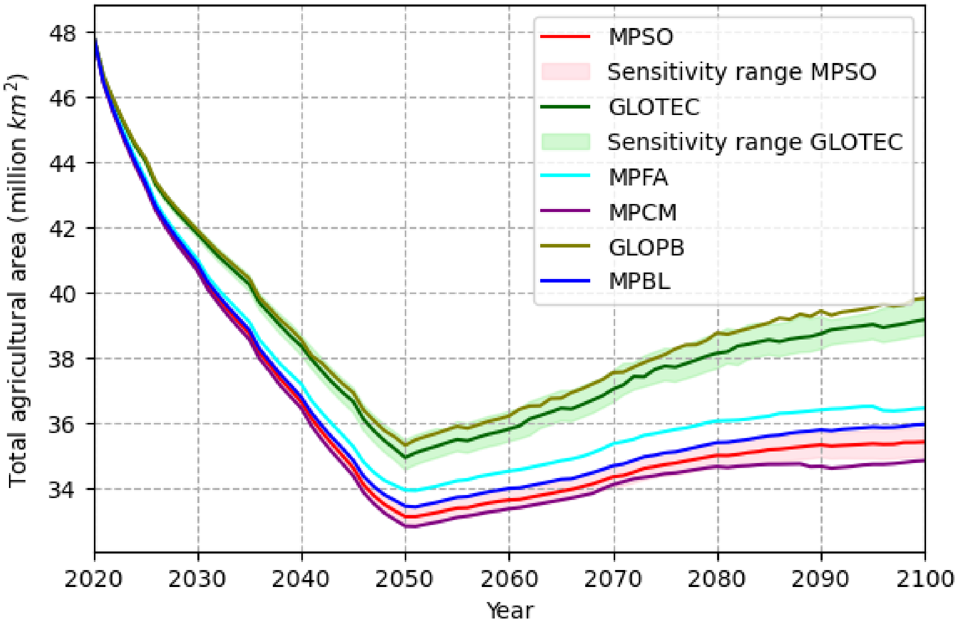
4.3 SENSITIVITY ANALYSIS

In this section, the results of the sensitivity runs are presented and assessed. This is done by presenting the results of SRSH and SRSL as the boundaries of an area around the results of MPSO to show the extent to which the results of MPSO might vary based on small variations of the input variables. The same is done for GLOTEC and the associated sensitivity runs SRGTH and SRGTL.

For the sake of brevity and conciseness, the results are only displayed for land use and global warming. This is done because water consumption, which is dominated by irrigated water demand as seen above, is linked strongly to land use, and the differences in emissions are ultimately reflected in global warming. Analysis of the sensitivity of land use and global warming therefore paints a complete picture with all the necessary information.

Figure 21 shows the agricultural land use results of the sensitivity runs, zooming in on the land use results and additionally plotting MPFA, MPBL, MPCM and GLOPB to see if these scenarios fall within the calculated uncertainty ranges.

