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Reduced environmental footprint through novel food production technologies: Four case studies from Finland

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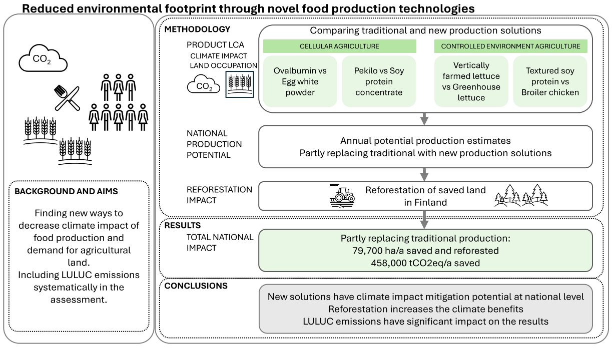
HIGHLIGHTS

- First trial for assessing the impact of multiple new products at national level.
- Including LULUC emissions has a significant impact on the results.
- Using renewable bio-based energy causes large land occupation.
- Side streams lower the impact for cellular agriculture.
- Reforestation of the saved land increases the climate benefits of new solutions.

GRAPHICAL ABSTRACT



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ABSTRACT

New ways to reduce the climate impact and land occupation of agriculture and food production are needed. This study assessed the potential of four new food production solutions to mitigate the climate impact at the national level in Finland by partly replacing conventional food production solutions. The climate mitigation potential of reforestation of saved land was also assessed. The new production solutions assessed represent cellular agriculture and controlled environment agriculture (CEA). The climate impact and land occupation were assessed for the four new production solutions and for four conventional production solutions using life cycle assessment (LCA). Land use and land use change (LULUC) emissions were systematically included in the LCA. The LCA results were scaled up to the national level with estimated production amounts for Finland.

The results showed that these four new solutions can have an impact at the national level when partly replacing conventional solutions. There is mitigation potential in reforestation of the saved land, but the main impact was achieved by replacing conventional production. Cellular agriculture and CEA can provide significant reductions in climate impact, but for CEA reductions in the climate impact depend on the energy sources used. Using low-carbon energy sources ensures that reductions in land occupation can be achieved, as bio-based renewable energy causes large land occupation. The results highlight the importance of considering LULUC emissions in LCAs of conventional agricultural products, especially in areas with organic soils. Decreasing cultivation on organic soils has a high climate impact mitigation potential for conventional food production.

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1. Introduction

Agriculture is directly responsible for 14 % of greenhouse gas (GHG) emissions in Finland (Statistics Finland, 2024), and for 21 % globally (EPA, 2024). In Finland 8 % and globally 38 % of the land area is used for agriculture (Natural Resources Institute Finland, 2024; Ministry of Agriculture and Forestry Finland, 2024; Our World in Data, 2024). The food sector's contribution of total GHG emissions in Finland is around 30 % when considering the whole food sector and cropland-related land use and land use change (LULUC) emissions (Saarinen et al., 2023). Global food production must meet the demands of the growing human population, and at the same time there is an urgent need to decrease the environmental impacts of food production. Converting more area from forestry to agricultural use is not a solution as it leads to deforestation, which causes carbon stock and biodiversity losses. In addition to the replacement of animal-based protein by current plant-based options and improving livestock production system efficiencies (e.g. Röös et al., 2016; van Zanten et al., 2016), one solution could be novel food production technologies, that is, cellular agriculture, and controlled environment agriculture, which is the focus of this research. These new production solutions are expected to enable efficient year-round food and feed production with reduced land area requirements and GHG emissions (e.g. Mazac et al., 2022; El Wali et al., 2024).

Cellular agriculture refers to culturing animal, plant, or microbial cells in bioreactors to produce alternatives to traditional agricultural products (Rischer et al., 2020). Proteins produced through microbes can be classified as single-cell proteins (SCP) or as acellular precision fermented proteins also referred to as recombinant proteins (RP). With SCP the whole cellular biomass is utilized as food or as a feed ingredient. With RP the proteins are produced by micro-organisms and are separated from the cellular biomass.

Plant production in controlled environments usually refers to cultivation in plastic tunnels, greenhouses, or vertical farming. In this article, we defined controlled environment agriculture (CEA) as novel plant factory and greenhouse solutions to grow vegetables and protein plants year-round in optimized growth conditions. This includes vertical farming of lettuce and production experiments for growing soybeans in greenhouses in Finland. Traditionally, soybean is cultivated outdoors in the field, mainly in Brazil and the United States of America, and increasingly in Europe. CEA could also be a potential way to improve the quality of the cultivation of protein-rich crops. Furthermore, CEA enables more crop cycles per year, and the protein yield per square meter of crop could be enormously higher than in the open field (Righini et al., 2024).

A recent Finnish survey (Niemi et al., 2022) highlighted that food system experts and stakeholders view environmental benefits as key in marketing novel products, but these benefits should be supported by scientific LCA results.

Recently, there has been an increasing number of LCAs of novel food production technologies. Järviö et al. (2021a) assessed the environmental impacts of microbial protein (MP) produced by autotrophic hydrogen-oxidizing bacteria (HOB), finding that compared with animal-based protein sources for food production, MP had 53–100 % lower environmental impacts depending on the comparison product and energy source. According to Behm et al. (2022), the climate impact and water scarcity footprint of microbially produced milk protein were of the same magnitude as for extracted dairy protein, but there is significant potential for a reduction when renewable energy and more sustainable carbon sources are used and combined with evolving knowledge and technology in microbial production. Kobayashi et al. (2023) assessed the environmental impacts of yeast-based single-cell protein (SCP), using oat side stream as feedstock and found that compared with conventional products like soy protein concentrate the climate impact and other impacts were higher for the yeast-based SCP. Only land use was smaller for yeast-based SCP. However, their process relied on natural gas for heating and nutrient production, and the average country-specific electricity mixes were used for electricity. This highlights the importance of renewable and low-carbon energy sources (non-combustion-based energy) in cellular agriculture.

Martin et al. (2023) showed that lettuce produced on a large-scale commercial vertical farm in Sweden had a lower climate impact than lettuce production in open fields or greenhouses but for other impact categories, vertical farming might cause higher impacts due to high energy consumption. Joensuu et al. (2024) studied the environmental impacts of vertically farmed lettuce and conventional greenhouse production in Finland with different energy production scenarios. Vertically farmed lettuce with wind power and hydropower and waste heat recovery had the lowest environmental impacts in all impact categories. However, without waste heat recovery and with average energy, vertical farming was not necessarily better than conventional greenhouse production.

Previous research on the environmental impacts of cellular agriculture and CEA shows that these novel food production technologies can reduce the climate and land occupation impacts compared to animal-based and conventional production solutions when certain prerequisites are met (e.g. Behm et al., 2022; Järviö et al., 2021a; Järviö et al., 2021b; Martin et al., 2023; Joensuu et al., 2024). In many cases these novel production solutions are energy-intensive, and the reductions in environmental impacts require the use of renewable or low-carbon energy sources. In cellular agriculture, the carbon source for the microbial process has the second largest impact on climate impact after energy source (Behm et al., 2022; Järviö et al., 2021b).