Figure 23: Land-use area results of sensitivity analysis

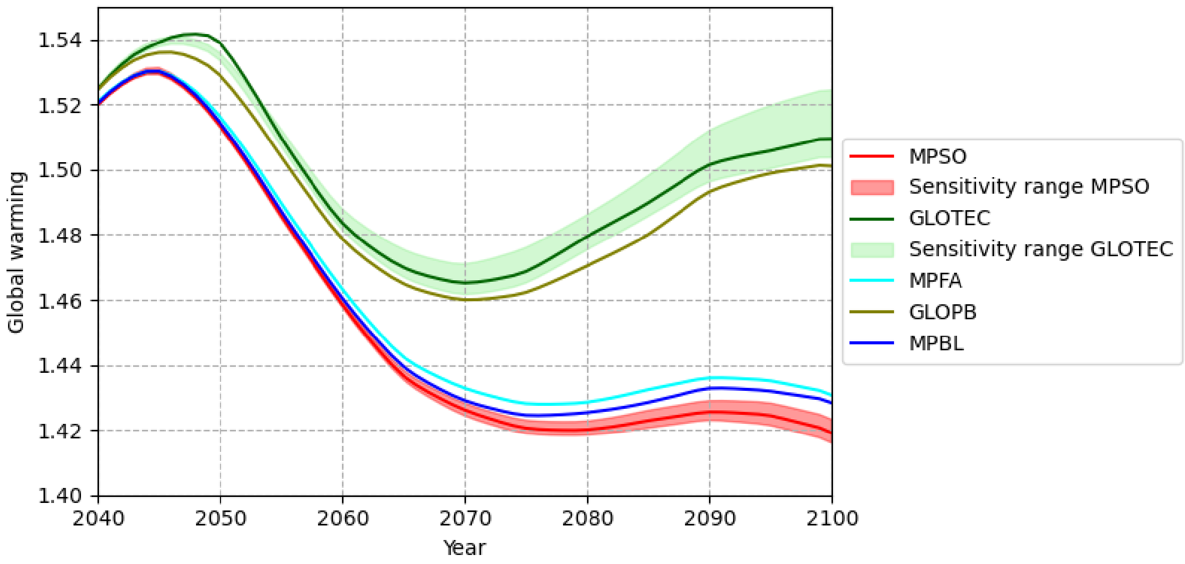


As seen in Figure 21, the land-use results of GLOPB fall within the sensitivity range for GLOTEC. This suggests that GLOPB could perform better than GLOTEC in terms of land use, if the real-world development of crop requirements for cultivated meat and plant-based meat analogues turn out slightly differently than the data used in this research. The same can be seen for MPCM and MPBL, which fall just within the sensitivity range of MPSO for the majority of the modeled time period, while MPFA does not.

Sensitivity runs were not performed for MPCM, MPFA, or the other maximum potential scenarios. However, the size of the sensitivity range of MPSO and the relative closeness of the results for all the meat-replacing maximum potential scenarios observed in Figure 6 suggests that there would be significant overlap between the sensitivity ranges of most of these scenarios, even if the input variables are only varied by a relatively small 15%.

Figure 22 plots global warming in MPSO and GLOTEC with their sensitivity ranges together with MPFA, MPBL and GLOPB. Unlike with the results for land use, we don’t see the MPFA, MPBL or GLOPB falling within the sensitivity range of MPSO or GLOTEC, but the results are still so close that, had sensitivity runs been carried out for MPFA, MPBL or GLOPB, there would be overlap between the sensitivity ranges.

Figure 24: Global warming results of sensitivity analysis



As a result, ranking the performance of the different animal-source food alternatives based on this modeling analysis should be seen as indicative rather than absolute, since small variations in the values used to establish the crop and resource demands of the scenarios could change the ranking of the scenarios. This is relevant since the ingredients and/or feedstock demands of the different options used in this research were established through literature review, and certain inferences had to be made in order to use the data in this modeling analysis. The recipes for the soy- and faba-based meat analogues, for example, were intentionally simplified in order to deal with the wide heterogeneity of commercially available options. As shown in the sensitivity analysis, this uncertainty is significant enough to potentially change the outcome when comparatively ranking the different animal-source food alternatives in terms of the studied environmental impacts.

5 CONCLUSIONS

In this chapter, the results presented in Chapter 4 are used to answer the research questions. The significance of these conclusions, as well as recommendations for future research, are subsequently presented in Chapter 6.

5.1 RESEARCH QUESTION 1

What are the environmental impacts of scenarios in which different animal-source food alternatives fully replace their animal-source equivalent?

The results of the maximum potential scenarios enable this subquestion to be answered. In each of the maximum potential scenarios, the environmental benefits are substantial. In the scenarios which replace meat, agricultural land use is reduced by by 32-39%, water consumption by 8-12%, CH_4 emissions by 60%, N_2O emissions by 44%, land-use CO_2 emissions by over 100%, and global warming is reduced by up to 0.43 degrees Celsius.