Most of the research published thus far on cellular agriculture CEA focuses on LCA of a certain product and a comparison with an animal-based option. Some assessments have also been made to estimate the impacts at a larger scale, such as dietary, or global level. Humpenöder et al. (2022) presented an analysis of microbial protein as a substitute for ruminant meat in forward-looking global land-use scenarios toward 2050. Their results showed that by substituting 20 % of per-capita ruminant meat consumption globally with microbial protein by 2050, increases in the global pasture area could be offset, annual deforestation and related CO_2 emissions could be cut roughly in half, and methane emissions lowered. Mazac et al. (2022) estimated with linear programming that global warming potential, water use, and land use could be reduced by over 80 % by replacing animal-based foods with novel or plant-based foods in European diets while also meeting nutritional adequacy and consumption constraints. El Wali et al. (2024) analyzed with a global dynamic model and different LCA scenarios of replacing traditional livestock products with cellular agriculture from 2020 to 2050. They found that compared to current agriculture emissions, a transition to cellular agriculture by 2050 could reduce annual GHG emissions by 52 %, reduce demand for phosphorus by 53 %, and use 83 % less land. According to El Wali et al. (2024), the transition to cellular agriculture is not limited by resource availability and provides a wide range of environmental benefits.

At this stage of the climate crisis, new disruptive ways of reducing the climate impact and land occupation of agriculture and food production are needed. The aim of this study was to estimate the potential of four new food production solutions to mitigate the climate impact at national level in Finland when partly replacing conventional food production solutions. The aim was also to assess as an additional mitigation measure the impact of reforestation of the land area saved by changing from conventional production to new production solutions. The new production solutions assessed represent cellular agriculture and CEA. Land use and land use change (LULUC) emissions were systematically included in the climate impact according to a new specified methodology for including LULUC emissions in LCAs of agricultural and forestry products (Lehtilä et al., 2025).

The work is linked to current Finnish carbon neutrality targets 2035, to find and assess new ways and options for Finland to achieve carbon neutrality. To our knowledge this was the first attempt to map these impacts in Finnish context including LULUC emissions and reforestation.

As cellular agriculture and controlled environment agriculture have global markets, the results are relevant also globally.

2. Materials and methods

The climate impact and land occupation were first assessed for the four new production solutions and for four conventional production solutions using LCA. The product level LCA results were then scaled up to national level to assess the total potential reductions in climate impact and potential reforestation impact.

2.1. Case descriptions

The environmental impacts were assessed for four case studies described in Table 1. The environmental performance of the novel production solutions was compared to conventional production solutions which are also listed in Table 1. Cell-cultured ovalbumin was compared with egg white production. Single-cell protein Pekilo® was compared with soy protein concentrate produced in Brazil as Pekilo® can substitute for soy protein concentrate in fish feed. The soy used in fish feed is often from Brazil (Johansen et al., 2022). Vertically farmed lettuce was compared with greenhouse grown lettuce as that is the prevailing method for lettuce production in Finland. Open field cultivation is only possible during summer in Finland, which is why it was not included in the comparison. Textured soy protein from greenhouse grown soybean was compared to broiler chicken. Broiler chicken was chosen as comparison because it represents on effective way of producing protein for human consumption in a nearly industrialized way. Textured soy products are also often used to replace broiler chicken in diets. All production was assumed to happen in Finland except for soy protein concentrate, which was assumed to be produced in Brazil.

2.2. Life cycle assessment

2.2.1. Goal and scope

The goal of the LCAs was to assess the climate impact and land occupation of four new food and feed production solutions and to compare them with conventional production solutions at the product level.

The functional units used in the case studies were 1 kg of protein (Cases 1, 2 and 4) and 1 kg of lettuce (Case 3). System boundaries were defined as cradle-to-gate and covered all the processes relevant to the production of each product. System boundaries for each case study are described in more detail in 2.2.3. Life cycle inventory and system boundaries for the new production solutions are presented in the supplementary material.

Table 1
Novel production solutions and conventional production solutions studied.

Production solution	Definition of the selected food and feed production solutions studied	Conventional production solution
Case 1 Ovalbumin	Cell-cultured recombinant protein for food: Production of ovalbumin (the most abundant protein in egg whites) in a bioreactor with Trichoderma reesei fungus	Egg white production
Case 2 Pekilo®	Cell-cultured single-cell protein for replacing protein feeds for animals: Pekilo®mycoprotein production from xylitol (from oat hull) side stream feedstocks	Soy protein concentrate production*
Case 3 Vertically farmed lettuce	Automated vertical farming of lettuce based on renewable energy	Greenhouse-grown lettuce
Case 4 Greenhouse soy protein	Year-round production of soybean in greenhouses and processing to textured soy protein for food	Broiler chicken production

* Assumed to be produced in Brazil.

SimaPro 9.5. software package with ecoinvent v3.9.1 database (Wernet et al., 2016) was used for impact assessment calculation and background data. For climate impact, *Environmental Footprint 3.1 (adapted for SimaPro) V1.00* method with global warming potential (GWP) over a 100-year time horizon based on IPCC 2021 (Forster et al., 2021) was used. Land occupation was calculated using the *Selected LCI results V1.06* method in SimaPro (Hischier et al., 2010). Land occupation refers to the continuous use of a certain area of land for a certain period expressed in m^2a (area*time) with no characterization factors.

2.2.2. Energy production scenarios

Cellular agriculture and CEA are energy-intensive technologies, and the energy production profile is likely to dominate the climate impacts. Different energy production scenarios were created to be used in all cases. For heat and steam, the average Finnish heat and average renewable heat were used, based on production in 2022. For electricity, three scenarios were used: average Finnish electricity (2022), average renewable electricity (2022), and low-carbon electricity (non-combustion-based electricity, that is nuclear power and renewable electricity from wind, hydro, and solar). For consistency between the different case studies, the low-carbon electricity scenario was modeled in the same way Järviö et al. (2021b) used for ovalbumin. The aim for creating different scenarios was to assess if cellular agriculture and CEA can be viable in Finland with average energy (largely based on bio-based renewable energy) or if low-carbon energy should always be used. The land occupation of different energy sources should also be considered.

2.2.3. LULUC

Land use and land use change (LULUC) covers the carbon stock changes in land carbon stocks: living biomass, soil (mineral and organic), and dead organic matter (DOM). The Finnish national-level LULUC emissions (CO_2 and CH_4) were assessed according to the methodological framework by Lehtilä et al. (2025) and applied to Cases 1, 2, and 4 as specified below in 2.2.4. Life cycle inventory. In the framework by Lehtilä et al. (2025) LULUC emissions are assessed by utilizing annual national-level GHG inventory data. The framework distinguishes mineral and organic soils which is especially relevant in countries with significant share of organic soil such as Finland. Additionally, the LULUC-related N_2O emissions from the cultivation of drained organic soils were included by employing the IPCC (2014) emission factors.

The data used in the LULUC emissions assessment were derived from the GHG inventory of Finland (Statistics Finland, 2023) for Finnish products. The average share of organic soil cropland (11 %) in Finland was used in all assessed cases.

In case 2 Brazilian soy protein concentrate was used as comparison. Brazil does not participate in National GHG inventory reporting under the UNFCCC and the Kyoto Protocol. The method to estimate the cropland LULUC emissions in Brazil is described more in detail below in 2.2.4. Life cycle inventory.

2.2.4. Life cycle inventory

2.2.4.1. Case 1 Ovalbumin. Case 1 concerned the production of cell-cultured ovalbumin using the fungus Trichoderma reesei and further processing to powder format. Case 1 was assessed using data and results from Järviö et al. (2021b). The system boundary was defined the same as in Järviö et al. (2021b), that is, cradle-to-gate, including the production of raw materials, production of ovalbumin using T. reesei (fermentation and downstream processing), processing to end product in powder format (drying), energy inputs in each phase, and treatment of production waste. The inventory data used by Järviö et al. (2021b) were gathered and estimated from a functioning production-scale pilot. Their results for ovalbumin production in Finland with average electricity and with low-carbon electricity were used as the base case and as low-carbon electricity scenario in this study. Based on their results, the source of carbon (glucose) used in the process had the biggest impact on climate impact and land use. Two scenarios with alternative sources of carbon were therefore assessed in this study: 1.) lignocellulosic sugar from straw and 2.) lactose from whey. Carbon source and electricity source were the only parameters modified, and other values were kept the same as in Järviö et al. (2021b).

For the scenario with straw, lignocellulosic sugar was assumed to be used as a source of carbon. Lignocellulosic sugar is produced from straw with steam explosion and enzymatic hydrolysis. The data for lignocellulosic sugar production's energy consumption were based on Voutilainen et al. (2021). Secondary data from ecoinvent were used for oat straw and energy production (updated with electricity country mix for 2018–2022 for Finland). LULUC emissions were assessed for oat straw based on Lehtilä et al. (2025).

For the scenario with whey, low-quality whey was used as a source of carbon. The sugar in whey is lactose, which is hydrolyzed to glucose and galactose. It was assumed that both glucose and galactose, can be utilized by the microbes in the fermentation process. The amounts of low-quality whey were based on estimates from Valio. Low-quality whey is currently utilized as animal feed or partly in biogas production. The secondary data for whey were from the WFLDB (World Food LCA Database, version 3.5, Nemecek et al., 2019), but the allocation was modified to reflect the economic allocation with 1,14 % allocated to whey. Economic allocation was chosen because it was assessed to better reflect the relationship between the main dairy products and low-quality whey with very little value currently. LULUC emissions for dairy cow feed were assessed based on Lehtilä et al. (2025).

Cell-cultured ovalbumin (in powder format) was compared with chicken-based egg white powder. The data from Järviö et al. (2021b) were used for modeling egg white powder production but the data for egg production were changed to Finnish egg production (Silvenius et al., 2021), which uses primary data, whereas Järviö et al. (2021b) used secondary data for German egg production. The system boundary for egg white powder was kept the same as in Järviö et al. (2021b), that is, cradle-to-gate, including the egg production system (feed, laying hens), egg white powder production, and energy inputs in each phase. LULUC impacts for feed for laying hens were assessed based on Lehtilä et al. (2025).

2.2.4.2. Case 2 Pekilo®. Case 2 concerned a cell-cultured single-cell protein, Pekilo®mycoprotein, for replacing protein feeds for animals. Pekilo® is derived from the mycelium of the fungus Paecilomyces variotii, which is grown in fermentation tanks. A specific new side stream was chosen for this case study as a source of carbon for the fermentation process. Side streams from a xylitol factory, producing xylitol from oat hulls, were used as they were found suitable for Pekilo® in test runs by Enifer. The system boundary for Pekilo® production using xylitol-based side streams was defined as cradle-to-gate, including the cultivation of oats, production of other raw materials, oat mill processes, xylitol factory processes, the Pekilo® production process (including media preparation, fermentation, separation and drying), all the energy inputs in each phase, and the treatment of production waste. Pekilo® production was assumed to happen next to the xylitol factory and no transportation was included in this phase. The side streams from the xylitol factory are oat hull-based as xylitol is made from oat hulls. All the processes related to oat (oat cultivation, oat mill) were therefore also included in the system boundary. The data for oat cultivation were based on Hietala et al. (2022) but the share of organic soils was modified to the average share of organic soil cropland in Finland (11 %). LULUC emissions for oat cultivation were assessed based on Lehtilä et al. (2025). The inventory data for the oat mill and xylitol factory were collected from Fazer's production sites. For the xylitol factory data were partly based on estimates as the factory was not yet in full production. An economic allocation was used to allocate the impacts of the oat mill between oat flakes and oat hulls and the impacts of the xylitol factory to different outputs. All the data from the oat mill and xylitol factory are confidential. The data for the Pekilo® production process with a xylitol side stream were based on pilot runs conducted by Enifer. The data for Pekilo® production are confidential.

Soy protein concentrate produced in Brazil was used as the conventional production system for comparison as Pekilo® can substitute for soy protein concentrate in fish feed. The soy used in fish feed is often from Brazil (Johansen et al., 2022). The system boundary for soy protein concentrate was cradle-to-gate, including soybean cultivation and related LULUC emissions in Brazil, the soy protein concentrate production process and energy inputs in each phase. The data for soy protein concentrate were based on the Agri-footprint database, version 6.3 (Blonk et al., 2022). LULUC emissions were estimated as uniformly as possible with the Finnish products, but Brazil does not have National GHG Inventory data available. Therefore, the LULUC emissions were estimated based on database data (Agri-footprint) enhanced with N2O and CH4 emissions from organic soils based on IPCC (2014) emission factors and N2O emissions from N mineralisation and immobilisation on mineral soils based on IPCC (2006) emission factors.

2.2.4.3. Case 3 Vertically farmed lettuce. The results from Joensuu et al. (2024) were utilized for the new production technology (vertical farming of lettuce) and the conventional technology (traditional greenhouse-grown lettuce). The system boundary for vertical farming of lettuce and greenhouse-grown lettuce were the same: cradle to farmgate. This included the inputs used in production (fertilizer, pesticides, seeds, substrate, irrigation water and pots), packing and packaging materials, temporary onsite refrigerated storage, hazardous waste management, energy and transportation in all phases and direct and indirect emissions caused by fertilizer use. The system boundaries were the same as presented in Joensuu et al. (2024) including structures.

Joensuu et al. (2024) used four different energy production scenarios for vertical farming: average energy production in Finland with or without waste heat utilization and renewable energy production in Finland with or without waste heat utilization. The renewable energy scenario they had included only electricity from wind power and hydropower and heating with biobased energy. To be consistent with other case studies in this article, we re-named this scenario low-carbon energy, as it uses only low-carbon electricity, even though heat is produced with biobased energy. For greenhouse production, Joensuu et al. (2024) used two energy production scenarios: average energy production in Finland and average renewable energy production in Finland.

2.2.4.4. Case 4 Greenhouse soy protein. Case 4 concerned growing soybean year-round in Finland and processing it to textured soy protein for food. The system boundary was cradle-to-gate, including the cultivation of soybeans in the greenhouse and all inputs related to cultivation, production of other raw materials, the textured soy protein production process (including drying, transportation, storage, and soybean oil production), all the energy inputs in each phase and treatment of production waste. The inventory data for soybean cultivation were based on cultivation experiments (CE) in Finland. The cultivation experiment and inventory data are described in more detail by Kotilainen et al. (2025). It was assumed that four crops could be produced annually. The heating method for the greenhouse was based on the average heating of Finnish greenhouses (Silvenius et al., 2022). All the impacts of cultivation were allocated to soybean. The process for textured soy protein production was based on the French textured soy protein production in the AGRIBALYSE database, version 3.1 (Asselin-Balençon et al., 2022). The process was modified with Finnish energy profiles and with ecoinvent background data. Economic allocation was used in soybean oil production according to the AGRIBALYSE process.