Replacement of milk by plant-based options can reduce agricultural land use by 6-7%, CH_4 emissions by 14%, N_2O emissions by 14%, land-use CO_2 emissions by 44-47%, and reduce global warming by up to 0.1 degrees Celsius.

Table 8 ranks the maximum potential scenarios in terms of performance in each environmental impact category, as modelled using IMAGE. MPSS, the scenario in which meat is replaced by a soy-based meat analogue, and milk is replaced by soy milk, performs the best, since it is the only scenario in which all animal-source foods are replaced at the same time.

Table 8: Ranking of the maximum potential scenarios per impact category

	Land use	Water consumption	CH_4 and N_2O emissions	CO_2 emissions	Global warming
Scenarios ranked from best to worst performance	1. MPSS 2. MPCR 3. MPCM 4. MPSO 5. MPBL 6. MPFA 7. MPSM 8. MPOM	1. MPSS 2. MPCR 3. MPBL 4. MPSO 5. MPFA 6. MPCM 7. MPSM 8. MPOM	1. MPSS 2. MPCR, MPCM, MPBL, MPFA, MPSO 3. MPSM, MPOM	1. MPSS 2. MPCR 3. MPCM 4. MPSO 5. MPBL 6. MPFA 7. MPSM 8. MPOM	1. MPSS 2. MPCR 3. MPSO 4. MPBL 5. MPFA 6. MPCM 7. MPSM 8. MPOM

Out of the individual meat alternatives, the cricket-based product performs best in each category. Cultivated meat is second-best in terms of land use and CO_2 emissions, but ranks fifth in terms of water consumption and global warming. Note that, though MPCM scores slightly better than MPSO, MPBL and MPFA in terms of CO_2 emissions and equal in terms of CH_4 and N_2O emissions, it performs slightly worse in terms of global warming. This can be attributed to a slight difference in emissions of other greenhouse gases that were not presented in Figure 11.

The diet based on beans and legumes is second-best in terms of water consumption, fourth in terms of CO_2 emissions and land use, and third in terms of global warming.

The soy-based meat analogue scores second-best in terms of global warming, and third for CO_2 emissions, land use and water consumption. The faba-based meat analogue ranks fourth in terms of water consumption and global warming, and fifth and last in terms of land use and CO_2 emissions. Out of the two plant-based milks assessed, soy milk outperforms oat milk in each impact category.

Overall, the cricket-based product is the option that performs best in the modeled analysis. This is an interesting result, since it is the only one of the options that is technically an animal-source food itself. However, as shown in the sensitivity analysis in Section 4.3, the results of each of the modeled alternatives are very close together, to the extent that minor variations in the alternatives' composition, crop demand, water consumption and energy demand have the potential to completely change the ordering of the different options.

Keeping this in mind, the different options cannot be conclusively ranked. The ranking provided in Table 8 must therefore be seen as an indication.

A much more definitive conclusion to be made is the fact that each of the modeled animal-source food alternatives offers substantial benefits in terms of each of the four assessed environmental impact categories, compared to the baseline scenario. The differences *between* the different alternatives are much smaller than the overall environmental benefit offered by moving away from animal-source foods *at all*. This is the case even for cultivated meat, with its high energy use.

5.2 RESEARCH QUESTION 2

What are the environmental impacts of global dietary change scenarios, in which different animal-source food alternatives are adopted according to distinct storylines?

The global storyline scenarios, in which two-thirds of animal-source food consumption is replaced by different alternatives, lead to a reduction of 27-29% in agricultural land use, 7.2-8.5% in water use, 51% in CH_4 emissions, 33% in N_2O emissions, 51-53% in land-use CO_2 emissions, and up to 0.35°C less global warming.

In the Global North scenarios, agricultural land use is reduced by 9.0-9.6%, water consumption by 3.9-4.5%, CH_4 emissions by 15%, N_2O emissions by 15%, land-use CO_2 emissions by 29-33%, global warming by 0.09-0.10°C.

Compared to the relatively small population size of the Global North, the impact of the scenarios in which dietary change occurs only there is substantial. In 2100, the Global North comprises only 15.2% of the global population. Yet, the scenarios in which dietary change occurs only in the Global North achieve approximately one-third of the land-use reduction and global warming reduction of the global scenarios and half of the reduction in water consumption. This happens even though the consumption of animal-source foods in Global South regions increases greatly in the SSP2 baseline.

In Table 9, the storyline scenarios are ranked in terms of their performance in each of the environmental impact categories, as a recapitulation of the results presented in Section 4.2. This allows research question 2 to be answered.

For land use, CH_4, N_2O and CO_2 emissions, the scenarios in which technological solutions are emphasized, GLOTEC and GNTEC, outperform the scenarios with a focus on plant-based diets, GLOPB and GNPB.

Similar to what was seen for the maximum potential scenarios, the scenarios with a focus on plant-based diets score best in terms of global warming, despite scoring slightly worse in terms of GHG emissions. Again, this can be attributed to emissions of other GHGs that were not discussed in this paper.

The scenarios with a focus on plant-based diets also outperform the technology-focused scenarios when it comes to water consumption.

Table 9: Ranking of the storyline scenarios per impact category

	Land use	**Water consumption**	**CH_4 and N_2O emissions**	**CO_2 emissions**	**Global warming**
Scenarios ranked from best to worst performance	1. GLOTEC 2. GLOPB 3. GNTEC 4. GNPB	1. GLOPB 2. GLOTEC 3. GNPB 4. GNTEC	1. GLOTEC 2. GLOPB 3. GNTEC 4. GNPB	1. GLOTEC 2. GLOPB 3. GNTEC 4. GNPB	1. GLOPB 2. GLOTEC 3. GNPB 4. GNTEC

As was the case for the maximum potential scenarios, however, the sensitivity analysis of these scenarios showed that the results are so close together that minor variations in the alternatives' composition, crop demand, water consumption and energy demand have the potential to change the ordering of the different options. Therefore it cannot be conclusively stated that one scenario outperforms the other. Still, the results of this scenario analysis are valuable. They show that replacing two-thirds of animal-source food consumption by alternatives leads to substantial environmental benefits. In these scenarios, one in every three meals in which animal-source foods are consumed are unaffected by the dietary change. As a result, the cultural and culinary importance that animal-source foods carry for many people can still be enjoyed often.

The significance of these conclusions to the academic literature and societal stakeholders is further elaborated on in the following chapter, and methodological limitations are discussed.

6 DISCUSSION

In this chapter, the contributions to the literature and to society achieved by this research are reflected upon. Next, the limitations of the applied methods are discussed and recommendations for future research are made.

6.1 CONTRIBUTIONS TO LITERATURE AND SOCIETY

Summarizing the conclusions presented in the previous chapter, two main takeaways can be made from the results of this research.

The first is that the differences in environmental impact between different animal-source food alternatives are very minor compared to the large effect that moving away from animal-source food products at all makes. This research project set out with the intention to quantify the environmental benefits of dietary change to animal-source food alternatives, which was successfully done – the benefits are substantial. Dietary change away from animal-source foods has the potential to turn a scenario in which the 'well below 2°C' target from the Paris Agreement is achieved, into a scenario in which the more ambitious climate target of limiting global warming to 1.5°C is achieved. Dietary change is thus a very powerful tool to combat climate change. Furthermore, this research aimed to compare the environmental impact of the different options, in order to recommend certain options ahead of others. Based on the model results, a ranking of the different options was made per category, which was presented in the previous chapter. The sensitivity analysis, however, showed that the differences between the options are very small, and the relative ranking is sensitive to small changes in composition and resource demands. The same was true for the storyline scenarios, in which two approaches which are very different at face value – a plant-based mindset or a focus on technological fixes – ended up with barely any difference between them in terms of environmental impact. This makes the main outcome of this research - that as long as you're replacing animal-source food products you can expect to see significant environmental benefits, regardless of which option you choose – a valuable addition to the literature in the field. An analysis of the different options such as the one performed in this research had not previously been performed, and thus this somewhat surprising, and valuable, conclusion was not known.