Finnish broiler chicken production was used as conventional production for comparison. The system boundary for broiler chicken production was cradle-to-gate, including feed production, broiler chicken parents, egg laying, hatching, and fattening, the slaughter process, and all energy inputs in each phase. The data for broiler chicken production were based on Usva et al. (2023) and Hietala et al. (2022), and land demand S. Hietala (personal communication, 20 February 2024). Values were updated with LULUC emissions for average Finnish cropland (11 % organic soil). LULUC emissions related to feed production were assessed based on Lehtilä et al. (2025).

2.3. Approach to assess total climate impact at the national level

A simple approach was used to roughly assess the total potential reduction in climate impact if the four new production solutions replaced some of the conventional production at the national level. First, the product level results for climate impact and land occupation were scaled up to potential annual impacts by multiplying them by the estimated production amounts in Finland. The scenarios with the lowest climate impact were used from each case. The climate impacts between the new and conventional production solutions in each case were compared and the reductions from all cases were summed. The land occupation, expressed in area-time (m^2a), was then converted to only area (m^2) by dividing it by the time of occupation. The land area needed for the new production solutions was compared with the conventional solutions. In cases where the new solution required less land area, the saved land was assumed to be reforested, and the climate impact of reforestation and the total climate impact were summed.

2.3.1. Annual production estimates

The potential annual production amounts were estimated firstly based on availability of raw materials and secondly on a realistic share of conventional production that could be replaced. The estimated potentials are presented in Table 2. The assumptions used for estimating the potentials are presented in the supplementary material.

2.3.2. Reforestation potential

The reforestation potential of the saved land area was assessed based on the same methodological framework (Lehtilä et al., 2025) as LULUC emissions. For simplicity, reforestation was only assessed for the saved land in Finland. This means that any land saved in case 2 between Pekilo® and Brazilian soy protein concentrate was not considered in the reforestation potential. The reforestation potential includes the total net carbon sequestration in living biomass (i.e., tree biomass) and mineral soils related to conversion from cropland to forest land. The estimates for the carbon sequestration per ha of cropland converted to forest were based on the national GHG inventory of Finland (Statistics Finland, 2023). The total carbon sequestration in the reforested area was divided by 20 years to allocate the sequestration for a single year according to the IPCC (2006). In addition to carbon sequestration, the emissions from drained organic soils, which will continue after reforestation, were included. The data used to estimate the annual organic soil emissions on forest land were from the national GHG inventory of Finland (Statistics Finland, 2023). The reforestation impacts were presented as t CO_2 eq/year.

Table 2
Estimated potential annual production amounts.

Production system	Estimated annual production
Case 1 Ovalbumin	10,000 t protein
Case 2 Pekilo®	3800 t protein
Case 3 Vertically farmed lettuce	5000 t product
Case 4 Greenhouse soy protein	12,000 t protein

3. Results

3.1. Product level

3.1.1. Case 1 Ovalbumin

Both the climate impact (Fig. 1) and land occupation were lower for cell-cultured ovalbumin than for chicken-based egg white powder. Climate impact, including LULUC emissions for cell-cultured ovalbumin, was 52–74 % smaller (16–59 % excluding LULUC emissions), and land occupation 88–93 % smaller than for egg white powder. The best results for cell-cultured ovalbumin were obtained with carbon source from a side stream, either from straw or from low-quality whey, and using low-carbon electricity. For cell-cultured ovalbumin, the impacts (both climate impact and land occupation) were mainly caused by the carbon source and the process's energy use. For chicken-based egg white powder, the impacts were caused mainly by the production of feed for laying hens and the feed-related LULUC emissions from cropland (Fig. 1).

3.1.2. Case 2 Pekilo®

Pekilo® had a 65–77 % lower climate impact, including LULUC emissions (Fig. 2), than soy protein concentrate. If LULUC emissions were not considered, Pekilo® had a 29–35 % lower climate impact with renewable and low-carbon energy production scenarios, and with the average energy production scenario, Pekilo® had a 24 % higher climate impact than soy protein concentrate. For Pekilo®, the climate impact was mainly from energy use in different life cycle stages and nutrients used. For soy protein concentrate, the climate impact came mainly from LULUC emissions. For land occupation (Fig. 2), the differences were relatively small: 6.66–9.54 m^2a/kg protein for Pekilo®, and 7.49 m^2a/kg protein for soy protein concentrate. Pekilo® had a slightly higher land occupation in one scenario. This was because of the renewable wood-based energy used in that scenario. Wood-based renewable energy has a large land occupation, as land occupation also considers the time aspect, and the growing period for wood is long. If considering only cropland occupation, Pekilo® had a smaller occupation than soy protein concentrate. For Pekilo®, the cropland land occupation was from an oat hull-based side stream used as the carbon source.

3.1.3. Case 3 Vertically farmed lettuce

With vertical farming, the climate impact of lettuce was 25–70 % lower than for greenhouse-grown lettuce with average energy (Fig. 3). If compared to greenhouse-grown lettuce with renewable energy, the climate impact of vertically farmed lettuce was 30–51 % lower, except for the scenario with no waste heat utilization and average energy, which had 22 % higher climate impact. Using low-carbon electricity and utilizing waste heat provided the best results for vertical farming. For vertical farming, the land occupation was more efficient than for a traditional greenhouse (Fig. 3). The decrease in land occupation also depended on the use of average energy or low-carbon energy.

3.1.4. Case 4 Greenhouse soy protein

The climate impact and land occupation for textured soy protein from soybeans grown in a greenhouse (Fig. 4) depended heavily on the source of electricity and heat as growing soybeans year-round in a greenhouse in Finland is very energy intensive. The climate impact for textured soy protein varied between 10.25 and 82.41 $kgCO_2eq$/kg protein, while the climate impact for broiler chicken was 25.28 $kgCO_2eq$/kg protein, including LULUC (14.81 $kgCO_2eq$/kg protein excluding LULUC). With an average Finnish energy profile, the climate impact for textured soy protein was higher than for broiler chicken. If renewable energy or low-carbon electricity was used, the climate impact was lower for textured soy protein than for broiler chicken. Due to the high energy consumption, land occupation was higher for textured soy protein (73.82–180.77 m^2a/kg protein) than for broiler chicken (42.80 m^2a/kg protein). This is because the heating was assumed to be partly