Additionally, it means that easily understandable, policy-relevant recommendations can be made to interested policymakers and other stakeholders. Since there is little difference in the environmental performance of the different options, those aiming to make the global food system more sustainable may choose to focus their efforts on promoting the option that is most acceptable to the public. What option this might be is, of course, heavily dependent on cultural, culinary and economic factors.

Furthermore, the analysis of scenarios in which dietary change takes place in the Global North showed that these regions have a disproportionally large potential to aid food system sustainability. The per-capita impact of dietary change to animal-source food alternatives is much larger in the Global North regions. When additionally considering that these regions have historically been responsible for the majority of animal-source food consumption, a justice-based argument can be made that the Global North has the responsibility to lead the way in a global transition to sustainable protein sources.

6.2 LIMITATIONS AND RECOMMENDATIONS

Being a highly advanced Integrated Assessment Model, IMAGE is one of the best-suited modeling tools available for this research. Nevertheless, some aspects of the model and its mechanisms, as well as the methods by which the model was applied, come with limitations. These are discussed in this section, and recommendations for future research to address them are made.

6.2.1 Stylized prescription of agricultural production

The dietary change scenarios were implemented in IMAGE using a stylized approach, in which animal-source foods are replaced at the same rate in each IMAGE region, and the resulting production of crops is prescribed exogenously based on calculations made outside the model. The simplification had to be made that the animal-source food alternatives and their requisite ingredients and resources are produced within the region that consumes them. As a result, potential global dynamics in the production of the alternatives are ignored. For example, certain countries may produce more of the ingredients for these analogues than is consumed for the purpose of export. Conversely, other regions could import large parts of the required ingredients rather than producing them domestically. These global dynamics may have an impact on the distribution of land use and water consumption as well as the resulting emissions and global warming.

Such global economic dynamics as described above could not be modeled using the approach taken in this research. In IMAGE, it could possibly be done using the agricultural-economical submodel MAGNET, which is able to model aspects like import and export of agricultural goods. Modifying MAGNET to be able to do this for the animal-source food alternatives would, however, have been a time-consuming activity and was deemed to be outside the feasible scope of this research. This would be a substantial improvement in future research and is recommended. It could allow future research to link the consumption of novel animal-source food alternatives to economic factors like GDP in a similar way to how meat consumption currently is. This could yield many interesting and relevant results and add an entirely new use-case to the IMAGE modeling framework.

Because of this limitation, it is mostly the model results at the global scale that are interesting and meaningful to analyze. It is for this reason that the results presented in Chapter 4 are focused on global-scale trends. Despite this limitation, the methods applied in this research yield global results that enabled the conclusions presented in Chapter 5, and provided an important contribution to the literature in doing so.

6.2.2 Crop residues and by-products

In determining the necessary crop production to produce the animal-source food products, the assumption is made that all these crops are farmed specifically for that purpose. The usage of by-products and residue streams of other food system processes as ingredients or feedstocks is excluded. This simplification may have an impact on the results of the scenarios. This is particularly relevant for the scenarios with cultivated meat and cricket farming, since here crops are not used as ingredients for a food product, but rather as a feedstock for further biological processes in these scenarios. It is conceivable that these feedstocks could come from residual streams of maize, soy or cereal products. For cricket farming, this is already common practice (Halloran et al., 2017).

The employment of residual streams could further reduce the required virgin crop production and have an additional impact on the resulting land use, water consumption, emissions and global warming. Consideration of the possibilities of using crop residues for animal-source food alternative production is recommended for future research.

6.2.3 Efficiency gains and technological development

In this research, the ingredients, feedstocks, energy and water required to produce animal-source food alternatives is kept constant throughout the modeled time period. This simplification was made to keep the scope of the research feasible within the allotted time. The sensitivity ranges provide some insight into what the results may look like if these variables did change over time.

As the scale at which the alternatives are produced increases, it is possible that these production processes become more efficient, as the production technology is developed and refined. This could particularly play a role for cultivated meat, which is still in its technological infancy, and may see rapid gains in resource efficiency as the cultivation technology develops.

Introduction of a dynamic by which the resource consumption of the production of the alternatives becomes more efficient as global production increases would be a worthwhile addition in further research.

6.2.4 Limitation of extensification

In the IMAGE-land runs, extensification of agricultural area is explicitly disallowed (see Section 3.3.3). This means that, as the demand for crop production decreases, the model allocates less land for the production of crops at an equal intensity as before, and makes the leftover land that is no longer needed for crops available for other land-use categories, such as nature. If extensification were allowed, which is a possibility in the model, this would not necessarily happen. Instead, it may occur that the overall agricultural area does not decrease as a result of the decrease in crop production, but rather remain equal with a lower production intensity in that area. This is called extensification.

To investigate the maximum potential land-use reduction in the scenarios, it was decided to disallow extensification, but this is a simplification of much more complex real-world dynamics. Model runs in which extensification is allowed, or partially allowed, could provide additional insights into the land-use effects of dietary change.

6.2.5 Impact of baseline selection

After deliberation, SSP2-2.6 was chosen as the baseline for this research, for the reasons outlined in Section 2.3. The baseline scenario and the underlying assumptions had an impact on the final results of this research. In SSP2-2.6, global warming is limited to 1.85°C. It could be argued that this is in itself a very ambitious benchmark, in which the Paris Agreement targets are already being met even before the modeled dietary shifts are applied. The relative impact of the dietary change scenarios could look different if a different baseline scenario was selected. Particularly, emissions from food processing could play a much larger role if the energy system isn't decarbonized to the same extent it is in SSP2-2.6. This is especially relevant for cultivated meat, the production of which is very energy-intensive. In further research, it is highly recommended to perform the analysis based on multiple baseline scenarios, to gain further insight into the effect of dietary change to animal-source food alternatives.

6.2.6 Nutrition and health aspects of animal-source food replacement

In this research, animal-source food products were replaced on a mass basis. This was done partly to facilitate easier implementation in the IMAGE model, and partly because it was deemed more reasonable that people would replace parts of their food intake on a mass basis, rather than counting other nutritional values such as protein content for each meal.

In Table 6, the approximate protein content of the researched animal-source food alternatives is listed. Care was taken to ensure that the protein content of the alternatives did not deviate widely from the protein content of the equivalent animal-source food, so that none of the scenarios would introduce a large protein deficit.

However, a global dietary transition to animal-source food alternatives in the real world will have an impact on nutritional intake. This is particularly the case for plant-based meat and dairy alternatives, since there may be differences in nutritional quality between animal-source proteins and plant proteins. Furthermore, animal-source products contain many other important micronutrients that are not necessarily present in the alternatives, but may be added through fortification.

An additional health concern regarding plant-based meat analogues in particular is that they are considered ultra-processed. Potential negative health impacts of ultra-processed foods have recently become widely recognized (Lane et al., 2024). Consumer perception of plant-based meat analogues as ultra-processed and unhealthy may reduce the potential of these alternatives to replace meat.

Analysis of nutrition and health aspects of the modeled scenarios was outside the aim and scope of this research. The interested reader is referred to Nájera Espinosa et al. (2024), a comprehensive and recent overview of the evidence regarding nutrition and health aspects of plant-based animal-source food alternatives. This study posits that the health effects of these alternatives is highly dependent on their ingredients and production method, but that replacement of animal-source foods with carefully selected plant-based alternatives may have positive health impacts in high-income settings. Due to the novelty of the technique, potential (long-term) health impacts of cultivated meat consumption have not been researched at the time of writing.