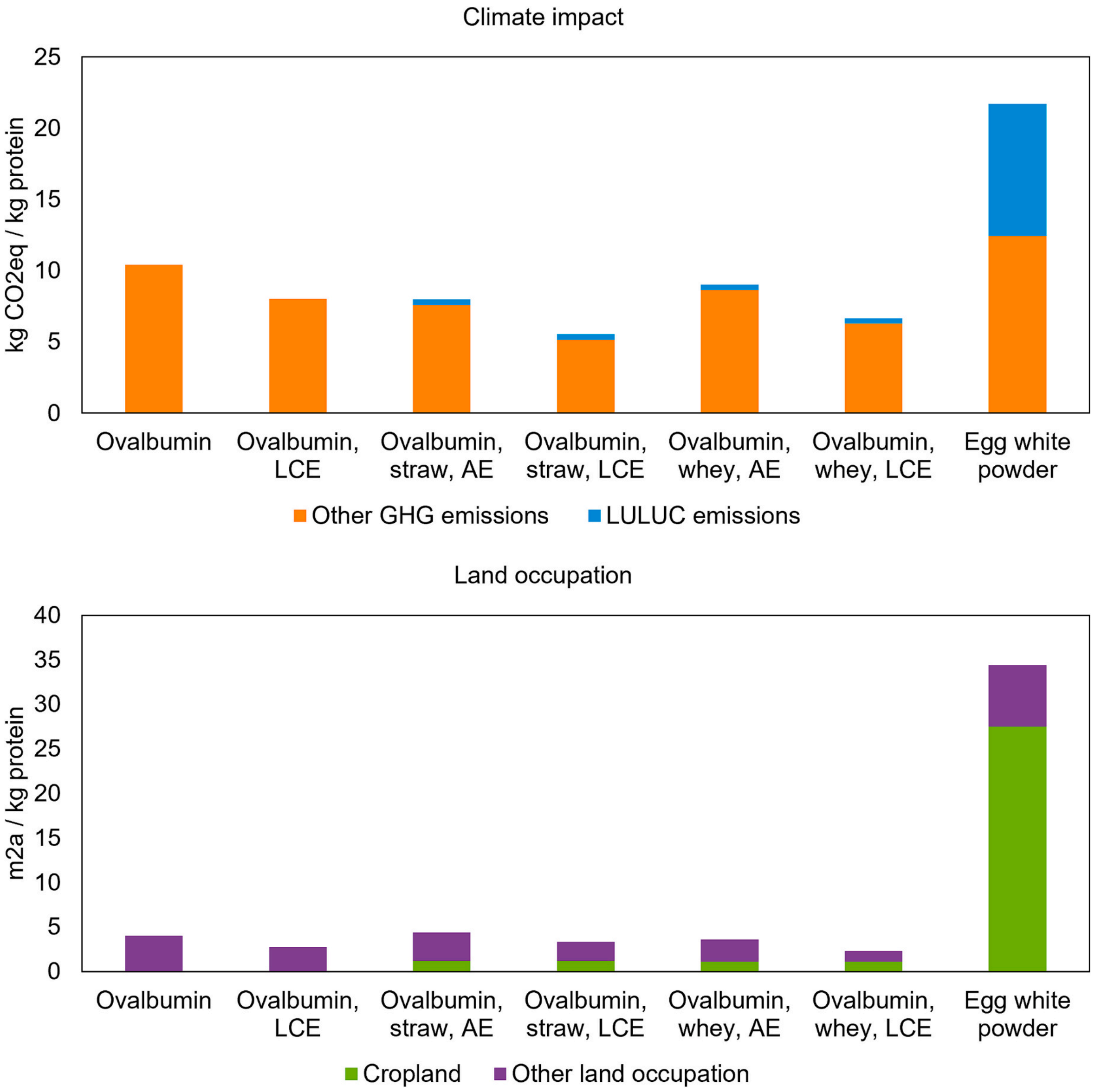

Fig. 1. Climate impact (kgCO$_2$e / kg protein) and land occupation (m^{2}a / kg protein) for ovalbumin and egg white powder. AE – average Finnish energy, LCE – Low carbon energy.

combustion-based renewable energy, which has a high land occupation as land occupation also considers the time aspect, and the growing period for wood is long. There was still a decrease in cropland when comparing textured soy protein to broiler chicken, as soy grown in a greenhouse requires no cropland.

3.2. National level

The scenarios with low-carbon energy were used from each case to assess the national impact, as these scenarios had the lowest climate impacts. At the national level, the potential reductions in the climate impact achieved by replacing conventional production with these four new solutions were 360,000 tCO$_2$eq/a. The land area saved with new solutions was 79,700 ha (of which 76,700 ha in Finland and 3000 ha in Brazil), which is around 3 % of Finland's total agricultural area (Natural Resources Institute Finland, 2024). If the saved land area in Finland was reforested, the total climate impact reductions would amount to 458,000 tCO$_2$eq/a, equivalent to around 1 % of Finland's total GHG emissions (Statistics Finland, 2024) and around 4 % of all food-related GHG emissions, including LULUC emissions (Saarinen et al., 2023). The largest potential reductions are in Cases 1 and 4 (Fig. 5). This is because these cases had higher annual production estimates than Case 3, and because in these cases, animal-based products were replaced. For case 2, no reforestation was assessed as the reforestation would not happen in Finland.

4. Discussion

4.1. Product level

The climate and land occupation impacts from new and conventional solutions were dominated by different factors. The impacts from the new solutions came mainly from direct energy consumption and raw materials, while for the conventional solutions, the impacts originated mainly from the cultivation of crops for food or feed production. GHG emissions from LULUC contributed significantly to the climate impact of the conventional solutions. While the average share of organic soil cropland in Finland is 11 %, these organic soils cause 79 % of LULUC emissions from average Finnish cropland (Lehtilä et al., 2025). N2O emissions from organic soils also contribute significantly to the climate impact of

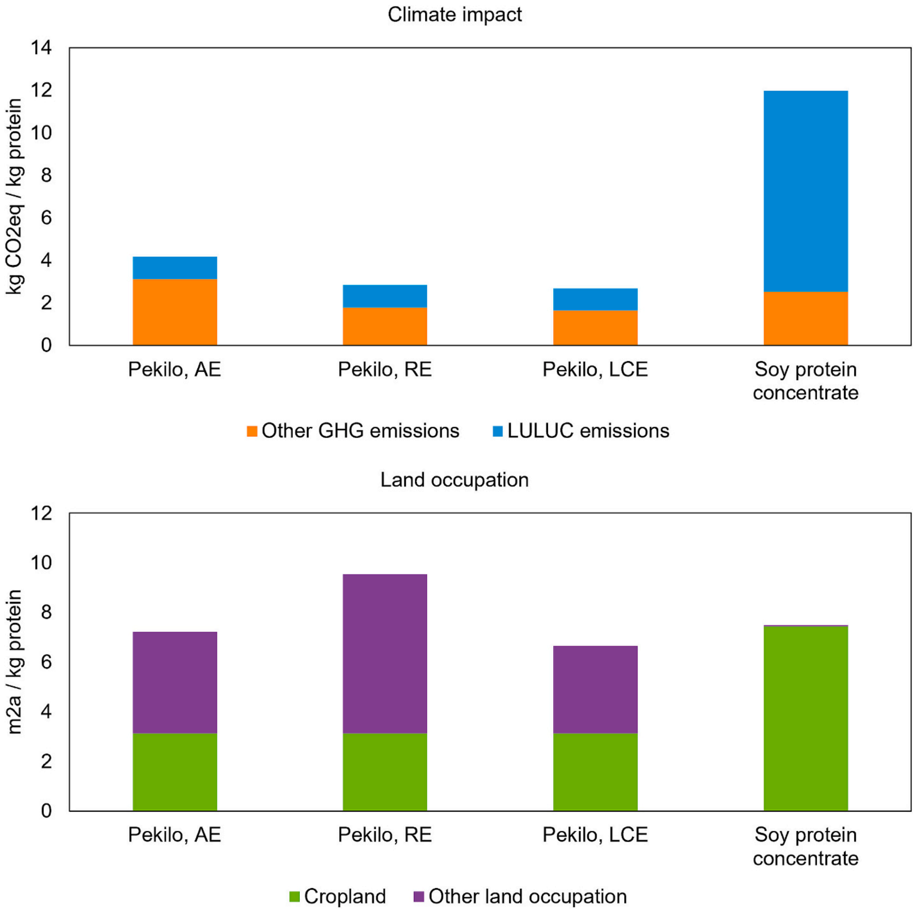

Fig. 2. Climate impact (kgCO$_2$e / kg protein) and land occupation (m^{2}a / kg protein) for Pekilo® and soy protein concentrate. AE – average Finnish energy, RE – average Finnish renewable energy, LCE – Low carbon energy.

feed production (Hietala et al., 2022). Decreasing cultivation on organic soils has a high mitigation potential for conventional food production.

For Case 1 ovalbumin, there was one clear difference between Järviö et al. (2021b) and this study regarding the origin of eggs used for chicken-based egg white powder. Järviö et al. (2021b) used secondary data for German egg production, with a climate impact of 4.77 kgCO$_2$eq/kg egg (without LULUC emissions), while we used data for Finnish eggs, with a climate impact of 1.67 kgCO$_2$eq/kg (without LULUC emissions) from a source with primary data (Silvenius et al., 2021). The difference in climate impact can partly be explained by the use of primary vs. secondary data and partly by the different feed mixes used in Finland and Germany. If German eggs had been used for egg white powder, the difference in favor of cell-cultured ovalbumin would have been higher.

In Case 1, the impacts of whey as a carbon source largely depended on the allocation method used to allocate the impacts of cheese production on different products and side streams. In this case, the whey used as a carbon source was low-quality whey, which is currently used as animal feed or in biogas production, and considered a side stream, not a product such as good-quality whey. Low-quality whey comes from many different processes, mainly from the production of cottage cheese, ricotta, and quark. It was therefore impossible to estimate the economic value of low-quality whey, and therefore secondary data was used.

In Case 2, the results for Pekilo® compared to soy protein concentrate differ from Kobayashi et al. (2023), who found in their study that a yeast-based SCP with oat-based feedstock had a higher climate impact than soy protein concentrate and smaller land use. However, the land use results are not comparable, as Kobayashi et al. (2023) measured land use as crop equivalents, whereas we used land occupation in m2a. According to them, the SCP production process relied on natural gas for heating and nutrient production for medium preparation, which contributed to the climate impact, but the share of natural gas in the climate impact was not specified. The use of natural gas is probably one of the main reasons for different results as in this study heat was produced with bio-based renewable energy or with average Finnish industrial heat (also produced mainly with bio-based energy). According to our results, Pekilo® had a lower climate impact than soy protein concentrate but due to the bio-based energy used for heat, the land occupation was at the same level as for soy protein concentrate, and in one scenario, even a little higher.

In Case 3, which was directly based on a recent study by Joensuu et al. (2024), the main finding was that the energy source and waste heat utilization were key aspects for enabling a lower climate impact for VF than for conventional greenhouse production. This is in line with previous studies (e.g. Martin et al., 2023, Casey et al., 2022, Blom et al., 2022) where the climate impact with renewable or low-carbon energy sources for VF was around 1 kgCO$_2$eq/kg lettuce. One methodological issue is whether structures should be included in the LCA of VF. Joensuu et al. (2024) recommend including structures for VF in the LCA, as they can have a significant impact on the results. In their study, structures and energy use were the most significant factors in the climate impact of vertically farmed lettuce. However, as Martin et al. (2023) point out the impact of structures is sensitive to assumptions related to the life expectancy of structures and whether the VF is in an existing building envelope or a new building. In addition, a review of LCAs of building systems by Fnais et al., 2022 showed that building energy use and other use phase impacts are prevailing in building system life cycle impacts, and the building envelope itself does not contribute significantly to the

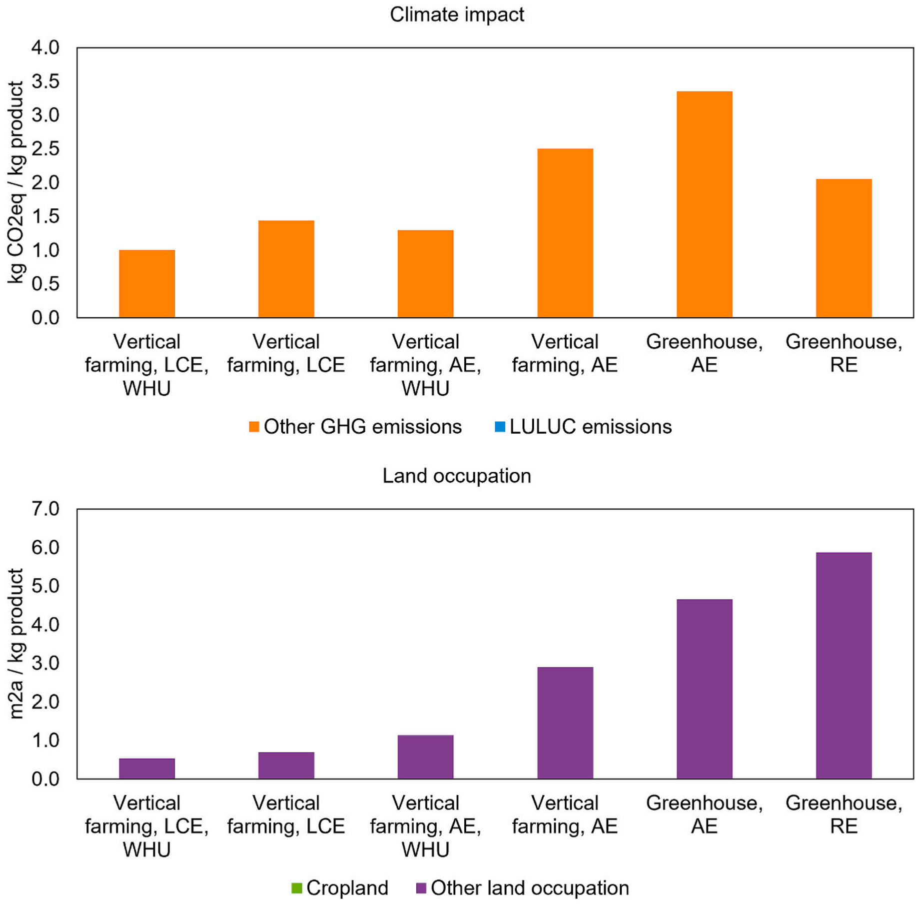

Fig. 3. Climate impact (kgCO$_2$e / kg product) and land occupation (m^{2}a / kg product) for vertically farmed lettuce and traditional greenhouse-grown lettuce. AE – average Finnish energy, RE – average Finnish renewable energy, LCE – Low carbon energy, WHU – waste heat utilization.

impacts.