Further research into the health and nutrition impacts of global dietary change to animal-source food alternatives is recommended. Additionally, it would be valuable to compare these impacts to potential health and nutrition effects of climate change in a baseline scenario, to evaluate whether there is a net benefit to dietary change away from animal-source foods.

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APPENDIX

A.1 INGREDIENTS CALCULATIONS

A.1.1. Soy-based meat-analogue

Recipe per kg: 700g hydrated soy TVP, 200g vegetable oil, 100g cereal flour

Protein content dry soy TVP: 51.5%, dry soy TVP: 23% (Hong et al., 2022)

Ratio dry to hydrated TVP: 23/51.5 = 0.446

Per kg of hydrated TVP, 446g of dry TVP and 1000-446 = 554g of ingredient water

Plus 17.5 L of process water (Saerens et al., 2021)

Per kg of dry TVP, 1.08 kg soy meal (Saerens et al., 2021)

Per kg of soy meal, 1.21 kg soybean (Dalgaard et al., 2008)

Tropical oil crop milling yield: 47% , Temperate oil crop milling yield: 35% (Waseem et al., 2017)

Cereal flour milling yield: 70% (Baasandorj et al., 2015; Pourmehdi & Kheiralipour, 2020)

Energy consumption:

Soy meal milling: 0.427 MJh/kg, 0.0432 MJe/kg (Pourmehdi & Kheiralipour, 2020)

TVP production: 0.936 MJe/kg (Saerens et al., 2021)

Vegetable oil production: 0.672 Mje/kg (Waseem et al., 2017)

Cereal milling: 0.42 MJe/kg, 0.03 MJh/kg (Baasandorj et al., 2015)

Pressing of patty from ingredients: 0.081 MJe/kg (Saerens et al., 2021)

To produce 1kg of soy-based meat analogue:

Soybeans: 0.7 * 0.446 * 1.08 * 1.21 = 0.41 kg

Water: 0.7 * (17.5 + 0.554) = 12.6 L

Electricity: 0.7 * 0.446 * (0.936 + 1.08*0.0432) + 0.2 * 0.672 + 0.1* 0.42 + 0.081 = 0.56 MJe/kg

Heat: 0.7 * 0.446 * 1.08 * 0.427 + 0.1* 0.03 = 0.15 MJh/kg

Tropical oil crops: 0.2 / 0.47 = 0.43 kg, Temperate oil crops: 0.2/0.25 = 0.57 kg

Cereal: 0.1 / 0.7 = 0.14 kg

A.1.2. Faba-based meat analogue

Due to lack of separate data, the calculations made for the soy-based meat analogue are used for the faba-based analogue.

A.1.3. Cultivated meat

Table A.1 – Feedstocks per kg of cultivated meat (Sinke et al., 2023)

	Low (SRGTL)	Mid (MCPM, GNTEC, GLOTEC)	High (SRGTH)
soy hydrolysate	0.15 kg	0.212 kg	0.3 kg
amino acids from conventional production	0.05 kg	0.071 kg	0.1 kg
maize glucose	0.32 kg	0.4 kg	0.5 kg
salt	0.1 kg	0.224 kg	0.5 kg

Due to lack of data, the assumption is made that soy hydrolysate is produced from soy at the same efficiency as soy meal.

To produce feedstocks above: (Marinussen & Kool, 2010)

1.21 kg soybean / kg soy hydrolysate

1.682	kg corn / kg corn glucose syrup
10.5	kg corn / kg L-lysine (amino acid)
14	Mje / kg L-lysine
13	Mjh / kg L-lysine

To produce 1kg of cultivated meat:

Table A.2 – Crop requirements per kg of cultivated meat

	Low (SRGTL)	Mid (MCPM, GNTEC, GLOTEC)	High (SRGTH)
Soybean	0.18	0.26 kg	0.36 kg
Maize for amino acids	0.53kg	0.75 kg	1.05 kg
maize for glucose	0.32 kg	0.67 kg	0.84 kg
Total maize	0.85 kg	1.42 kg	1.89 kg
Salt	0.1 kg	0.224	0.5 kg
Heat for cultivation	8.3 MJ	8.3 MJ	8.3 MJ
Electricity for cultivation	80.3 MJ	80.3 MJ	80.3 MJ
Heat for amino acids production	0.7 MJ	1.0 MJ	1.3 MJ
Electricity for amino acids production	0.65 MJ	0.9 MJ	1.4 MJ

A.1.3. Cricket-based product

Ingredients per kg: 0.36 kg cricket powder, 0.1kg vegetables, 0.54 kg water (Halloran et al., 2017)

Due to lack of data, the assumption is made that cricket powder is milled from crickets at the same yield and energy use as soy meal milling. Per kg of cricket powder: 1.21 kg crickets, 0.43 MJh, 0.043 MJe

Feed per kg of crickets: 0.7 kg soy meal, 1.3 kg maize, 0.23 kg rice

Water per kg of crickets (cultivation stage) : 0.54 L

Total per kg of cricket-based product:

Soybeans: 1.21 * 0.36 * 0.7 = 0. 37 kg

Maize: 1.21 * 1.3 * 0.36 = 0.56 kg

Rice: 1.21* 0.36 * 0.23 = 0.10

Water: 0.54 + 0.54 = 1.08

Cricket powder milling: 0.42 MJh/kg, 0.043 MJe/kg

Electricity to press patty: 0.12 MJe/kg

A.1.4 Oat milk

Per liter: 0.13 kg oat meal (Riofrio & Baykara, 2022)

Cereal milling efficiency: 70%

Per liter: 0.13 / 0.7 =0.19 kg oat grains

Electricity: 0.18 MJe for processing, 0.29 MJe for oat milling, 0.19 MJh for oat milling (Riofrio & Baykara, 2022)

Water: 1 L

A.1.5 Soy milk

Per liter: 0.07 kg soybean, 0.03 kg sugar crop, 0.9 L water (Ercin et al., 2012)

Processing energy use unknown, values for oat milk used.

A.2 LIVESTOCK SERVICE WATER CALCULATIONS

The following data were taken from Chapagain & Hoekstra (2003), Tables 3.8 and 3.9.

Table A.3 – Drinking and service water consumption for different livestock types

Unit: m^3	Per day						Yearly	
	Drinking Water		Service water		Total		Total	
	Industrial	Grazing	Industrial	Grazing	Industrial	Grazing	Industrial	Grazing
Beef calf	5	5	2	0	7	5	2555	1825
Beef adult	38	22	11	5	49	27	17885	9855
Dairy Calf	14	11	0	0	14	11	5110	4015
Dairy Heifer	48	24	11	4	59	28	21535	10220

Dairy adult	70	40	22	5	92	45	33580	16425
Swine piglet	1.8	1.8	5	0	6.8	1.8	2482	657
Swine adult	14	8	50	25	64	33	23360	12045
Sheep lamb	0.38	0.3	2	0	2.38	0.3	868.7	109.5
Shep adult	7.6	6	5	5	12.6	11	4599	4015
Goat kid	0.38	0.3	0	0	0.38	0.3	138.7	109.5
Goa adult	3.8	3.5	5	5	8.8	8.5	3212	3102.5
Broiler Chick	0.02	0.02	0.01	0.01	0.03	0.03	10.95	10.95
Broiler adult	0.18	0.18	0.09	0.09	0.27	0.27	98.55	98.55
Laying chick	0.02	0.02	0.01	0.01	0.03	0.03	10.95	10.95
Laying adult	0.3	0.3	0.15	0.15	0.45	0.45	164.25	164.25

Beef cattle: 16.7% of lifetime as calf, 83.3% as adults

Dairy: 10% calf, 20% heifer, 70% adult

Pigs: 15% piglet, 85% adult

Sheep/goats/meat poultry: 10% lamb/kid/chick 90% adult

Laying poultry: 5% chick, 95% adult