In Case 4 greenhouse soy protein, the data for soybean cultivation were from one growing experiment and not from full-scale farming. To our knowledge, not many protein crops were grown in greenhouses before this experiment. A recent study by Righini et al. (2024) assessed the production and resource efficiency of soybean proteins in VF finding that while VF allowed more efficient use of land area and water for protein production than open field cultivation, high electricity consumption counterbalances the advantages. However, they only compared the results with open-field cultivation and not with animal-based proteins. In our case, the energy sources used for greenhouse production also dominated the climate impact and land occupation of textured soy protein. Furthermore, results and differences between novel and conventional food production solutions were highly dependent on the selection and assumptions made of conventional food production solutions. For example, if soybeans replaced Finnish beef, the climate benefits would be much higher than with broiler chicken, as the climate impact of (any type of) beef is many times higher than broiler chicken (e.g. Hietala et al., 2021; Humpenöder et al., 2022; Mazac et al., 2022; Mazac et al., 2023; Usva et al., 2023).

4.2. National level

This was the first, research trial of its kind to map the potential climate benefits of chosen novel food production solutions in the Finnish context with reasonable and realistic scenarios. The results showed that the studied new food production solutions could mitigate the climate impact at the national level when replacing conventional food production solutions.

One aim of this study was to estimate the mitigation potential of reforestation. Reforestation is of course not the only possible land occupation for the saved land. From the market perspective it is difficult to say what would be the most realistic land occupation. It is possible that the land would remain in its current occupation in agricultural use. However, in Finland any land that would be freed from agricultural use, would likely be slowly naturally reforested, if no other specific use would be assigned to it.

The reforestation impact (tCO$_2$eq/year) was allocated to 20 years following reforestation. This means that the impact of reforestation was temporary, and no longer considered 20 years after the reforestation year. Reforestation was estimated only to saved land in Finland. The reforestation impact could be higher if also saved land between Pekilo® (Case 2) and soy protein concentrate produced in Brazil would have been considered. Biodiversity impact was not considered in this study but would be of interest especially regarding the saved land in Brazil.

The total potential reductions estimated for climate impact and land occupation depended on the choices and assumptions made regarding for example the energy source, the conventional solution for comparison, and how the new production solutions were assumed to replace conventional production. All the total potential reductions were estimated using the scenarios with low-carbon energy, as they had the lowest climate and land occupation impacts in each case study. With biobased renewable energy, the reductions in land occupation would be lower, and the total climate impact reductions would therefore also be lower.

It can be debated what would be the conventional production solutions to be replaced, and whether the new solutions would replace any conventional production at all or would they be just additional to the

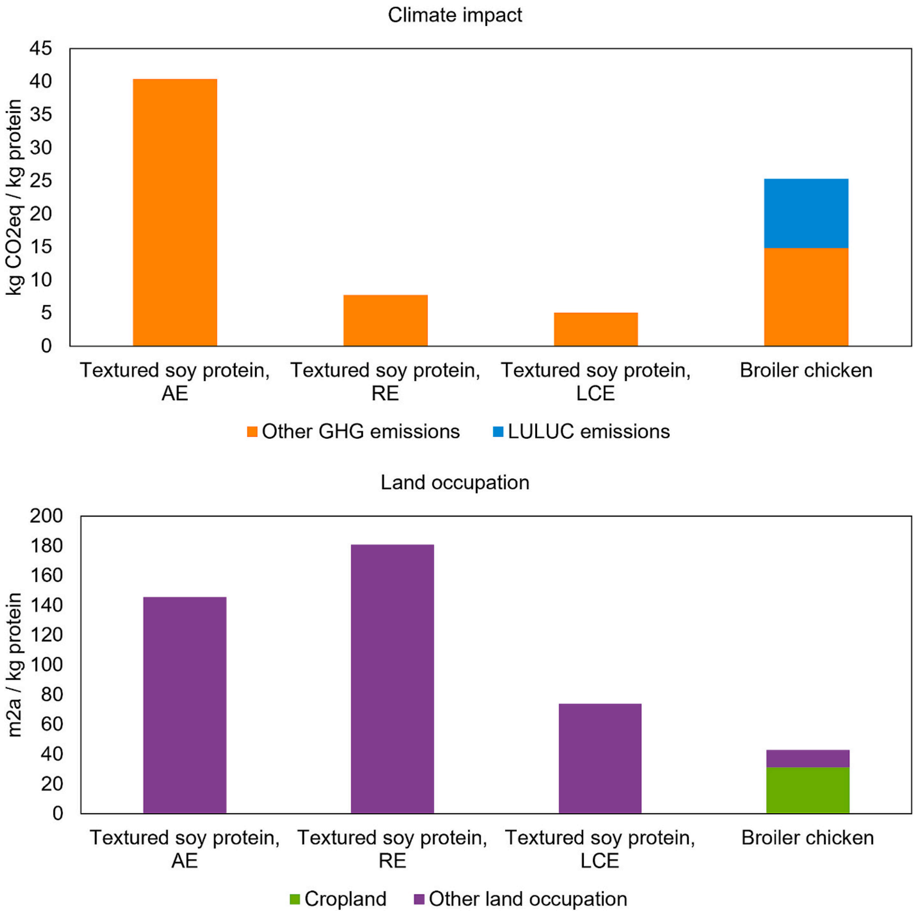

Fig. 4. Climate impact (kgCO_2e/kg protein) and land occupation (m^2a/kg protein) for textured soy protein and broiler chicken. AE – average Finnish energy, RE – average Finnish renewable energy, LCE – Low carbon energy.

current production. However, the aim was to find ways to decrease climate impact and land occupation related to food production, and animal-based products have generally higher climate impacts and land occupation than plant-based products. Therefore, replacing animal products, when possible, yields higher potential reductions.

Annual production amounts, which were used for scaling up the product level results, have high uncertainties. New food production solutions are mainly developed by start-up companies, and data on possible production amounts and scale-up plans is confidential. However, the estimates were considered to sufficiently reflect the possible potential of the new food and feed production solutions. It should be noted that the potentials were estimated for Finland and only for specific feedstocks and production processes. For example, in Case 2, Pekilo® could have higher production potential with various feedstocks, but in this study, a limiting factor was the choice of feedstock. In cellular agriculture, feedstocks can be varied, and markets are global. The total reductions for climate impact and land occupation can be much higher globally.

4.3. Other methodological uncertainties and future research

From the LCA methodological perspective, individual assumptions and choices might differ to some extent between case studies especially in the case of conventional products, as secondary data sources were used for them, and allocations and system boundaries are critical elements as previously discussed. Moreover, some methodological harmonization procedures were launched, for example most importantly, LULUC assessments for all Finnish products assessed were harmonized. This is especially critical because LULUC emissions and removals are addressed in a very variable way currently in food LCAs, and their contribution to the total climate impact is remarkable (Bessou et al., 2020, de Rosa, 2018, Hörtenhuber et al., 2014, Joensuu et al., 2021). The method used for assessing LULUC emissions by Lehtilä et al. (2025) is especially developed for considering LULUC emissions in the LCA of agricultural and forestry products.

Concerning energy, the average electricity grid mix for Finland (2022) that was used includes a share of renewable electricity, and as such, some double counting occurs when compared to renewable electricity. As the aim was to assess average production in Finland, it was still seen as appropriate to use the average mix as one scenario for electricity. It should be noted that using residual mix for electricity would significantly raise the GHG emissions of novel production solutions from all cases, as the use of energy plays a dominant role. The current remarkable shift in energy in Finland toward renewable and low-carbon energy production supports the advancement of the climate soundness of novel energy-intensive production systems.

As cellular agriculture is not yet in large-scale industrial use, there is a lack of industrial-scale data. Many previous LCAs on cellular agriculture are based on pilot-scale or laboratory-scale data and estimations (e.g. Järviö et al., 2021b; Kobayashi et al., 2023). The results need to be verified later with industrial-scale data. This is also the case for three of our case studies: Case 1 ovalbumin, Case 2 Pekilo®, and Case 4 greenhouse soy protein are based on pilot-scale data, test runs, and growing experiments. Using data from industrial-scale production would improve the accuracy of the results. Furthermore, many technical details could still be changed and improved in novel production systems, as found by Righini et al. (2024) in the case of soybean production in a greenhouse, for example. Specific uncertainty analysis, considering LCA

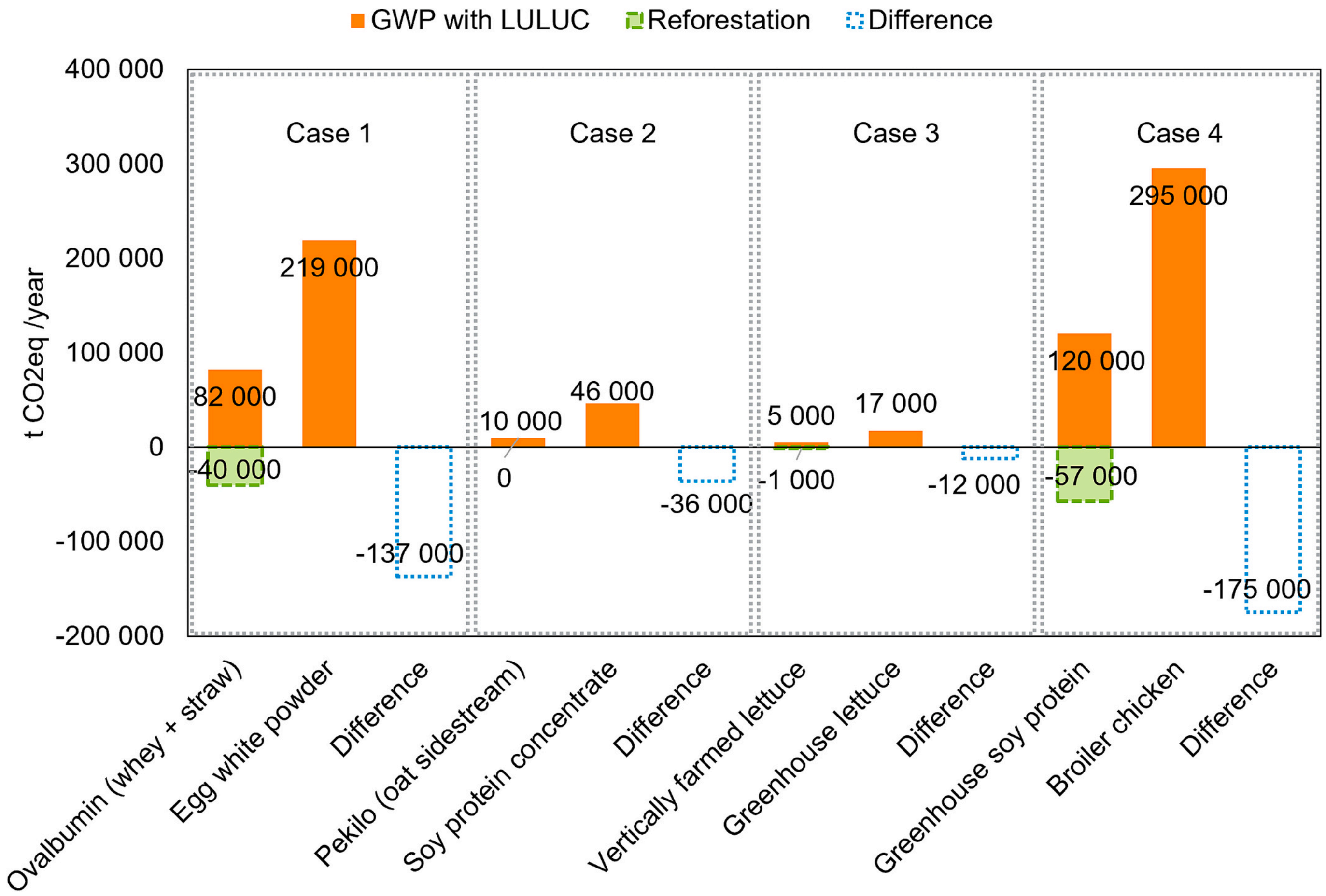

Fig. 5. Total national potential climate impact and reforestation impact for the four case studies.

methodological issues, such as LULUCs in food production, the evaluation of different energy production systems, and the characteristics of the production maturity level of novel production systems, should be considered in future research.

5. Conclusions

There is a need to find new ways to feed the growing population globally and at the same time decrease global GHG emissions. At the national level, Finland needs to find new ways to reach national carbon neutrality targets, and as one of the most emitting sectors, the food sector equally needs to contribute. The results showed that these four new solutions can have an impact at the national level when replacing conventional solutions already implemented at this scale. There is also mitigation potential in reforestation of the saved land, but main impact was achieved by replacing conventional production. The results highlight the importance of considering LULUC emissions in LCAs of conventional agricultural products, especially in areas with high shares of organic soils. For conventional food production, decreasing cultivation on organic soils is a possibility to mitigate the climate impact. The LCA results confirm that cellular agriculture and controlled environment agriculture can provide significant reductions in climate impact. When LULUC emissions are included in the assessment, cellular agriculture solutions have lower climate impacts than conventional production even with average energy sources. However, for CEA the results were not that clear. In all scenarios vertically farmed lettuce had lower impacts than greenhouse lettuce with average energy, but vertically farmed lettuce with average had higher climate impact than greenhouse lettuce with renewable energy. Textured soy protein from greenhouse grown soybean also had higher impacts with average energy than broiler chicken, and with renewable or low-carbon energy lower impacts. Using low-carbon energy sources ensures that reductions in land occupation can also be achieved, as bio-based renewable energy causes large land occupation. Furthermore, the results strengthen the view, that utilizing side streams is an essential factor supporting the environmental benefits of cellular agriculture.

New food and feed production solutions are being developed all the time. The environmental performance of these new solutions depends largely on the energy intensity of the process and energy sources. It is important to continuously and systematically assess the environmental impacts of the new solutions as the technologies are further developed to ensure that conclusions on environmental performance are based on the latest data. More information is needed about other environmental impacts besides climate impact and land occupation, economic competitiveness and consumer acceptance of technical solutions and related products, especially in the context of cellular agriculture options. Further research on other environmental impacts, such as biodiversity, is also needed.

CRediT authorship contribution statement

Katri Leino: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation. **Frans Silvenius:** Writing – review & editing, Methodology, Investigation. **Anniina Lehtilä:** Writing – review & editing. **Juha-Matti Katajajuuri:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Funding acquisition, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2025.180197.

Data availability

The data used for the new production solutions in Cases 1 and 2 are confidential. The data used for the new production solutions in Cases 3 and 4 are reported in other publications.

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